ΕΛΛΗΝΙΚΗ ΔΗΜΟΚΡΑΤΙΑ
Εθνικόν και Καποδιστριακόν
Πανεπιστήμιον Αθηνών
ΙΔΡΥΘΕΝ ΤΟ 1837

European Research Policy and Techno-scientific Networks: the solar energy technologies case study

Efthymia Nakopoulou

A thesis submitted for the degree of Doctor of Philosophy

Department of History and Philosophy of Science
National and Kapodistrian University of Athens

Athens

2023

This research is co-financed by Greece and the European Union (European Social Fund- ESF) through the Operational Programme «Human Resources Development, Education and Lifelong Learning» in the context of the project "Strengthening Human Resources Research Potential via Doctorate Research" (MIS-5000432), implemented by the State Scholarships Foundation (IKY)

Ευρωπαϊκή Ένωση
European Social Fund

Operational Programme
Human Resources Development,
Education and Lifelong Learning
Co-financed by Greece and the European Union

ΕΣΠΑ
2014-2020
ανάπτυξη - εργασία - αλληλεγγύη

Examination Committee

Supervisor Dr. Efstathios Arapostathis, Associate Professor, National and Kapodistrian University of Athens, Department of History and Philosophy of Science

Dr. Aristotle Tympas, Professor, National and Kapodistrian University of Athens, Department of History and Philosophy of Science (member of the advisory committee)

Dr. Ioannis Caloghirou, Professor Emeritus, National Technical University of Athens, School of Chemical Engineering (member of the advisory committee)

Dr. Rigas Arvanitis, Research Director, CEPED, Institut de Recherche pour le Développement – University Paris Descartes

Dr. Per Högselius, Professor, KTH Royal Institute of Technology

Dr. Aggelos Tsakanikas, Associate Professor, National Technical University of Athens, School of Chemical Engineering

Dr. Theodore Arabatzis, Professor, National and Kapodistrian University of Athens, Department of History and Philosophy of Science

Acknowledgements

Doing a PhD can be a very lonely path but you are never truly alone. First and foremost, the person that has supported me throughout this journey has been my supervisor, Stathis Arapostathis. It is hard to capture his help in a few sentences and it is equally hard to properly thank him. Not only he guided me through this entire process, taught me how to write and formulate arguments but he always encouraged me to do the best I can. I still remember his advice before I began my Masters, which I tried to hold on to throughout the PhD journey. Equally, I will not forget some of our meetings during the first months. These meetings made me determined to try finding as many answers as I could and to improve. He has been an inspiration. I would like to express my deepest appreciation to Yiannis Caloghirou, who has always been willing not only to discuss with me but also provided help in a number of ways. Without him this PhD could not have been completed. I am extremely grateful to Aristotle Tympas. He is the person that introduced me to the world of STS. His way of teaching made STS fun, interesting and understandable. He knows how to make complicated concepts easy to grasp. He had a great impact on the academic course I followed.

I was very fortunate to spend a few months in the UK, at Imperial College London, Centre for Environmental Policy, where Robert Gross was there to welcome me and discuss with me. I would like to express my deepest gratitude to Peter Pearson. His help was instrumental for the completion of this PhD. I am very grateful to him for dedicating time to me and sharing some of his wisdom and knowledge. The discussions we had during my time at Imperial are still with me and continue to inspire me. Anna Guagnini, with whom I had an opportunity to discuss my research during its early stages, provided me with insightful comments. Moreover, she helped me with a scholarly existential crisis for which I am extremely thankful for.

It is important to be part of a group that provides you with a sense of belonging but that also is willing to hear you and give you feedback. This was made feasible by the PhD Seminar series of Arapostathis and the ‘Desperate PhDs’ chat. Many thanks to Sotiri, Melina, Taylor, Ioanni (K.), Vaso, Dimitri, Matina, Dimitra, Niko, Yanni (F.), Vasiliki, Irakli.

Apart from the people that help you along the way, there are two additional things that are instrumental for all PhDs, namely funding and (access to) archives. This research would not have been feasible had it not been for the scholarship from the State Scholarships Foundation (IKY), for which I am very grateful. I need to thank Susanne from WIP Renewables for helping me with the Conference Proceedings, without her help this PhD could not have been completed. Equally, I am very thankful to all the interviewees who were willing in taking the time and talking with me. Had it not been for these interviews this PhD would not have been able to reach as deep as it did.

Friends and family can help you maintain your sanity, provide you with kind words of encouragement when you most need them and they are the people you enjoy sharing your happy moments. My friends, especially Dan, Markos and Erika have always been there for me. Sharing mutual concerns, pondering about what the future may hold for us and sharing a laugh. I am deeply grateful to have you in my life. Also, thank you Mpimpi for remining me there is more to life than the PhD and for being persistent in it. Last but definitely not least, a huge thanks to my family. They have been my rock, standing by me through thick and thin, providing me with all sorts of help and support. Simoni, mommy thank you for all that you have done for me and for your immense support and help.

Athens, December 2022

Articles

(i) E. Nakopoulou and S. Arapostathis, “Reconfiguring technologies by funding transitions: priorities, policies, and the renewable energy sources in the European Community funding schemes”, *Journal of Energy History/Revue d'Histoire de l'Énergie* [Online], n°4, published 27 July 2020. http://energyhistory.eu/en/special-issue/reconfiguring-technologies-funding-transitions-priorities-policies-and-renewable

(ii) E. Nakopoulou and S. Arapostathis, “Material flows and the geopolitics of PV: Constructing the geographies of the EU research networks for solar PV technologies”, *ICON*, forthcoming.

(iii) E. Nakopoulou and S. Arapostathis, “The need for holistically defined missions: from RRI in research projects to responsible research agendas”, *Journal of Responsible Innovation*, forthcoming.

Abstract

Our research examines the European Union's (EU) research and development (R&D) programmes for renewable energy technologies (RES), with a focus on photovoltaics (PV). In this context, we examine the funding flows of EU R&D programmes for the period from 1975 to 2020. Based on our analysis, we show how EU funding for R&D shaped the material dimension(s) of the energy system, and how these material dimensions simultaneously enabled different (integration) options while posing challenges in terms of who participates, on what terms, etc. The analysis is based on the distinction of two periods. The first period starts in 1975 and ends in 1998, while the second period begins in 1999 and is still ongoing. The criterion for this periodization is the relationship between EU research policy and energy and industrial policy, and how changes in the relationship between these EU policy areas affected the character and content of research activities and led to a reorientation of research priorities. The dissertation has three aims. First, it aims to examine the conditions under which EU energy policy and research policy had been co-produced during the period under study, with a focus on how the changing relationship between the two has redirected research priorities for PV (and the RES field/sector). Concurrently, the conditions under which EU RES research policies and priorities have been shaped are examined. Finally, the research aims to reconstruct the historical configuration (and reconfiguration) of technoscientific research networks for PV, as they have formed in the context of national and transnational competitions (for different technologies) and the changing EU political economy for/of research. Towards this end we pose the following research questions: How has EU research policy for RES changed over time? What is the character of the PV technoscientific research networks that emerge from collaborations (supported and) promoted by EU research policy? How has the field of RES changed in terms of technology and raw material selection?

The dissertation is divided into eight chapters. Chapter 1 presents our topic and its originality, methodology, analytical framework, contribution and structure of the dissertation. The main landmarks in the history of EU research and energy policy are examined in chapters 2-3. Chapters 4-7 are the empirical chapters. In chapters 4-6 we analyse our case studies (c-Si, a-Si and CPV). In chapter 7 we extend the analysis to global supply chains and material flows for PV and in chapter 8 we summarize our main findings, draw our conclusions and make suggestions for future research.

Περίληψη

Η έρευνά μας εξετάζει τα προγράμματα έρευνας και ανάπτυξης (Ε&Α) της Ευρωπαϊκής Ένωσης (ΕΕ) για τεχνολογίες ανανεώσιμων πηγών ενέργειας (ΑΠΕ), με έμφαση στα φωτοβολταϊκά (ΦΒ). Σε αυτό το πλαίσιο, εξετάζουμε τις χρηματοδοτικές ροές των προγραμμάτων Ε&Α της ΕΕ για την περίοδο από το 1975 έως το 2020. Με βάση την ανάλυσή μας, δείχνουμε πώς η χρηματοδότηση της ΕΕ για Ε&Α διαμόρφωσε τις υλικές διαστάσεις του ενεργειακού συστήματος και πώς αυτές οι υλικές διαστάσεις ταυτόχρονα επέτρεπαν διαφορετικές επιλογές (ενσωμάτωσης) ενώ έθεταν προκλήσεις ως προς το ποιος συμμετέχει, με ποιους όρους κ.λπ. Η ανάλυση βασίζεται στη διάκριση δύο περιόδων. Η πρώτη περίοδος ξεκινά το 1975 και τελειώνει το 1998, ενώ η δεύτερη περίοδος αρχίζει το 1999 και συνεχίζεται ακόμη. Το κριτήριο για αυτήν την περιοδολόγηση είναι η σχέση μεταξύ της ερευνητικής, ενεργειακής και βιομηχανικής πολιτικής της ΕΕ, και πώς οι αλλαγές στη σχέση μεταξύ αυτών των πολιτικών της ΕΕ επηρέασαν τον χαρακτήρα και το περιεχόμενο των ερευνητικών δραστηριοτήτων και οδήγησαν στον επαναπροσανατολισμό των ερευνητικών προτεραιοτήτων.

Η διατριβή έχει τρεις στόχους. Πρώτον, στοχεύει να εξετάσει τις συνθήκες υπό τις οποίες η ενεργειακή και ερευνητική πολιτική της ΕΕ συμπαρήχθηκαν κατά την εξετασθείσα περίοδο, με έμφαση στο πώς η μεταβαλλόμενη σχέση μεταξύ των δύο έχει ανακατευθύνει τις ερευνητικές προτεραιότητες για τα ΦΒ (και τον τομέα των ΑΠΕ). Παράλληλα, εξετάζονται οι συνθήκες υπό τις οποίες έχουν διαμορφωθεί οι ερευνητικές πολιτικές και προτεραιότητες της ΕΕ για τις ΑΠΕ. Τέλος, η έρευνα στοχεύει να ανακατασκευάσει τα τεχνοεπιστημονικά ερευνητικά δίκτυα των ΦΒ, όπως αυτά έχουν διαμορφωθεί (και αναδιαμορφωθεί) ιστορικά, στο πλαίσιο εθνικών και διεθνικών διαγωνισμών (για διαφορετικές τεχνολογίες) και στο πλαίσιο της μεταβαλλόμενης πολιτικής οικονομίας της ΕΕ για την έρευνα. Για το σκοπό αυτό θέτουμε τα ακόλουθα ερευνητικά ερωτήματα: Πώς έχει αλλάξει η ερευνητική πολιτική της ΕΕ για τις ΑΠΕ, κατά την εξετασθείσα περίοδο; Ποιος είναι ο χαρακτήρας των τεχνοεπιστημονικών ερευνητικών δικτύων των, τα οποία προκύπτουν από τις συνεργασίες που προωθεί η ερευνητική πολιτική της ΕΕ; Πώς έχει αλλάξει ο τομέας των ΑΠΕ σε επίπεδο τεχνολογιών και πρώτων υλών;

Η διατριβή χωρίζεται σε οκτώ κεφάλαια. Στο Κεφάλαιο 1 παρουσιάζεται το θέμα μας και η πρωτοτυπία του, η μεθοδολογία, το αναλυτικό πλαίσιο, η συμβολή και η δομή της διατριβής. Τα κύρια ορόσημα στην ιστορία της έρευνας και της ενεργειακής πολιτικής της ΕΕ εξετάζονται στα κεφάλαια 2-3. Τα κεφάλαια 4-7 είναι τα εμπειρικά κεφάλαια. Στα κεφάλαια 4-6

αναλύουμε τις περιπτωσιολογικές μελέτες (c-Si, a-Si και CPV). Στο κεφάλαιο 7 επεκτείνουμε την ανάλυση σε παγκόσμιες αλυσίδες εφοδιασμού και ροές υλικών για ΦΒ και στο κεφάλαιο 8 συνοψίζουμε τα κύρια ευρήματά μας, παραθέτουμε τα συμπεράσματά μας και κλείνουμε με προτάσεις για μελλοντική έρευνα.

Table of Contents

Chapter 1. Introduction……………………………………………………….………1

1.1 Originality………………………………………….…………………………..2

1.1.1 Aims and research questions……………………………………………………4

1.2 Analytical framework……………………………………………….……………5

1.2.1 From EU research policy history to Innovation Studies: the importance of mission-oriented policies…………………………………………………….………...6

1.2.2 Transnational Historiography of (technological) infrastructures: the knowledge infrastructures………………………………………….………………...8

1.2.3 The technoscientific research networks: bringing technologies to the fore……..11

1.2.4 Geopolitics, externalities and scarcity: following the raw material flows………13

1.2.5 On power, power relations and empowerment………………………………...15

1.3 Methodology ……………………………………..………………………………17

1.4 Contribution……………………………………….……………………………19

1.5 Dissertation structure…………………………………………….…………….22

References…………………………………………..……………………………..24

Chapter 2. An EU research policy history……………………………...30

2.1 EU research policy in the first period…………………………………………30

2.1.1 From the first links of research to economic growth to the Single European Act and the Treaty of Maastricht……………………………………………….……31

2.1.2 Research priorities and the role of RES and PV in the Framework Programmes………………………………………………………………………….35

2.1.2.1 The start of renewable energy research: the trigger of the 1973 (oil) energy crisis……………………………………………….…………35

2.1.2.1.1 The 'place' for each RES: defining the geographic boundaries and possible uses for each RES……………………………………38

2.1.3 Formulating an EU research policy to promote the competitiveness of European industry………………………………………………………………41

2.1.3.1 Allocation of research funding in the energy sector……………………44

2.1.3.1.1 The place of PV in research funding………………………..46

2.1.3.2 Low crude oil prices, the Chernobyl accident, and the climate change 'rescue'…………………………………………………………………47

2.2 Establishing an EU-wide research policy: narrowing the gap between research and market……………………………………………………………………50

2.2.1 The European Research Area: aligning member states research policies with those of the EU………………………………………………………………50

2.2.2 The Strategic Energy Technology Plan and the European Technology Platforms………………………………………………………………………52

2.2.2.1 The Strategic Research Agenda(s) for PV……………………………53

2.2.3 The second period Framework Programmes……………………………...55

2.3 Concluding remarks……………………………………………………………63

References……………………………………………………………………..65

Chapter 3. An EU energy policy history……………………………………70

3.1 Introduction…………………………………………………………………70

3.1.1 An EU energy history: landmarks and energy crises…………………………71

3.1.1.1 The first and second oil crises: the oil 'era' begins to crumble………72

3.1.1.2 Establishing a common European energy market: liberalization of the electricity market………………………………………………………73

3.1.1.3 The current energy crisis: shortages along the gas pipeline…………..76

3.1.2 Different types of generating and consuming electricity: users, scale, and the infrastructures they require……………………………………………………….……77

3.1.2.1 RES reconfiguring the electricity grid: smart grids, smart meters, and net metering……………………………………………………….……………80

3.1.3 The role and place of RES in EU's energy policy………………………………82

3.1.3.1 The inaugural steps towards an EU-wide energy policy: the role of RES and RES entanglers…………………………………………………….……..82

3.1.3.1.1 The relationship between the EU-member state priorities: the role of Germany……………………………………………………89

3.1.3.1.2 The RES Directives: from indicative to binding targets……94

3.1.3.1.3 The establishment of the European Renewable Energy Council...……………………………………………………………..98

3.1.4 The Treaty of Lisbon: towards an EU-wide, common, energy policy?………..100

3.1.4.1 The EU's long-term energy strategy and the ongoing energy crisis: the role of RES…………………………………………….……………101

3.1.4.1.1 The place of RES in the EU electricity generation mix……103

3.2 Concluding remarks………………………………………….……………..104

References……………………………………….…………………………107

Chapter 4. The PV sector was built on c-Si: the dominance of the Northern European semiconductor electronics industry………….115

4.1 Introduction……………………………………………….…………………...115

4.2 The initiation of PV research as a response to the energy crises: the directionality of the semiconductor electronics in selecting the dominant semiconductor………………117

4.2.1 Instrumentalizing research: the directionality of industrial policy in research policy…………………………………………….…………………………118

4.2.2 Laying the foundations: the first ten years of PV research……………………120

4.2.3 The actors that forged the basis of c-Si PV research: the semiconductor electronics industry structures the base of the PV field……………………………..122

4.2.4 The pilot programme: the first transnational PV networks are forged………..129

<u>4.2.4.1 The first pilot programme (1979-1983): constructing the first European PV market</u>…………………………………………………….……………..130

4.2.5 The competition runs high: shifting to a-Si and the emergence of the first technoscientific research networks…………………………………………………138

<u>4.2.5.1 The temporary shift to a-Si: tracing the events that led to the EC's R&D 'U-turn'</u>…………………………………………………….……………..139

<u>4.2.5.1.1 The Japanese competition runs high: a new market for PV!?</u>…………………………………………………………140

<u>4.2.5.1.2 Organizing the a-Si research: the desirable outcome is for the European industry to reach the commercialization stage</u>…………...142

<u>4.2.6.2 The first technoscientific c-Si network is established</u>……………….144

4.2.7 The return of c-Si: the 'traditional' frontrunner in R&D funding……………..145

<u>4.2.7.1 Oh a-Si, where are thou?</u> ……………………………………………146

<u>4.2.7.1.1 The views of the international PV community</u>……………..147

<u>4.2.7.1.2 The EC's rationale and research results</u>…………………..149

<u>4.2.7.1.3 Settling the standards dispute: the winner takes it all!</u> …….151

<u>4.2.7.2 The geography of c-Si funding: the dominance of the European North continues</u>…………………………………………….………........155

<u>4.2.7.3 The technoscientific c-Si research networks: the concentration in the European North continues</u>……………………………………………..158

4.2.8 The directionality of research policy to energy policy: demarcating the pilot, research, and demonstration components…………………………………………..172

4.2.8.1 Distinguishing between the research and pilot components of EU R&D programmes: delineating the means of achieving the R&D aim…...............173

4.2.8.2 Defining what 'demonstration' means: the relationship between research and demonstration and the 'place' of the market……………………………175

4.2.8.3 **From** Pilot **to** Demonstration: tracing the continuities and delineating their differences……………………………………………………..177

4.2.8.3.1 The actors and technologies of the demonstration programme: continuity with the R&D programmes………………………………178

4.3 Concluding remarks……………………………………………………...179

References…………………………………………………………………….182

Chapter 5. The politics of the c-Si research networks direct energy policy: towards energy market liberalization……………………………192

5.1 Introduction…………………………………………………………………192

5.1.1 The geographical distribution of c-Si funding…………………………………194

5.1.1.1 Distribution of EU R&D funding by technology……………………198

5.1.2 The directionality of EU's energy policy and the call for 'upscaled production': c-Si research 'enters' the factory and strives to deliver industrial pilot production lines…………………………………………………………………………199

5.1.3 Technoscientific c-Si research networks: the hegemony of the European North expands beyond c-Si…………………………………………………………...207

5.1.3.1 C-Si in Germany: research needs to be transferred to the industry…210

5.1.3.2 The Belgian framework and network………………………………..216

5.1.3.3 The Dutch framework and network…………………………………217

5.1.3.4 PV in Norway: from a marginal place domestically to solving Europe's Si problems……219

5.1.3.4.1 The Norwegian R&D landscape and c-Si networks……220

5.1.4 The c-Si periphery……223

5.1.5 Responding to the Si crisis: thin films come over to the c-Si side……225

5.1.5.1 The research agenda for c-Si thin films: appropriating a-Si know-how……225

5.1.5.1.1 The Swiss network: from cutting-edge research in thin films to innovative contributions to c-Si research……228

5.1.5.2 The directionality of c-Si to the a-Si R&D geography, networks, and research priorities……230

5.1.5.2.1 The influence of the c-Si thin film agenda on the geographical distribution of the a-Si R&D funding……230

5.1.5.2.2 The reformulation of the a-Si networks: mirroring the c-Si networks……232

5.1.5.2.3 An entry point for attaining larger R&D funding shares…233

5.1.6 The view from the market: the PV sector becomes industrial……234

5.1.6.1 International competition in PV: the rise and fall of the EU……237

5.1.7 The uses for PV: the unique options for integration offered by small-scale PV……239

5.2 Conclusions……243

References……247

Chapter 6. The marginalized alternative of CPV: the Southern option for large-scale power plants……253

6.1 The first steps of CPV: from marginalization to limited inclusion with the aid of the European North……………………………………………………………………253

6.1.1. Classifying the CPV systems: different scales for different applications and uses……………………………………………………………………………….253

6.1.2 CPV research priorities: the directionality of industrial policy……………….255

6.1.3 The first two energy R&D programmes: lack of adequate cell supply…………257

6.1.4 PV as a technological option for all?: the exclusion of (Southern European) CPV from R&D funding………………………………………………………………..261

<u>6.1.4.1 Failure to complete: the vested interests of c-Si industrial actors stand in the way of completing the first CPV demonstration project</u>………………261

<u>6.1.4.2 Geography as an exclusion criterion: EC excluded the Southern European technological option</u>……………………………………………...263

<u>6.1.4.3 One person's trash is another's treasure: Si feedstock shortage</u>……265

6.1.5 Geographical distribution of CPV funding: a collaboration between the European South and the European North……………………………………………………266

6.1.6 The UK and Spanish national research landscape……………………………267

6.1.7 A Spanish, university-driven, network: UPM as ***the*** *core of the CPV network*...269

6.2 The technoscientific CPV research networks: a technological pathway *by* the South and *for* the South……………………………………………………………………...273

6.2.1 CPV system and material coupling shift: a response to the Si crisis in PV and a technology for the Global South…………………………………………………..277

6.2.2 The reorientation of research: towards 'upscaled research'…………………280

6.2.3 The Spanish framework and network…………………………………………282

<u>6.2.3.1 The Spanish-led technoscientific research network</u>…………………285

6.2.4 The Italian framework and network……………………………………………...289

6.3 Concluding remarks: a break with the dominant technological pathway…………293

References………………………………………………………………………….298

Chapter 7. Material politics and geopolitics in PV: the dependency of the Global North to the Global South in achieving the RES transition……………………………………………………………….303

7.1 The material intensive side of the RES transition in PV…………………………303

7.2 Following the material flows: material dependencies and changing geopolitical dynamics……………………………………………..…………………………..305

7.2.1 Pressures along the silicon supply chain: the silicon feedstock shortages of the 1980s and the silicon crisis in PV…………………………………………………305

7.2.1.1 The Si feedstock shortage caused by the electronics industry: the EU research response…………………………………………………….……..306

7.2.1.2 The silicon crisis in PV: the first tremors in the raw material supply & the PV sector on the path to industrialization………………………………313

7.2.2 Tracing the geopolitics of the PV raw materials: a mining production transfer from the Global North to the Global South…………………………………………319

7.2.3 From mining to refining: tracing the mineral flows…………………………..327

7.2.4 From production to installation: the geographical concentration in the Global South continues……………………………………………………….……………..331

7.2.5 Externalities accounted for: the impact of extractive industries and the production steps for PV…………………………………………………….…………………333

7.2.6 The EU research networks' response to the Si crisis: geopolitics and externalities accounted for? ……………………………………………………….……………..338

7.2.6.1 Building a market for PV: what about the users? …………………..341

7.2.7 Escalating the tensions between the EU and China……………………………344

7.3 Concluding remarks…………………………………………………….…………..345

References……………………………………………….……………………………350

Chapter 8. Conclusions…………………………………………………….……..359

8.1 RES transition: fostering new dependencies and re-defining the Global North – South divide……………………………………………….……………………………362

8.1.1 Constructing the technology market of the EU………………………………..362

8.1.2 Dependencies and geopolitical dynamics shift fostered and reinforced by the RES transition………………………………………………………….…………………...365

8.1.3 Global North-South divide: the unique case of China…………………………369

8.2 The political economy of the EU for/of research: insights into the characteristics of the Knowledge-Based Economy………………………………………………….…….370

8.2.1 The Commission-member states interplay: the chicken and the egg problem…371

8.2.1.1 Pilot and Demonstration: the 'risk' overlap…………………………374

8.2.2 It has never been equal: the politics of the networks…………………………..374

8.2.2.1 Technological competitions: marginalizing CPV…………………...379

8.2.3 Insights for the Knowledge-Based Economy characteristics: the analytical concept of upscaled research……………………………………………………..…380

8.3 The co-production of the EU research and energy policies: constructing a new social order in the energy market………………………………………………….…………..388

8.3.1 A new social order: constructing and liberalizing the EU energy market……..391

8.4. Moments of 'intervention' and 'opportunity' and the necessity in defining holistically the problems…………………………………………….…………………………392

8.4.1 Crises as 'opportune moments'………………………………………………..392

8.4.2 The need for holistically defined problems: based on how the problem is defined it will determine the solutions we will provide……………………………………394

8.5 Future research recommendations…………………………………………………399

References…………………………………………..…………………………401

Bibliography…………………………….……………………………..………407

Appendix A…………………………………………..…………………...462

List of Tables

Table 4.1 Breakdown of the pilot projects: coordinators, solar cell material and manufacturer……………………………………………………………………………...133

Table 5.1 Norwegian actors, directing the national R&D activities on c-Si PV, throughout the Si value chain. ……………………………………………………..…………………...220

Table 5.2 A-Si funding share and comparison, 1999-2013. …………………………………233

Table 7.1 Polysilicon feedstock production volume (in metric tons) by manufacturer, 2005 – 2013…………………….……………………………………………………….…………..329

List of Figures

Figure 2.1. FP1-FP7 Energy R&D Funds (in EUR million). ……………………………………45
Figure 2.2 Actors setting-up the research priorities for PV listed by country and their respective geographical distribution (2007 SRA left, 2011 SRA right).……………………………………55
Figure 3.1 EU-28 gross electricity production (in TWh) per fuel, 1990-2013……………..104
Figure 4.1 Geographical distribution of c-Si funding, 1975-1984…………………………...121
Figure 4.2 Geographical funding distribution of pilot projects, 1979-1984………………...132
Figure 4.3 Map of the PV pilot project installations………………………………………..132
Figure 4.4 Annual global PV production (in MWp), 1976-1992……………………………136
Figure 4.5 Production capacity of European PV manufacturers in 1979, by company. ……136
Figure 4.6 R&D funding distribution by technology (1985-1988)…………………………138
Figure 4.7 Market share by PV technology, 1980-1990……………………………………141
Figure 4.8 The first c-Si technoscientific research network………………………………...145
Figure 4.9 PV R&D funding distribution by technology and activity, (1989-1998)………...146
Figure 4.10 Geographical distribution of c-Si funding, 1989-1998…………………………156
Figure 4.11 The c-Si technoscientific research networks, 1989-1998………………………159
Figure 5.1 Geographical distribution of c-Si R&D funding, 1999-2013. …………………...195
Figure 5.2 Geographical distribution of c-Si R&D funding, by programme………………...196
Figure 5.3 EU R&D funding distribution by PV technology, 1999-2013…………………..199
Figure 5.4 The c-Si technoscientific research networks of the second period………………209
Figure 5.5 Comparison of geographical funding distribution of a-Si R&D funding (1989-2013)………………………………………………………………………………...232
Figure 5.6 Comparison of a-Si technoscientific research networks (1989-2013)………………………………………………………………………………...233
Figure 5.7 Global annual cell production (in MWp), 1996-2005……………………………236
Figure 5.8 Global annual cell/module production, 2005-2016e……………………………..236
Figure 6.1 Geographical distribution of CPV funding, 1989-1998…………………………267
Figure 6.2 The CPV networks, 1989-1998…………………………………………………271
Figure 6.3 Geographical distribution of CPV based on funding, 1999-2013……………….275
Figure 6.4 Annually installed CPV capacity (in MW) ……………………………………278
Figure 6.5 CPV geographical funding distribution by FP, 1999-2013……………………..283
Figure 6.6 CPV networks, 1999-2013………………………………………………………287
Figure 7.1 Regional production of Si, (1994-2019) ………………………………………318

Figure 7.2 Minerals (in blue) and their by-products (in orange) for the PV cells……………322
Figure 7.3 Regional production of Zinc and Copper (1994-2019) …………………………324
Figure 7.4 Regional production of Bauxite and Aluminum (1994-2019) …………………...324
Figure 7.5 Regional production of Indium and Germanium – Zinc by-products (1994-2019)…………………………………………………………………………………...325
Figure 7.6 Regional production of Arsenic and Selenium – Copper by-products (1994-2019)…………………………………………………………………………………...325
Figure 7.7 Regional production of Gallium – Zinc, Aluminum and Bauxite by-product (2019)…………………………………………………………………………………326
Figure 7.8 The PV production chain: from mining to recycling……………………………335
Figure 8.1The relation between the KBE and the technoscientific research networks……..387
Figure 8.2 A schematic representation of the relationship between EU research and energy policies, 1975-2020……………………………………………………………………389

Page intentionally left blank

Chapter 1. Introduction

Following the Paris Agreement, the European Commission has proposed a series of measures to respond to the climate change crisis.[1] Most notably, the EU has committed to reducing greenhouse gas emissions by 55% by 2030, while under the EU's long-term energy strategy, the goal is to become carbon-neutral by 2050.[2] In this context, it was envisioned that RES would account for 32% of final energy consumption (in 2030), with solar photovoltaic energy (PV) being an important pillar in this vision. This share has (further) increased to 45% due to the energy crisis triggered by the ongoing war between Russia and Ukraine. The climate crisis put pressure on the transformation of the energy system, while the current and ongoing energy crisis adds to this urgency. The decisions taken give clear priority to RES, especially solar PV energy.[3] In the midst of this energy crisis, the choices of (RES) technologies depend largely on efforts done at the level of research and development (R&D), which provide the technical and technological solutions available to the EU to address this crisis. Our research examines the European Union's (EU) R&D programmes for renewable energy technologies (RES), with a focus on PV. In this context, we examine the funding flows of EU R&D programmes for the period from 1975 to 2020.[4] Based on our analysis, we show how EU funding for R&D shaped the material dimension(s) of the energy system, and how these material dimensions simultaneously enabled different (integration) options while posing challenges in terms of who participates, on what terms, etc.

Our analysis is based on the distinction of two periods. The first period begins in 1975 and ends in 1998, while the second period begins in 1999 and is still ongoing.[5] The criterion for this periodization is the relationship between EU research policy and energy and industrial policy and how the changes in the relationship between these EU policy areas affected the character and content of research activities and led to a reorientation of research priorities. In the first period, industrial policy directed research policy. During this period, the actors forming

---

[1] For more information about the Paris Agreement and the European Green Deal see: UN, "Paris Agreement", 2015 (https://unfccc.int/sites/default/files/english_paris_agreement.pdf).; European Commission, *The European Green Deal*, COM (2019) 640 final, Brussels, 11.12.2019.

[2] Regarding EU's commitments and long-term strategy see: European Commission, *A Clean Planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*, COM (2018) 773 final, Brussels, 28.11.2018.

[3] EcoGreen Energy, 27 May 2022, *EcoGreen Energy*, Solar Energy Deployment in EU 2030, Available online: https://www.eco-greenenergy.com/solar-energy-deployment-in-eu-2030-global-energy-crisis/, (accessed 1 June 2022).

[4] The EU research programmes (research and development – R&D) are also known as the Framework Programmes (FPs).

[5] The first period includes the first two energy R&D programmes and the first four Framework Programmes. The second includes the remaining three Framework Programmes and Horizon 2020.

the PV technoscientific research networks explored the potential applications of different PV technologies and designs, resulting in a technological pluralism. However, research efforts remained limited to a single system component, namely the solar cell. In the second period, EU energy and research policies were co-produced. The technological frontrunner determined by the EU-funded research networks formed the basis for setting the EU's energy policy targets for PV and enabled the transition to distributed generation and production and the reconfiguration of the entire energy system. On this basis, it was incorporated in the EU energy policy. The EU energy policy targets for PV installation gave the green light for the PV sector to become industrial (in terms of production). In turn, these goals reoriented research to solve production problems, while the targets led to a raw material crisis in PV (silicon crisis in PV). The technological decisions made by the networks and legitimized by the European Commission had an impact on constructing the technology market. Furthermore, the EU's long-term energy strategy forms the basis for the member states' vision. The Commission has been successful in setting the targets and providing a variety of choices to achieve them. Although not all member states have promoted and/or favoured the transition to distributed generation and consumption, the transition to RES represents a reconfiguration of the energy system as these technologies enable a transition to decentralized electricity generation and consumption. At the same time, EC has provided (via research) another option for reconfiguring the energy system and expanding the energy market (small-scale PV systems for distributed electricity generation and consumption).

1.1 Originality

The originality of our research stems from the gap in the literature examining EU research policy for RES. Through an extended search on Science Direct using keyword combinations (e.g. EU's or European or European Union's *and* research and development or R&D or RD&D or research development *and* renewable energy sources or RES or renewables or solar), we were able to distinguish between three broad themes: (i) energy policy, (ii) collaborative networks and (iii) EU R&D.[6]

The articles of the first theme primarily analyse legislative material and policy instruments for energy policy.[7] In this context, R&D is being presented as an instrument that acts in a way

---

[6] Please note that the analysis of EU research policy history literature is provided in section 1.2

[7] Ackermann T., and Soder L., "An overview of wind energy-status 2002", *Renewable and Sustainable Energy Reviews,* 2002, p. 67-128.; Blok K., "Renewable energy policies in the European Union", *Energy Policy*, 2006, p. 251-255.; Faaij A. P., "Bio-energy in Europe: changing technology choices", *Energy Policy*, 2006, p. 322–

complementary to policy and legislative material. In these articles EU R&D in general or EU R&D for RES concerns (little information on) specific sub-programmes such as JOULE, the RES technology-related R&D efforts and the funds of the FPs and/or the specific (RES) programmes. Therefore, although information on the different aspects of RES R&D is provided, it is not examined or evaluated. More so, although R&D is recognised as an important factor related to funds and policies, it is neither evaluated nor further questioned. The information on R&D, the Framework Programmes and the specific programmes for renewable energy is brief and not analysed in depth. The articles in the second theme discuss cooperative EU-funded networks, but the approach is different.[8,9] A common 'parameter' discussed in some of the articles is innovation. Innovation is linked to geographical distance and market exploitation. So, although innovation is a common parameter, it is associated with different variables it is studied in a different framework and for different reasons. Specific technologies and their networks are not examined. The articles in the third theme discuss EU research policy, focusing on and/or based on the FPs. In this framework, EU research policy is discussed in relation to FP funding, aims, objectives, policies and in relation to key institutions such as the ERA and the ERC, and in relation to the Lisbon agenda and to a lesser extent the Barcelona objectives.[10]

342.; Gan L., Eskeland G. S., Kolshus H. H., "Green electricity market development: Lessons from Europe and the US", *Energy Policy*, 2007, p. 144-155.; Kanellakis M., Martinopoulos G., Zachariadis T., "European energy policy - A review", *Energy Policy*, 2013, p. 1020-1030.; Mancisidor I. d., Uraga d. P., Mancisidor I. d., Lopez P. d., "European Union's renewable energy sources and energy efficiency policy review: The Spanish perspective". *Renewable and Sustainable Energy Reviews*, 2009, p, 100-114.; Mirasgedis S., Sarafidis Y., Georgopoulou E., Lalas D. P., "The role of renewable energy sources within the framework of the Kyoto Protocol: the case of Greece", *Renewable and Sustainable Energy Reviews*, 2002, p. 249–272.; Mittra B., Lucas N., Fells l., "European energy: Balancing markets and policy". *Energy Policy*, 1995, p. 689-701.; Ragwitz M., and Miola A., "Evidence from RD&D spending for renewable energy sources in the EU", *Renewable Energy*, 2005, p. 1635-1647.

[8] Defazio D., Lockett A., Wright M., "Funding incentives, collaborative dynamics and scientific productivity: Evidence from the EU framework program", *Research Policy*, 2009, p. 293–305.; Geuna A., "Determinants of university participation in EU-funded R&D cooperative projects", *Research Policy*, (1998), p. 677-687.; Kang M. J., and Hwang J., "Structural dynamics of innovation networks funded by the European Union in the context of systemic innovation of the renewable energy sector", *Energy Policy*, 2016, p. 471–490.; Laredo P., "The networks promoted by the framework programme and the questions they raise about its formulation and implementation", *Research policy*, 1998, p. 589-598.

[9] Please note that this literature is extensively analysed in the Analytical Framework section of the present chapter.

[10] Guy K., Amanatidou E., Psarra F., "Framework Programme 5 (FP5) impact assessment: a survey conducted as part of the five-year assessment of European Union research activities (1999–2003)", *Science and Public Policy*, 2005, p. 349–366.; Kaiser R., and Prange-Gstöhl H., "A paradigm shift in European R&D policy? The EU Bidget Review and the economic crisis", *Science and Public Policy*, 2010, p. 253– 265.; Luukkonen T., "Old and new strategic roles for the European Union Framework Programme", *Science and Public Policy*, 2001, p. 205–218.; Luukkonen T., "The European Research Council and the European research funding landscape", *Science and Public Policy*, 2014, p. 29–43.; Ormala E., and Vonortas N. S., "Evaluating the European Union's Research Framework Programmes: 1999-2003", *Science and Public Policy*, 2005, p. 399–406.; Pavitt K., "The inevitable limits of EU R&D funding", *Research Policy*, 1998, p. 559– 568.; Rodríguez H., Fisher E., Schuurbiers D., "Integrating science and society in European Framework Programmes: Trends in project-level solicitations", *Research Policy*, 2013, p. 1126– 1137.; Scherngell T., and Barber M. J., "Spatial interaction modelling of cross-

In summary, previous analyses of EU research policy have focused on institutional change, while the relation between EU R&D funding flows and RES technologies has never been examined. In addition, the analysis for networks examines their structural characteristics, focusing on innovation rather than different technologies. Lastly, the relationship between EU energy policy and research policy, has not been explored in the literature.

1.1.1 Aims and research questions

The dissertation has three aims. First, it aims to examine the conditions under which EU energy policy and research policy had been co-produced during the period under study, focusing on how the changing relationship between the two has redirected research priorities for PV (and the RES field/sector). Concurrently, the conditions under which EU RES research policies and priorities have been shaped are examined. Finally, the research aims to reconstruct the historical configuration (and reconfiguration) of technoscientific research networks for PV, as they have formed in the context of national and transnational competitions (for different technologies) and the changing EU political economy for/of research. To achieving the above aims, we have set a series of objectives. We examine EU research and energy policies and how they had been co-produced. We examine the relationship between EU R&D funding programmes and the formation of knowledge and innovation in the field of PV. We examine the PV technoscientific research networks, as they have been historically configured and reconfigured, and their impact on EU research policy. At the same time, we map the changes (continuities and discontinuities) in the PV technoscientific research networks.

We pose three main research questions, which are further specified by follow-up research questions to guide our research. In particular, we ask the following research questions: **(i)** How has EU research policy for RES changed over time? To this end, we have formulated the following research questions: How have changes at the legislative, institutional and regulatory levels reshaped EU research policy? What are the characteristics of the EU political economy for/of research? How has the EU political economy for research for PV changed in each period? **(ii)** What is the character of the PV technoscientific research networks that emerge from collaborations (supported and) promoted by EU research policy? To answer this question, we ask the following research questions: What is the (dynamic) relationship between the public and private sectors of PV technoscientific research networks, that defines and guides EU

---

region R&D collaborations: empirical evidence from the 5th EU framework programme", *Papers in Regional Science*, 2009, p. 531-546.

research policy? How has the above relationship affected the relationship between knowledge and technology production and the shaping of the energy paradigm? **(iii)** How has the field of RES changed in terms of technology and raw material selection? To answer this, we ask the following questions: What criteria does the EU apply when selecting technologies and raw materials? How are visions reflected in the selection of technologies and raw materials? What changes have there been in PV with regard to the geopolitics of raw materials? How have raw material flows been reconfigured and how do they relate to or influence the successful implementation of the RES transition?

1.2 Analytical Framework

Our research is embedded in and influenced by constructivist approaches from Science and Technology Studies (STS), which emphasize the inherently social and political character of science and technology. We draw inspiration from the seminal work "The Social Construction of Technological Systems", edited by Wiebe E. Bijker, Thomas P. Hughes and Trevor Pinch, the work of Bruno Latour's "Science in Action" and the work of Thomas P. Hughes "Networks of Power".[11] Even though we do not explicitly use the above approaches, they have been imperative to our reasoning and thinking. They provide us the lens through which we understand the interactions and/or relationships between the social, the scientific and the material.

Coming from the other side of the pond, Sheila Jasanoff developed an agenda that proposes to follow and examine co-production along four pathways: "making *identities*, making *institutions*, making *discourses* and making *representations*".[12] While we acknowledge the Jasanoff's work as an attempt to avoid determinism at either end of the prism in STS, we do not adopt or follow Jasanoff's co-production idiom as an approach.[13] Rather, our research is influenced Jasanoff's work in that we analyse the social and the material and their interactions symmetrically. We use the term of co-production to discuss and describe the relationship

---

[11] Bijker Wiebe E., Hughes Thomas P., Pinch Trevor (eds.), *The Social Construction of Technological Systems*, The MIT Press (Cambridge Massachusetts, London England: 1989).; Latour Bruno, *Science in Action*, Harvard University Press (Cambridge Massachusetts: 1987).; Hughes Thomas P., *Networks of Power: Electrification in Western Society 1880-1930*, The John Hopkins University Press (Baltimore, London: 1983).

[12] Jasanoff Sheila, "Ordering knowledge, ordering society", *in* States of Knowledge: The co-production of science and social order, Sheila Jasanoff (ed.), Routledge (London and New York: 2004), p. 38.

[13] We understand Jasanoff's as an attempt to overcome shortcomings of other STS work. The author proposed the co-production idiom to remedy the strongly social constructivist character of SCOT and the more material-geared ANT.; Jasanoff Sheila, "The idiom of co-production", *in States of Knowledge: The co-production of science and social order*, Sheila Jasanoff (ed.), Routledge (London and New York: 2004), p. 1-12.

between the EU energy and research policies. In particular, we show how these two policies have constructed a new social order in the energy market.

1.2.1 From EU research policy history to Innovation Studies: the importance of mission-oriented policies

The insofar analyses of EU research policy history have provided an "institutional account". In essence, the focus has been on tracing and examining institutional changes in EU research policy. Although EU research policy spans for over 70 years, the literature on the subject is sparse. The first to write about the history of European research policy was Luca Guzzetti.[14] Guzzetti provides an informative account of the institutional changes in European research policy, covering the period from (the prehistory of Community research) 1948 to the early 1990s. Paraskevas Caracostas and Ugur Muldur, place the FPs as the focal point of their analysis, covering the period from 1984 to 2007.[15] By essentially examining the (main) institutional changes, the authors focus mainly on the significance of the creation of the European Research Area (ERA) for the future of the European research policy and its direction. More recently, Veera Mitzner has written an insightful account of the emergence of European research policy, examining its 'contested origins', while offering her views on the future of European research policy.[16,17]

Our analysis departs from the above approaches by linking EU R&D funding flows to technoscientific (research) networks and their technological choices and examining how these choices have in turn shaped the material dimension(s) of the energy systems. This analysis allows us to trace and examine which actors have been involved in the above processes and which actors were marginalized (and excluded) in relation to particular technological choices. By examining technoscientific research networks and looking at how their selections were determined and defined, we can understand both how research priorities were shaped and how the network priorities were determined. The technological selection(s) of the network actors went hand in hand with their traditions, know-how, and skills in using specific semiconductors

---

[14] Luca Guzzetti, *A brief history of European Union Research Policy*, Office for Official Publications of the European Communities (Luxembourg: 1995).

[15] Paraskevas Caracostas and Ugur Muldur, *Koinonia: o anoichtos orizontas erevnas kai kainotomias* [Society: the open horizon of research and innovation], Ellinika Grammata (Athens: 2007).

[16] Veera Mitzner, *European Union Research Policy: Contested Origins*, Palgrave MacMillan (2020).

[17] Apart from her book, Mitzner has written the corresponding European research policy chapters in the Volume series "The European Commission 1958-2000: History and Memories of an Institution". In this Volume series, the emphasis is on the institutional changes of European research policy.

(i.e. the materials used for solar cells). Tracing this dimension led to a transnational history analysis for access to raw materials, as this issue was impactful for the networks and important for their technical selection(s). Access to raw material for (critical) technologies is a dimension that has not been considered in the historical analyses of EU research policy, nor in analyses of Innovation Studies that examine innovation(s). For our analysis, we draw on previous work in Innovation Studies, especially mission-oriented policies.[18]

Mazzucato and Semieniuk developed the concept of mission-oriented policies.[19] The emphasis these scholars place on the study of public funding schemes and their impact in directing innovations has influenced our approach to the analysis of EU R&D funding schemes for RES technologies.[20] Our research corroborates Mazzucato and Semieniuk's argument regarding the importance of mission-oriented policies and innovations. In our analysis, we show that EU R&D funding schemes have indeed fostered mission-oriented RES innovations. These innovations were influenced by the oil crises, climate change and energy policy that required a rapid implementation of the RES transition. Public funding, in the form of EC R&D funding programmes was risky.[21] However, our research goes beyond the relationship between public funding and its directionality on innovations. We stress and explore the impact of the technoscientific research networks in steering and directing research activities and later the research agenda. Moreover, this work seems to have forgotten important aspects such as access to resources. The importance of this dimension lies in the construction of innovation(s). Our contribution is this both historiographical and a more complex understanding of innovation(s) and its/their emergence.

---

[18] Mazzucato Mariana and Semieniuk Gregor, "Public financing of innovation: new questions", *Oxford Review of Economic Policy*, 2017, p. 24-48.; Mazzucato Mariana and Semieniuk Gregor, "Financing renewable energy: Who is financing what and why it matters", *Technological Forecasting & Social Change*, 2018, p. 8-22.

[19] Mazzucato has applied the concept of mission-oriented policies to the current EU research policy. We discuss this work separately in section 1.5.

[20] Mariana Mazzucato, Gregor Semieniuk, "Financing renewable energy: Who is financing what and why it matters", *Technological Forecasting and Social Change*, vol. 127, 2018; Mariana Mazzucato, Gregor Semieniuk, "Public financing of innovation: new questions", *Oxford Review of Economic Policy*, vol. 33/1, 2017.

[21] Booth Roger, Bernardini Oliviero, Meyer-Henius Ulf, Nuesser Hans, Williams Robert, Pereira de Moura Domingos, *Evaluation of the JOULE Programme (1989-1992),* Office for Official Publications of the European Communities (Luxembourg: 1994), p. 74.; Chrysochoides Nicholas, Casey Thomas, Lapillonne Bruno, Roe Julie, *Clean, Safe and Efficient Energy for Europe: Impact assessment of non-nuclear energy projects implemented under the Fourth Framework Programme,* Office for Official Publications of the European Communities (Luxembourg: 2003), p. 8.; Directorate General for Research and Innovation, *Non-nuclear energy programme (1990-94) JOULE II – Vol I,* Office for Official Publications of the European Communities (Luxembourg: 1997), p. 75.

1.2.2 Transnational Historiography of (technological) infrastructures: towards knowledge infrastructures

Our research is embedded in contemporary transnational historiographies that examine technological infrastructures and raise questions of access(-ibility) that arise from these infrastructures.[22] This literature moves away from national-level analyses that cannot examine the transnational dynamics of critical infrastructures. By focusing on the historical development of technological infrastructures, this literature asks a series of questions about how and why these infrastructures have developed over time in the way that they have. By combining transnational history with technological infrastructures, the literature essentially provides a different account of what kind of Europe is being constructed (or shaped) and how these material dimensions can shed light on how Europe has developed the way it has. Moreover, this literature offers a different view for European integration through the lens of (critical) technological infrastructures. By placing technological infrastructures at the centre of the analysis, the literature essentially asks how and why European integration came about in this way.

The literature emphasizes the need to empirically analyse the historical development of critical infrastructures. Taking into account and highlighting country-specific and unique cultural dimensions through a number of different case-studies, the literature examines both the emergence and governance of these infrastructures and their vulnerabilities.[23] The concept of critical infrastructures is used to denote a paradox that is central to these analyses. In particular, the same infrastructure can simultaneously connect and disconnect different countries and people. Connection and disconnection coexist and can occur simultaneously. This critical paradox plays a prominent role in these analyses, especially as it opens the way to a number of important historical questions: "when, by whom and for what reasons infrastructure was made to connect or splinter."[24]

---

[22] Högselius Per, Hommels Anique, Kaijer Arne, van der Vleuter Erik (eds.), *The Making of Europe's Critical Infrastructure: Common Connections and Shared Vulnerabilities*, Palgrave Macmillan (UK and US: 2013).; Högselius Per, Kaijer Arne, van der Vleuter Erik, *Europe's Infrastructure Transition: Economy, War, Nature*, Palgrave Macmillan (UK and US: 2015).

[23] See Parts I-III of Högselius Per, Hommels Anique, Kaijer Arne, van der Vleuter Erik (eds.), *The Making of Europe's Critical Infrastructure: Common Connections and Shared Vulnerabilities*, Palgrave Macmillan (UK and US: 2013).

[24] Van der Vleuten Erik, Högselius Per, Hommels Anique, Kaijer Arne, "General Introduction", in *The Making of Europe's Critical Infrastructure: Common Connections and Shared Vulnerabilities*, Högselius Per, Hommels Anique, Kaijer Arne, van der Vleuter Erik (eds.), Palgrave Macmillan (UK and US: 2013), p. 9.

An important objective of the Commission has been to promote and support pan- and/or trans-European collaboration through the R&D programmes. These programmes provide a fruitful starting point for transnational history, as collaboration (or connection) through joint scientific endeavours has historically been a point for/of consensus. These programmes were created with the aim of fostering collaboration that transcends national borders and establishes "connection". Our analysis is transnational as it examines the collaborations and the technoscientific research networks that were formed between member states. Technologies connected the actors in these networks in their joint undertakings, the conduct of research and the exchange of knowledge. However, our analysis inevitably expands geographically when we examine the global supply chains formed for the dominant PV technology. As van der Vleuten notes, a potential pitfall is "replacing nation-centered historiography with another essentialized scale—the globe, for example, or the European Union."[25] Although EU R&D programmes are our main entry point, we examine and situate actors (and their traditions, technological choices etc.) in their respective national contexts and research landscapes, recognizing the unique character, values and traditions of the actors. As van der Vleuten suggests, the Tensions of Europe group has already proposed a solution to the above problems. It is in line with these proposed solutions that we examine the programmes and networks. Within the framework of these programmes and networks, we can recognize and understand the dominance of certain national and corporate interests over others. The actors who form the networks "bring along" their own interests, preferences etc., adding the dimension of transnational competition. We call this as "competing while collaborating", which can be understood as equivalent to "connecting while disconnecting". Our research sheds light on how these collaborative technoscientific research networks have been configured and reconfigured historically. Furthermore, this reconfiguration is examined against the backdrop of major changes in EU research and energy policy, critical events for the field of PV and in the context of transnational and international competitions. The EU programmes provided a new 'arena' for collaborating while competing, which we examine through the technical choices that are made. In particular, we examine and shed light on the inclusion as well as exclusion and marginalization of countries, actors etc. Likewise, our analysis goes beyond the dominant technology as we show how an alternative design (CPV) was marginalized in the context of technological competitions.

---

[25] Van der Vleuten Erik, "Toward a Transnational History of Technology: Meanings, Promises, Pitfalls", *Technology and Culture*, 2008, p. 991.

The paradox of "connecting while disconnecting" has influenced our research and is at the heart of our analysis. By examining the technoscientific research networks (and who forms their core and periphery), we can simultaneously trace who is marginalized and excluded. The visualization of the networks and the allocation of research funds, we can see which actors and countries play a prominent role in shaping the technical choices available to the EU for the transition to RES. The formation of core(s) and periphery(-ies) serves as a means to understand the EU's strong knowledge hubs, or in other words, who forms the EU's knowledge and technical capacities. Simultaneously, the visualization of the networks gives us a direct picture of who has been "left out" of these processes. The exclusion and marginalization of actors and countries goes hand-in-hand with the non-selection of alternative technological pathways. Our research not only sheds light on the actors and countries that remained marginalized or excluded in the research networks, but also offers insights into the 'why' and 'how' these selections were made.

Another important issue addressed in the transnational history literature is that of accessibility. In particular, how access(-ibility) for some social groups can simultaneously mean inaccessibility for others. For our analysis, access to raw materials (for PV technologies) was also an important issue raised by our historical actors. A shortage of raw materials and a crisis led to the reorientation of the research priorities and technological choices of the actors that formed the networks. Given the significance of these events, we trace the flows of raw materials. This led to the study of global supply chains and, concurrently, to the study of the geopolitics that emerge from these global raw material supply chains. This inevitably led us to examine the changing geopolitical dynamics underpinning the ongoing transition to RES, while unravelling another dimension that could not remain unexamined. We refer to the notion of the Global North-South divide, which is examined in terms of the raw material flows required for PV technologies.

The above literature has not yet examined EU funding flows for research and their role in/for contemporary history. Our analysis complements the literature on transnational historiographies for technological infrastructures in the following ways:

(i) while the transnational dynamics of/for technological infrastructures have been studied, our work examines the transnational dynamics of/for technoscientific research networks and knowledge infrastructures.

(ii) the issue of access(-ibility) to technological infrastructures is central to this literature, while we redirect it to the supply of raw materials and their geopolitics.

(iii) the paradox of "connecting while disconnecting" is examined through the lens of technological infrastructures. We shift this paradox to "collaborating while competing" through the analysis of technoscientific research networks and knowledge infrastructures.

In essence, technological infrastructures have been studied, but the focus has not been on knowledge infrastructures, which we study through the examination of technoscientific research networks and knowledge infrastructures. Since these networks are crucial to our analysis, we now turn to the corresponding literature.

1.2.3 The technoscientific research networks: bringing technologies to the fore

There is a large body of work that uses Social Network Analysis (SNA).[26] The main aim of SNA is to study the structural form of (collaboration) networks and the structure of the relationships between the actors that form these networks.[27] Studies using SNA to examine the networks formed under the Framework Programmes emerged in the 2000s. Such analyses focus on short periods of time (usually examine only a one FP at a time) and are not always focused on a single sector/field.[28] This is because these analyses focus on geographical dimensions (e.g. R&D collaborations across geographical boundaries, geography of innovation(s), etc.). A recent trend in the literature using SNA is to examine specific case studies.[29] The literature studying the energy sector, follows a similar rationale and does not

---

[26] Given the rich body of work generated using SNA, here we will only focus and examine the literature that corresponds to analyses that share the same topic (i.e. Framework Programmes, energy sector, RES network analyses). This allows us to discuss a more focused body of this work, which however shares the same principles and characteristics as the overall SNA.

[27] Marin Alexandra and Wellman Barry, "Social Network Analysis: An Introduction", *in* The SAGE Handbook of Social Network Analysis, John Scott and Peter J. Carrington (eds.), SAGE Publications (Los Angeles, London, New Delhi, Singapore, Washington DC: 2011), p. 11-25.

[28] Breschi, S. and Cusmano, L., "Unveiling the texture of a European Research Area: Emergence of oligarchic networks under EU Framework Programmes", *International Journal of Technology Management*, 2004, p. 747-772.; Roediger-Schluga Thomas and Barber Michael J., "The structure of R&D collaboration networks in the European Framework Programmes", *UNU-MERIT Working Papers* (No. 036), Maastricht (UNU-MERIT), 2006, p. 1-41.; Scherngell Thomas and Barber Michael J., "Spatial interaction modelling of cross-region R&D collaborations: empirical evidence from the 5th framework programme", *Papers in Regional Science*, 2009, p. 531-546.

[29] Autant-Bernard Corinne, Billand Pascal, Frachisse David, Massard Nadine, "Social distance versus spatial distance in R&D cooperation: Empirical evidence from European collaboration choices in micro and nanotechnologies", *Papers in Regional Science*, 2007, p. 495-519.; Breschi Stefano, Cassi Lorenzo, Malerba Franco, Vorontas Nicholas S., "Networked research: European policy intervention in ICTs", *Technology Analysis & Strategic Management*, 2009, p. 833-857.; Muniz A. S. G. and Vicente Maria Rosalia, "Exploring research networks in Information and Communication Technologies for energy efficiency: An empirical analysis of the 7th Framework Programme", *Journal of Cleaner Production*, 2018, p. 1133-1143.; de Arroyable Juan Carlos Fernandez, Schumann Martin, Sena Vania, Lucas Pablo, "Understanding the network structure of agri-food FP7 projects: An approach to the effectiveness of innovation systems", *Technological Forecasting & Social Change*, 2021, 120372.

(and perhaps cannot) distinguish between demonstration and research.[30] The limited work that has examined the RES sector covers small time periods and does not focus on different RES or RES-specific (e.g. PV technologies) technologies.[31] Furthermore, the scholars do not examine the content of the research projects nor do they intend to link their analyses to changes in the character of research.

The work of the SNA was influential for the network analysis we conducted. Especially in relation to the formation of cores/peripheries, the relational dimension of the actors forming the networks, and the geographical dimension of the networks. However, we depart from these analyses in at least three important respects. First, we conduct a historically informed analysis that can provide explanations for changes in networks and in the selections and geography(-ies) of the networks. This allows for a more holistic view of the reasons for the changes at the time they occur, the broader context in which they are embedded, etc. A notable example is the Si crisis, which not only reoriented and impacted the research priorities but also resulted in the restructuring of the a-Si networks. Second, we link actors to geography, funding and specific technological choices over time. In this way, we can extend our analysis (and our findings) to the cultural, political and technological dimensions of the choices that are being made, while linking them to the broader issues (e.g. EU enlargements, politics of EU integrations). Third, and directly related to the first two points, we recognize the material possibilities of the technological choices made by the networks. This includes networks' politics for making their choices and leading to marginalizations for alternative technological pathways and actors, while extending to the various material possibilities that these options enable for system integration and the reconfiguration of the latter. To highlight these differences from the SNA, we employ the term 'technoscientific research networks' to indicate that these networks are places or spaces where knowledge is created and disseminated. This knowledge is geographically, culturally and historically situated. This knowledge is developed around different technological choices that are the criterion for distinguishing between the different networks. In this way, technology can come to the fore and be studied.

---

[30] Calvo-Gallardo Elena, Arranz Nieves, de Arroyabe Juan Carlos Fernandez, "Analysis of the European energy innovation system: Contribution of the Framework Programmes to the EU policy objectives", *Journal of Cleaner Production*, 2021, 126690.; Calvo-Gallardo Elena, Arranz Nieves, de Arroyabe Juan Carlos Fernandez, "Innovation systems' response to changes in the institutional impulse: Analysis of the evolution of the European energy innovation system from FP7 to Horizon 2020", *Journal of Cleaner Production*, 2022, 130810.

[31] Kang Moon Jung and Hwang Jongwoon, "Structural dynamics of innovation networks funded by the European Union in the context of systemic innovation of the renewable energy sector", *Energy Policy*, 2016, p. 471-490.

1.2.4 Geopolitics, externalities and scarcity: following the raw material flows

Gabrielle Hecht's work, "Being Nuclear", has influenced our research in at least two distinct but complementary ways.[32] First, by including the extraction step in our analysis and second, by exploring the hidden consequences of mining. In her work, Hecht introduces the term of *nuclearity* to show 'how places, objects, or hazards get designated as "nuclear"'while others are not.[33] Hecht's analysis follows the places where uranium and yellowcake are mined and the corresponding places where they are used. South Africa's lobbying to exclude uranium and yellowcake as nuclear things, resulted in the relevant mining activities to be exempt from the Nuclear Non-Proliferation Treaty. Essentially, this denuclearization of mining meant that the health problems of uranium and yellowcake miners remained hidden. Occupational health and safety issues in the mining of PV minerals come centre-stage in chapter 7. The research agenda, priorities and activities did not include these dimensions because they did not consider this step in the production chain. This hidden step results in not accounting for what is happening in the regions where these minerals are extracted. This allows for the reproduction of a number of inequalities between the regions that extract these minerals and those that use the end products. Occupational health and safety issues are among the externalities that we address for by following the mineral flows. Hecht's emphasis on mining inspired us to examine the regions where the minerals for PV cells are extracted. We wanted to see and include in our analysis the consequences and hidden inequalities that arise when we leave out this crucial step in the production chain of PV technologies.

Sujatha Raman, wrote about the rare earth mineral restrictions imposed by the Chinese government in 2009, arguing that "renewable energy technologies are becoming fossilized".[34] By this, Raman means that the strategies being pursued to secure the supply of rare earths are similar to those followed for fossil fuels. However, she points out that "there is complete silence over the environmental and social impacts of rare earth production".[35] By discussing these aspects of rare earth production, she inspired us to examine the wider (recorded) environmental impacts that result from the other steps in the PV production chain. By combining the work of Hecht and Raman, we wanted to examine the externalities arising from the entire production

---

[32] Hecht Gabrielle, *Being Nuclear: Africans and the Global Uranium Trade*, The MIT Press (Cambridge Massachusetts, London England: 2012).

[33] Hecht Gabrielle, "An elemental force: Uranium production in Africa, and what it means to be nuclear", *Bulletin of the Atomic Scientists*, 2012, p. 24.; Hecht Gabrielle, "Introduction", *in Being Nuclear: Africans and the Global Uranium Trade*, MIT Press (Cambridge Massachusetts, London England: 2012), p. 4.

[34] Raman Sujatha, Fossilizing Renewable Energies, *Science as Culture*, 2013, p. 172.

[35] Raman Sujatha, Fossilizing Renewable Energies, *Science as Culture*, 2013, p. 175.

chain of the dominant PV technology. In addition, Raman's work prompted us to also examine the broader geopolitical dynamics and interactions related to the supply of critical minerals for PV (i.e. silicon), as this has been at the centre of a major crisis that reoriented the PV research activities and technical choices or our historical actors. In this context, we can consider both the geopolitical empowerment of China through the transition to RES and the externalities that China has in accumulating more power in the production chain. To this end, we revisit the notion of the Global-North South divide and provide novel insights for the case of China.

Our analysis is inspired by the work of Hanna Vikström on scarcity.[36] Vikström theorizes scarcity and departs from the simplistic economic rationale where scarcity is explained through a supply-demand mismatch. She argues that this (over)simplification cannot shed light on the underlying reasons and events that led to a metal *becoming* scarce. In other words, it lacks and hinders the explanatory insights that a historical account can provide, including questions regarding why and how a metal are *made* scarce. In her work, Vikström explores the reasons associated with a mineral becoming scarce and how the actors experience scarcity (i.e. high prices, lack of substitutes, domestic unavailability, limited infrastructures and increased demand), while presenting the strategies actors have developed overtime for coping with scarcity (e.g. recycling, resource savings, substitution, diversification, new technological pathways etc.).[37] Our research corroborates Vikström's findings, as we observe all of the above factors during the silicon crisis in PV. Moreover, we complement her work as we show that several of the coping strategies have been employed by our historical actors even at the research level.

However, although the above factors and several of the scarcity coping strategies were employed to respond to the silicon crisis in PV, silicon was not characterized as critical or scarce. In fact, silicon was not included in the European Commission's initial list of "Critical Materials".[38] Possible explanations for this discrepancy include the belief that the industry will increase its capacity to meet the needs of the expanding PV industry, the perception of China as a 'good' supplier and the fact that the silicon crisis ended before the above list was published. When actors hold beliefs or expect that shortages can be overcome or are temporary, a raw material may not be classified as critical or scarce. In essence, actors' concerns may be

---

[36] Vikström Hanna, The Specter of Scarcity: Experiencing and Coping with Metal Shortages, 1870–2015, [Doctoral dissertation, KTH Royal Institute of Technology], 2017, p. xii.

[37] Vikström Hanna, The Specter of Scarcity: Experiencing and Coping with Metal Shortages, 1870–2015, [Doctoral dissertation, KTH Royal Institute of Technology], 2017, p. xii & p. 40-47.

[38] European Commission, *Tackling the Challenges in Commodity Markets and on Raw Materials*, COM(2011) 25 final, Brussels, 2.2.2011.

mitigated to some extent by the belief or expectation that shortages may be temporary. Moreover, the PV research community has completely ignored the geopolitical dimension and global supply chains in formulating research agenda and priorities, as well as in its technical choices. Rendering our historical actors blind to such concerns. This is mainly because they focused on the value chain. As soon as tensions arose between the EU and China over the supply of PV panels, and after the rare earths incident, silicon was added to the Commission's list of Critical Minerals (along with rare earths).

Our research expands the work of Vikström by showing that it is possible to trace all factors and coping strategies without officially classifying or characterising a mineral as critical or scarce. Vikström argues that "access and control are key elements of perceptions of scarcity".[39] In other words, scarcity is a matter of power. We extend this notion of scarcity as an issue of power over the entire production chain. Even though extraction is an important step and an important factor in scarcity, when we follow the production chain we see that power and control are dispersed. Silicon extraction is geographically dispersed. On this basis one could argue that silicon is not scarce because issues of control and access can easily be mitigated by finding other suppliers. However, if one looks at the entire production chain for PV (for the dominant technology), a different picture emerges. China has expanded and accumulated power throughout the PV production chain and has been able to exert geopolitical pressure as a result. Although silicon became scarce due to the targets set by the European Commission in 1997, this mineral was not considered critical until geopolitical tensions arose. Thus, when geopolitical pressure arises, this becomes the determining factor for classifying a raw material as scarce or critical, especially when its use impacts critical sectors. To this end, the geopolitical pressure that can emanate from the entire production chain of a technology should be analysed, as it can further enrich our understanding of scarcity.

1.2.5 On power, power relations and empowerment

Power, power relations and empowerment emerge as important concepts in our analysis. To help conceptualize them, we draw on the work of Philip Brey.[40] As Brey argues:

> "… technical artefacts and systems are used to construct, maintain or strengthen power relations between agents, whether individuals or groups, and how their

---

[39] Vikström Hanna, The Specter of Scarcity: Experiencing and Coping with Metal Shortages, 1870–2015, [Doctoral dissertation, KTH Royal Institute of Technology], 2017, p. 38.

[40] Brey Philip, "The Technological Construction of Social Power", *Social Epistemology*, 2008, p. 71-95.

> introduction and use in society differentially empowers and disempowers agents."[41]

In other words, technology can be understood as the core or centre around which power and power relations are formed. As we have already noted, the various technologies are a starting point for organizing our analysis. Following this, Brey's work has inspired us to examine the actors who form the technoscientific research networks around the different technologies and to trace the differences between the actors who form the networks of each technology. The questions of why these actors made these choices and others did not, what they had in common, and when and why they 'clashed' were critical to our analysis. The result was an examination of common interests, different traditions, competitions etc.

Empowerment is explored both for networks and for the relationship between technology and society. In the second period, the introduction of the Knowledge-Based Economy (KBE) and the concurrent launch of the European Technology Platforms (ETPs) further empowered the already powerful actors, resulting in the disempowerment of all non-powerful actors. Furthermore, (dis)empowerment can refer to the impact of the different technologies in society. Examining the particular uses and applications that a technology may find, as well as the intentions and/or expectations of the actors who promoted their development, can lead to different outcomes in terms of (dis)empowerment of users. In our study, we analyse the material possibilities that each technological choice enabled. We show that the material possibilities offered by small-scale c-Si flat plate PV enabled the diffusion of power in civil society. Moreover, the c-Si network promoted the development of this technology by the understanding that it could reconfigure the architecture of the energy system while empowering users! In contrast, the actors that formed the CPV networks promoted a design (HCPV) that moved in the opposite direction and that could not mitigate the supply of electricity away from the dominant paradigm. Power can refer to issues of control. In this sense, we may refer to the acquisition or accumulation of power as empowerment.[42] This dimension of power comes centre stage in chapter 7, where we discuss global supply chains and material flows along the production chain. Through this analysis we show that China gradually became geopolitically empowered and used this form of power to exert pressure on different occasions.

---

[41] Brey Philip, "The Technological Construction of Social Power", *Social Epistemology*, 2008, p. 71.

[42] Brey Philip, "The Technological Construction of Social Power", *Social Epistemology*, 2008, p. 71-95.

1.3 Methodology

The material for the present study consists of various published yet hitherto unstudied sources, which contributes to the originality of the present work. We have used qualitative methods of analysis for the analysis of the primary and secondary sources and the interviews, while we have used quantitative methods of analysis for the statistical and economic data.

Our research is based on the analysis of the first two energy R&D programmes, the eight Framework Programmes (FPs), their respective sub-programmes for RES (and PV), the funded projects for PV technologies for electricity generation, as well as various FP and sub-programme assessments, evaluation reports, legislative materials and secondary sources.[43,44] As there is no single organized archive for this material (see also limitations) we conducted a series of advanced searches in the "Europa", "Cordis", and "EUR-Lex" websites to retrieve the above described EU material.[45] We retrieved booklets from "Europa" containing the funded projects. These booklets contain the following information for the projects: (i) funding, (ii) contractors and participants names, (iii) aims and objectives, (iv) topic description etc.[46] Cordis was used only as a supplementary source of information, especially since this website has a series of shortcomings for researchers.[47] Consistent information is not always provided for the projects, and it is overall up to date for projects from 1999 onwards. For additional information for the projects, their contents and the actors involved we have largely drawn from the European Photovoltaic Solar Energy Conference Proceedings (see below). After compiling all the EU-funded PV projects we excluded the projects that did not concern electricity production and the projects working on hybrids (i.e. combining more than one RES). Similar was the selecting procedure for the demonstration PV projects included to our analysis.

---

[43] We should note that for Horizon 2020 we examined the PV projects published in cordis until 2019. Despite not incorporating this material for the entire analysis, which would have significantly delayed the completion of the dissertation, we have incorporated the Horizon 2020 findings regarding the relationship between EU's energy-research policies, funding distribution by technology, and overall trends in our analysis.

[44] Over five-hundred PV projects were collected and processed towards our analysis. After having collected our archive and by examining the funding distribution, as well as important issues addressed by our historical actors we made the selection of three case studies, namely c-Si, CPV, and a-Si. In addition, for these projects we collected a series of additional material from the Conference Proceedings, the websites of the actors etc. The above number does not include the demonstration PV projects, which were also retrieved and processed. Secondary sources include but are not limited to the following: PV technology and systems handbooks and articles, final project reports (when available), project outcomes and deliverables (when available), project publications, books and articles about European industrial policy, books about the history of the semiconductor electronics etc.

[45] https://europa.eu/european-union/index_en

[46] By contractors' name we mean all the information about the project leader (name, institution name etc.); the same information is provided for all partners involved in the project(s).

[47] https://cordis.europa.eu/

The calculations for the financing of the projects were based on the information contained in the above material and, for the first two energy R&D programmes supplemented by information from additional material published by the Commission (e.g. contractor meetings). The evaluations, assessments and reports were also retrieved from Europa and FP-specific websites. These sources served to enrich the analysis with further information and put our story and research material in context. To further support the analysis, we used the legislative and regulatory material accessible via the EUR-lex website.

An important source for our analysis is the Proceedings of the European Photovoltaic Solar Energy Conferences. These conferences were organized by the European Commission (1977-now) and helped establish a European-based PV platform with the participation of the entire global PV community (including politicians, policy makers, etc).[48] These conference proceedings, which are largely understudied, were crucial for our analysis.[49] They helped us to understand and contextualize the various crises (e.g. energy and raw materials), visions and EU policies and how they were understood and framed by historical actors. They were also an additional source of information on the continuity of people involved in the projects (collaborations), the content of the projects and the general links to grand challenges (e.g. energy crisis, climate change). Through these proceedings we were able to restructure the voice of important historical actors, their viewpoints and perspectives.

We conducted a total of five semi-structured interviews with policy makers, scientists, and EC officials. The semi-structured interviews were chosen to allow for the discussion to deviate from the prepared questionnaires. This allowed for an open dialogue between interviewer and interviewee that went beyond the interviewer's prepared questions. Of the people we asked to be interviewed, those listed below agreed to give us an interview. As some of our interviewees requested anonymity, we will describe their position and expertise in a way that does not hinder their identification. The individuals listed below were interviewed:

(i) Professor Jenny Nelson from the Department of Physics, Faculty of Natural Sciences, Imperial College London (described in text as "interview with Physics Professor at a UK university, specializing in the characterization of materials for PV, 21 November 2019, London, UK."), (ii) Dr. Dimitris Corpakis EU official, EC DGXII, (iii) former Scientific

---

[48] These Conferences have become a long-lasting tradition and are organized annually. The most recent, 38th Conference, took place in Lisbon in 2021.

[49] The majority of the Conferences (until the 1980s) were available through the Europa website. The majority of the Conferences that took place in the 2000s were obtained via a direct communication with the publisher (WIP-Renewable Energies) that agreed to send us a (CD-ROM) copy of the Proceedings. The majority of the Proceedings from the 2010s are available online. Filling the gap for the 1990s Proceedings was made feasible by a series of visits to the British Library (approximately three months).

Officer at RES unit, EC DGXII, (iv) Fraunhofer-ISE Head of Department, (v) Representative of the UK in Brussels in the 2000s.

Detailed information on the energy and technology markets was obtained mainly from books, publications from the European Photovoltaic Solar Energy Conferences, the European Photovoltaic Industry Association and JRC PV status reports. Using data from these sources, we were able to calculate regional market shares and quantitatively assess changes in the markets. For statistical data (e.g. the EU energy mix) we used data from Eurostat. Finally, for the minerals studied and analysed in chapter 7, we used data from the US Geological Survey, which formed the basis for calculating the regional production shares of the minerals used for solar cells.

The fact that the Commission does not have an archive of all project proposals submitted does not allow exploring the technological pathways not selected and limits the examination of the criteria employed for the selected projects. Although this was an original aim of this research, this gap in the archive was a direct limitation that affected the focus of the current research. The consistency of the lack of a complete archive also extends to the results of the funded projects (e.g. deliverables and outcomes). The lack of such an archive is a problem recognized by the evaluators of the R&D programmes. However, this fragmentation and inconsistency of archives goes beyond the limitations of current research and raises important questions about the EU economic policy, accountability and ‘ownership’ of publicly funded research. Two further limitations relate to restricted resources to conduct a series of interviews with other actors and to access in the archive of the discussion minutes of the DGs and the committees.

1.4 Contribution

Our analysis contributes to the Responsible Research and Innovation (RRI) approach, the literature on Environmental Justice, and to the current EU research policy discourse as developed by Marianna Mazzucato. Regarding the former, a relatively new and growing literature emphasizes the need to align Research & Innovation (R&I) with societal needs – calling for more ‘responsible’ R&I to address and solve the (grand) societal challenges (such as climate change).[50] Importantly, the role of society and/or citizen engagement, is expected to

---

[50] European Commission, Directorate-General for Research and Innovation, *Towards a Responsible Research and Innovation in the Innovation and Communication Technologies and Security Technology Fields*, Rene von Schomberg, (ed.), Publications Office (Luxembourg: 2011).; von Schomberg Rene, “A vision of responsible innovation”, *in* Responsible Innovation, Richard Owen, John Bessant, Maggy Heintz (eds.), John Wiley (London: 2013), p. 51-74.; Jakobsen Stig-Erik, Fløysand Arnt, Overton John, “Expanding the field of Responsible Research

play a crucial role in the implementation of the RRI approach. This was included in Horizon 2020, which referred (albeit briefly) to the concept of RRI. One concept derived from this RRI literature is the concept of 'Responsibility by Design' (RbD).[51] The authors proposed this concept "as a way to embed RRI in the governance and outcomes of research and innovation activities and to illuminate a dimension that the RRI community needs to address more deeply."[52] As the authors note, the RbD concept is not new. Its origins date back to an early assessment of RRI activities in 2012, which stated that "Research should be "responsible by design" and thus account for societal risks, benefits and impacts right at the beginning'".[53]

Based on our analysis, we show how R&D funding shaped the material dimension(s) of the energy system, and how these material dimensions simultaneously enable different (integration) options while posing challenges in terms of who is involved, how, under which conditions, etc. It is precisely for these dimensions that the question of political economy for research is relevant. Our research explores the questions of who funds, where these funds go, and what is funded, which is of great importance for the RRI approach.

Based on our research, we have shown that neither research policies nor networks have taken into account all the externalities of their choices. RRI plays an important role here as it raises issues of inclusion, deliberative democracy, etc. However, we believe that RRI should not only address the question of how to design R&I responsibly by targeting scientific processes and procedures. Rather, RRI needs to explore how responsibility can be addressed and incorporated into the governance of research policy as a whole. Therefore, RRI must go beyond influencing 'science or R&I in the making' and influence 'research policy in the making'. Here the externalities, the geopolitical and broader global dimensions of the problems need to be addressed and considered. At the same time, RRI needs to go beyond project-level analyses

---

and Innovation (RRI) – from responsible research to responsible innovation", *European Planning Studies*, 2019, p. 2329-2343.

[51] Stahl Bernd Carsten, Akintoye Simisola, Bitsch Lise, Bringedal Berit, Eke Damian, Farisco Michele, Grasenick Karin, Guerrero Manuel, Knight William, Leach Tonii, Nyholm Sven, Ogoh George, Rosemann Achim, Salles Arleen, Trattnig Julia, Ulnicane Inga, "From Responsible Research and Innovation to responsibility by design", *Journal of Responsible Innovation*, 2021, p. 175-198.

[52] Stahl Bernd Carsten, Akintoye Simisola, Bitsch Lise, Bringedal Berit, Eke Damian, Farisco Michele, Grasenick Karin, Guerrero Manuel, Knight William, Leach Tonii, Nyholm Sven, Ogoh George, Rosemann Achim, Salles Arleen, Trattnig Julia, Ulnicane Inga, "From Responsible Research and Innovation to responsibility by design", *Journal of Responsible Innovation*, 2021, p. 176.

[53] Technopolis and Fraunhofer ISI, *Interim Evaluation & Assessment of Future Options for Science in Society Actions Assessment of Future Options*, Technopolis Group (Brighton, UK: 2012), as cited in Stahl Bernd Carsten, Akintoye Simisola, Bitsch Lise, Bringedal Berit, Eke Damian, Farisco Michele, Grasenick Karin, Guerrero Manuel, Knight William, Leach Tonii, Nyholm Sven, Ogoh George, Rosemann Achim, Salles Arleen, Trattnig Julia, Ulnicane Inga, "From Responsible Research and Innovation to responsibility by design", *Journal of Responsible Innovation*, 2021, p. 186.

and broaden its scope to include production chains that need to be examined through the RRI lens.

One limitation is that the Global North-South and geopolitical dimensions are not addressed and analysed in RRI approaches. The (limited in number) analyses that include the Global North-South dimension treat them as two distinct spheres (i.e. RRI in the Global North and RRI in the Global South).[54] Using our case, we have shown that if we want to address such issues in the Global North, we must necessarily take into account the externalities that affect the Global South. This is because of global supply chains, which have not yet been included in the research agenda or in the discussion on how the EU research community needs to respond to urgencies and crises.

The literature on the analytical concept of energy justice and its three tenets (distributional justice, recognition justice and procedural justice) emphasizes the need to examine the inequalities and injustices arising from the insofar dominant – and centrally generated – energy sources (fossil fuels, nuclear energy) and recently this literature has extended to RES.[55] In this context, scholars have begun to explore the (in)justices and (in)equalities arising from the RES transition by examining renewable energy communities, smart local energy systems, the decision-making processes involved from setting RES priorities, etc.[56] Although this literature emphasizes the need to examine the injustices and inequalities that arise from both energy production and consumption, there seems to be a large gap. Energy consumption and production are only examined in the context of the 'final' technology. The intermediate production steps are not taken into account when assessing the energy injustices and inequalities resulting from the transition to RES. Thus, the costs and benefits (hazards,

---

[54] Wakinuma Kutoma, de Castro Fabio, Jiya Tilimbe, Inigo Vincent B., Bryce Vincent, "Reconceptualizing responsible research and innovation from a Blobal South perspective", Journal of Responsible Innovation, 2021, p. 267-291.

[55] McCauley D., Heffron R., Stephan H., Jenkins K., "Advancing energy justice: the triumvirate of tenets", *International Energy Law Review*, 2013, p. 107-110.; Sovacool B. and Dworkin M., "Energy Justice: Conceptual insights and practical applications", *Applied Energy*, 2015, p. 435-444.; Fuller S. and McCauley D., "Framing energy justice: perspectives from activism and advocacy", *Energy Research and Social Science*, 2016, p. 1-8.; Jenkins K., McCauley D., Heffron R., Stephan H., "Energy justice: a conceptual review", *Energy Research and Social Science*, 2016, p. 174-182.; Jenkins K., McCauley D., Forman A., "Energy justice: a policy approach", *Energy Policy,* 2017, p. 631-634.; Sovacool B., Heffron R., McCauley D., Goldthau A., "Energy decisions reframed as justice and ethical concerns", *Nature Energy*, 2016, (article number 6024), p. 1-6.; Sovacool B., Turnheim B., Hook A., Brock A., Martiskainen M., "Dispossessed by decarbonization: Reducing vulnerability, injustice, and inequality in the lived experience of low-carbon pathways", *World Development*, 2021, 105116.

[56] Eikeland Per Ove and Skjaerseth Jor Birger, "The politics of low-carbon innovation: Implementing the European Union's strategic energy technology plan, *Energy Research & Social Science*, 2021, 102043.; Hanke Florian, Guyet Rachel, Feenstra Marielle, "Do renewable energy communities deliver energy justice? Exploring insights from 71 European cases", *Energy Research & Social Science*, 2021, 102244.; Knox Stephen, Hannon Matthew, Stewart Fraser, Ford Rebecca, "The (in)justices of smart local energy systems: A systematic review, integrated framework, and future research agenda", *Energy Research & Social Science*, 2022, 102333.

externalities, access) are only examined for specific and limited geographical areas. This prevents a more holistic view and assessment of the emerging injustices and inequalities resulting from the transition to RES when considering the global supply chains for the raw materials needed to implement this transition.

The current EU research policy discourse is developed by Marianna Mazzucato. Mazzucatto emphasizes the need for mission-oriented policies and makes suggestions on how to govern them.[57,58] Through our analysis we show that the technoscientific research networks funded under the EU's R&D programmes have always been mission-oriented. In this respect, then, mission-oriented policies are not new. Having examined Mazzucato's agenda, we make concrete suggestions that can help strengthen mission-oriented policies.

The innovation-driven character of mission-oriented policies does not take into account the differences and inequalities in the innovation systems of member states. This can lead to the reproduction and reinforcement of inequalities that need to be addressed through inclusive policies. Our work sheds light on how current research policies are changing and putting pressure on research and innovation systems needed to be included in R&D programmes and thus economic growth. In addition, our research has emphasized the need for holistically defined missions. This can allow the inclusion of important dimensions that have been completely ignored so far (geopolitics of/by global supply chains, externalities). Mazzucato argues for the need of citizen engagement in the design of mission-oriented policies.[59] The EU can use already existing Platforms (e.g. ETPs) to democratize the decision-making processes of setting research agendas, while emphasizing the need for transdisciplinary and integrative processes.[60] This can lead to more inclusive research agendas, while reassuring the incorporation of user needs for future research activities and priorities.

1.5 Dissertation structure

In chapter 2, we examine the main landmarks in the history of EU research policy, covering the period from 1951 to 2020. This includes an analysis of treaties and events relevant to and

---

[57] Mazzucato Marianna, *Missions. Mission-Oriented Research & Innovation in the European Union: A problem-solving approach to fuel innovation-led growth*, Publications Office for the European Union (Luxembourg: 2018).; Mazzucato Marianna, *Governing Missions. Governing Missions in the European Union*, Publications Office for the European Union (Luxembourg: 2019).

[58] Mazzucato has extensively written about mission-oriented policy(-ies). For more information in her publications can be found in her personal website (https://marianamazzucato.com/). We have examined the work of Mazzucato and Semieniuk on mission-oriented policies in a previous section.

[59] Mazzucato Marianna, *Governing Missions. Governing Missions in the European Union*, Publications Office for the European Union (Luxembourg: 2019), p. 6-8.

[60] This is also directly aligned with the RRI approach.

related to the major changes in EU research policy. Next, in chapter 3, we provide a brief but comprehensive overview of the history of EU energy policy. The focus here is also on important landmarks (e.g. oil crises) and the place of RES in energy policy. We also analyse the three different types of electricity generation and consumption, focusing on the opportunities offered by RES and how they have the potential to reconfigure the electricity market and the energy system, while constructing different users. Chapters 4 and 5 cover the empirical analysis of c-Si flat plate, covering the two periods respectively. In chapter 6, we analyse the case of CPV, the marginalized technological option. In all three chapters (4-6) we follow a similar structure of analysis, adapted as necessary to the specificities of each case. Thus, in the case of c-Si case we also analyse the a-Si thin films (and their respective networks) as well as the delineation between pilot and demonstration, while in the case of CPV it was important to link the three different system configurations with their respective uses and applications, explicitly addressing the possible system integration each system enables. We link each technology to the corresponding geographical distribution of EU R&D funds, a visualization and analysis of the technoscientific research networks, the actors of the networks, their expertise and background, and a comprehensive analysis of the respective national research priorities and landscape. This is complemented by the overall distribution of EU R&D by PV technologies and the view on the market (installations). In addition, for each case (i.e. c-Si and CPV), we consider and analyse in depth the characteristics of research policies in the respective period, as well as the relationship between EU research, energy and industrial policies. In chapter 7, we trace the geography of the material flows of the minerals needed for PV technologies, from mining to installation. In this context, we analyse the changing geopolitical dynamic(s) that is being fostered by the transition to RES. Finally, in chapter 8, we summarize our main arguments, reach our final conclusions, which include policy recommendations, and make suggestions for future research.

References

Ackermann T., and Soder L., "An overview of wind energy-status 2002", *Renewable and Sustainable Energy Reviews,* 2002, p. 67-128.

Autant-Bernard Corinne, Billand Pascal, Frachisse David, Massard Nadine, "Social distance versus spatial distance in R&D cooperation: Empirical evidence from European collaboration choices in micro and nanotechnologies", *Papers in Regional Science*, 2007, p. 495-519.

Bijker Wiebe E., Hughes Thomas P., Pinch Trevor (eds.), *The Social Construction of Technological Systems*, The MIT Press (Cambridge Massachusetts, London England: 1989).

Blok K., "Renewable energy policies in the European Union", *Energy Policy*, 2006, p. 251-255.

Booth Roger, Bernardini Oliviero, Meyer-Henius Ulf, Nuesser Hans, Williams Robert, Pereira de Moura Domingos, *Evaluation of the JOULE Programme (1989-1992),* Office for Official Publications of the European Communities (Luxembourg: 1994).

Breschi, S. and Cusmano, L., "Unveiling the texture of a European Research Area: Emergence of oligarchic networks under EU Framework Programmes", *International Journal of Technology Management*, 2004, p. 747-772.

Breschi Stefano, Cassi Lorenzo, Malerba Franco, Vorontas Nicholas S., "Networked research: European policy intervention in ICTs", *Technology Analysis & Strategic Management*, 2009, p. 833-857.

Brey Philip, "The Technological Construction of Social Power", *Social Epistemology*, 2008, p. 71-95.

Calvo-Gallardo Elena, Arranz Nieves, de Arroyabe Juan Carlos Fernandez, "Analysis of the European energy innovation system: Contribution of the Framework Programmes to the EU policy objectives", *Journal of Cleaner Production*, 2021, 126690.

Calvo-Gallardo Elena, Arranz Nieves, de Arroyabe Juan Carlos Fernandez, "Innovation systems' response to changes in the institutional impulse: Analysis of the evolution of the European energy innovation system from FP7 to Horizon 2020", *Journal of Cleaner Production*, 2022, 130810.

Caracostas Paraskevas and Muldur Ugur, *Koinonia: o anoichtos orizontas erevnas kai kainotomias* [Society: the open horizon of research and innovation], Ellinika Grammata (Athens: 2007).

Chrysochoides Nicholas, Casey Thomas, Lapillonne Bruno, Roe Julie, *Clean, Safe and Efficient Energy for Europe: Impact assessment of non-nuclear energy projects implemented* *under the Fourth Framework Programme,* Office for Official Publications of the European Communities (Luxembourg: 2003).

de Arroyable Juan Carlos Fernandez, Schumann Martin, Sena Vania, Lucas Pablo, "Understanding the network structure of agri-food FP7 projects: An approach to the effectiveness of innovation systems", *Technological Forecasting & Social Change*, 2021, 120372.

Defazio D., Lockett A., Wright M., "Funding incentives, collaborative dynamics and scientific productivity: Evidence from the EU framework program", *Research Policy*, 2009, p. 293–305.

Directorate General for Research and Innovation, *Non-nuclear energy programme (1990-94) JOULE II – Vol I,* Office for Official Publications of the European Communities (Luxembourg: 1997).

EcoGreen Energy, 27 May 2022, *EcoGreen Energy*, Solar Energy Deployment in EU 2030, Available online: https://www.eco-greenenergy.com/solar-energy-deployment-in-eu-2030-global-energy-crisis/, (accessed 1 June 2022).

Eikeland Per Ove and Skjaerseth Jor Birger, "The politics of low-carbon innovation: Implementing the European Union's strategic energy technology plan, *Energy Research & Social Science*, 2021, 102043.

European Commission, Directorate-General for Research and Innovation, *Towards a Responsible Research and Innovation in the Innovation and Communication Technologies and Security Technology Fields*, Rene von Schomberg, (ed.), Publications Office (Luxembourg: 2011).

European Commission, *Tackling the Challenges in Commodity Markets and on Raw Materials*, COM(2011) 25 final, Brussels, 2.2.2011.

European Commission, *A Clean Planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*, COM (2018) 773 final, Brussels, 28.11.2018.

European Commission, *The European Green Deal*, COM (2019) 640 final, Brussels, 11.12.2019.

Faaij A. P., "Bio-energy in Europe: changing technology choices", *Energy Policy*, 2006, p. 322–342.

Fuller S. and McCauley D., "Framing energy justice: perspectives from activism and advocacy", *Energy Research and Social Science*, 2016, p. 1-8.

Gan L., Eskeland G. S., Kolshus H. H., "Green electricity market development: Lessons from Europe and the US", *Energy Policy*, 2007, p. 144-155.

Geuna A., “Determinants of university participation in EU-funded R&D cooperative projects”, *Research Policy*, (1998), p. 677-687.

Guy K., Amanatidou E., Psarra F., “Framework Programme 5 (FP5) impact assessment: a survey conducted as part of the five-year assessment of European Union research activities (1999–2003)”, *Science and Public Policy*, 2005, p. 349–366.

Guzzetti Luca, *A brief history of European Union Research Policy*, Office for Official Publications of the European Communities (Luxembourg: 1995).

Hanke Florian, Guyet Rachel, Feenstra Marielle, “Do renewable energy communities deliver energy justice? Exploring insights from 71 European cases”, *Energy Research & Social Science*, 2021, 102244.

Hecht Gabrielle, “An elemental force: Uranium production in Africa, and what it means to be nuclear”, *Bulletin of the Atomic Scientists*, 2012, p. 22-33.

Hecht Gabrielle, “Introduction”, *in* Being Nuclear: Africans and the Global Uranium Trade, MIT Press (Cambridge Massachusetts, London England: 2012).

Högselius Per, Hommels Anique, Kaijer Arne, van der Vleuter Erik (eds.), *The Making of Europe’s Critical Infrastructure: Common Connections and Shared Vulnerabilities*, Palgrave Macmillan (UK and US: 2013).

Högselius Per, Kaijer Arne, van der Vleuter Erik, *Europe’s Infrastructure Transition: Economy, War, Nature*, Palgrave Macmillan (UK and US: 2015).

Hughes Thomas P., *Networks of Power: Electrification in Western Society 1880-1930*, The John Hopkins University Press (Baltimore, London: 1983).

Jakobsen Stig-Erik, Fløysand Arnt, Overton John, “Expanding the field of Responsible Research and Innovation (RRI) – from responsible research to responsible innovation”, *European Planning Studies*, 2019, p. 2329-2343.

Jasanoff Sheila, “The idiom of co-production”, *in* States of Knowledge: The co-production of science and social order, Sheila Jasanoff (ed.), Routledge (London and New York: 2004), p. 1-12.

Jasanoff Sheila, “Ordering knowledge, ordering society”, *in* States of Knowledge: The co-production of science and social order, Sheila Jasanoff (ed.), Routledge (London and New York: 2004), p. 13-45.

Jenkins K., McCauley D., Heffron R., Stephan H., “Energy justice: a conceptual review”, *Energy Research and Social Science*, 2016, p. 174-182.

Jenkins K., McCauley D., Forman A., “Energy justice: a policy approach”, *Energy Policy,* 2017, p. 631-634.

Kaiser R., and Prange-Gstöhl H., “A paradigm shift in European R&D policy? The EU Bidget Review and the economic crisis”, *Science and Public Policy*, 2010, p. 253– 265.

Kanellakis M., Martinopoulos G., Zachariadis T., “European energy policy - A review”, *Energy Policy*, 2013, p. 1020-1030.

Kang M. J., and Hwang J., “Structural dynamics of innovation networks funded by the European Union in the context of systemic innovation of the renewable energy sector”, *Energy Policy*, 2016, p. 471–490.

Knox Stephen, Hannon Matthew, Stewart Fraser, Ford Rebecca, “The (in)justices of smart local energy systems: A system review, integrated framework, and future research agenda”, *Energy Research & Social Sciences*, 2022, 102333.

Laredo P., “The networks promoted by the framework programme and the questions they raise about its formulation and implementation”, *Research policy*, 1998, p. 589-598.

Latour Bruno, *Science in Action*, Harvard University Press (Cambridge Massachusetts: 1987).

Luukkonen T., “Old and new strategic roles for the European Union Framework Programme”, *Science and Public Policy*, 2001, p. 205–218.

Luukkonen T., “The European Research Council and the European research funding landscape”, *Science and Public Policy*, 2014, p. 29–43.

Mancisidor I. d., Uraga d. P., Mancisidor I. d., Lopez P. d., “European Union’s renewable energy sources and energy efficiency policy review: The Spanish perspective”. *Renewable and Sustainable Energy Reviews*, 2009, p, 100-114.

Marin Alexandra and Wellman Barry, “Social Network Analysis: An Introduction”, *in* The SAGE Handbook of Social Network Analysis, John Scott and Peter J. Carrington (eds.), SAGE Publications (Los Angeles, London, New Delhi, Singapore, Washington DC: 2011), p. 11-25.

Mazzucato Mariana and Semieniuk Gregor, “Public financing of innovation: new questions”, *Oxford Review of Economic Policy*, 2017, p. 24-48.

Mazzucato Marianna, *Missions. Mission-Oriented Research & Innovation in the European Union: A problem-solving approach to fuel innovation-led growth*, Publications Office for the European Union (Luxembourg: 2018).

Mazzucato Mariana and Semieniuk Gregor, “Financing renewable energy: Who is financing what and why it matters”, *Technological Forecasting & Social Change*, 2018, p. 8-22.

Mazzucato Marianna, *Governing Missions. Governing Missions in the European Union*, Publications Office for the European Union (Luxembourg: 2019).

McCauley D., Heffron R., Stephan H., Jenkins K., “Advancing energy justice: the triumvirate of tenets”, *International Energy Law Review*, 2013, p. 107-110.

Mirasgedis S., Sarafidis Y., Georgopoulou E., Lalas D. P., “The role of renewable energy sources within the framework of the Kyoto Protocol: the case of Greece”, *Renewable and Sustainable Energy Reviews*, 2002, p. 249–272.

Mittra B., Lucas N., Fells l., “European energy: Balancing markets and policy”. *Energy Policy*, 1995, p. 689-701.

Mitzner Veera, *European Union Research Policy: Contested Origins*, Palgrave MacMillan (2020).

Muniz A. S. G. and Vicente Maria Rosalia, “Exploring research networks in Information and Communication Technologies for energy efficiency: An empirical analysis of the 7th Framework Programme”, *Journal of Cleaner Production*, 2018, p. 1133-1143.

Ormala E., and Vonortas N. S., “Evaluating the European Union’s Research Framework Programmes: 1999-2003”, *Science and Public Policy*, 2005, p. 399–406.

Pavitt K., “The inevitable limits of EU R&D funding”, *Research Policy*, 1998, p. 559– 568.

Ragwitz M., and Miola A., “Evidence from RD&D spending for renewable energy sources in the EU”, *Renewable Energy*, 2005, p. 1635-1647.

Raman Sujatha, Fossilizing Renewable Energies, *Science as Culture*, 2013, p. 172-180.

Rodríguez H., Fisher E., Schuurbiers D., “Integrating science and society in European Framework Programmes: Trends in project-level solicitations”, *Research Policy*, 2013, p. 1126– 1137.

Roediger-Schluga Thomas and Barber Michael J., “The structure of R&D collaboration networks in the European Framework Programmes”, *UNU-MERIT Working Papers* (No. 036), Maastricht (UNU-MERIT), 2006, p. 1-41.

Scherngell Thomas and Barber Michael J., “Spatial interaction modelling of cross-region R&D collaborations: empirical evidence from the 5th EU framework programme”, *Papers in Regional Science*, 2009, p. 531-546.

Sovacool B. and Dworkin M., “Energy Justice: Conceptual insights and practical applications”, *Applied Energy*, 2015, p. 435-444.

Sovacool B., Heffron R., McCauley D., Goldthau A., “Energy decisions reframed as justice and ethical concerns”, *Nature Energy*, 2016, (article number 6024), p. 1-6.

Sovacool B., Turnheim B., Hook A., Brock A., Martiskainen M., “Dispossessed by decarbonization: Reducing vulnerability, injustice, and inequality in the lived experience of low-carbon pathways”, *World Development*, 2021, 105116.

Stahl Bernd Carsten, Akintoye Simisola, Bitsch Lise, Bringedal Berit, Eke Damian, Farisco Michele, Grasenick Karin, Guerrero Manuel, Knight William, Leach Tonii, Nyholm Sven, Ogoh George, Rosemann Achim, Salles Arleen, Trattnig Julia, Ulnicane Inga, “From Responsible Research and Innovation to responsibility by design”, *Journal of Responsible Innovation*, 2021, p. 175-198.

Technopolis and Fraunhofer ISI, *Interim Evaluation & Assessment of Future Options for Science in Society Actions Assessment of Future Options*, Technopolis Group (Brighton, UK: 2012).

The European Commission 1958-72: History and Memories of an Institution, Michel Dumoulin (eds.), Publications Office of the European Union (Luxembourg: 2014).

The European Commission 1973-86: History and Memories of an Institution, Éric Bussière, Vincent Dujardin, Michel Dumoulin, Piers Ludlow, Jan Willem Brouwer and Pierre Tilly (eds.), Publications Office of the European Union (Luxembourg: 2014).

The European Commission 1986-2000: History and Memories of an Institution, Vincent Dujardin, Éric Bussière, Piers Ludlow, Federico Romero, Dieter Schlenker and Antonio Varsori (eds.), Publications Office of the European Union (Luxembourg: 2019).

United Nations, “Paris Agreement”, 2015 (https://unfccc.int/sites/default/files/english_paris_agreement.pdf).;

Van der Vleuten Erik, “Toward a Transnational History of Technology: Meanings, Promises, Pitfalls”, *Technology and Culture*, 2008, p. 974-994.

Vikström Hanna, The Specter of Scarcity: Experiencing and Coping with Metal Shortages, 1870–2015, [Doctoral dissertation, KTH Royal Institute of Technology], 2017.

von Schomberg Rene, “A vision of responsible innovation”, *in* Responsible Innovation, Richard Owen, John Bessant, Maggy Heintz (eds.), John Wiley (London: 2013), p. 51-74.

Wakinuma Kutoma, de Castro Fabio, Jiya Tilimbe, Inigo Vincent B., Bryce Vincent, “Reconceptualizing responsible research and innovation from a Blobal South perspective”, Journal of Responsible Innovation, 2021, p. 267-291.

Chapter 2. An EU research policy history

In this chapter we examine the main institutional, legislative and regulatory changes in the history of EU research policy. The timeframe covers a broad period from the founding of – what is currently – the EU to 2020. This chapter does not claim to provide an exhaustive analysis of all changes or events in the history of European research policy history. Extensive work on the institutional and legislative changes in European research policy already exists (see analysis below). Rather, the aim of this chapter is to inform the reader about the main landmarks in the history of EU research policy, while providing an overview of what research policy is and how it has changed over time. At the same time, this chapter serves as a stepping stone that enables the link between the marco-level changes (EU research policy as a whole) that have been incorporated and/or translated in the EU's the research policy instrument (Framework Programmes – FPs) and the meso- and micro-levels (RES and PV, respectively). By making concrete connections at these three levels, this chapter allows us to place the empirically analysed changes (chapters 4-6) in a broader context. Within this framework, we examine how these changes affected the aims and general character of EU research policy. Furthermore, we trace how these changes were incorporated to the respective research aims and priorities for renewable energy technologies, with a focus on solar PV.

2.1 EU research policy in the first period

Despite the long history of European research policy, the literature is sparse.[61] The first to write on the history of EU research policy was Luca Guzzetti. Guzzetti provides an informative account of the institutional changes in EU research policy, covering the period from (the prehistory of Community research) 1948 to the early 1990s.[62] Paraskevas Carakostas and Ugur Muldur, place the FPs at the centre of their analysis, covering the period from 1984 to 2007. By essentially examining the (most important) institutional changes, the authors primarily focus on the importance of the European Research Area (ERA) for the future of EU research policy and its direction.[63] More recently, Veera Mitzner has written an insightful account of the emergence of EU research policy, examining its 'contested origins', while offering her

---

[61] Despite the literature being scarce, the insofar work done is both well informed and well sourced. Providing for a full and detailed account for the European research policy history, especially until the 1990s.

[62] Luca Guzzetti, *A brief history of European Union Research Policy*, Office for Official Publications of the European Communities (Luxembourg: 1995).

[63] Paraskevas Caracostas and Ugur Muldur, *Koinonia: o anoichtos orizontas erevnas kai kainotomias* [Society: the open horizon of research and innovation], Ellinika Grammata (Athens: 2007).

views on the future of European research policy.[64,65] Without duplicating the work above, in the following sections we analyse the main institutional, legislative and regulatory changes in European research policy.

2.1.1 From the first links of research to economic growth to the Single European Act and the Treaty of Maastricht

Shortly after the end of the World War II, six European countries signed the Treaty of Paris (1951) establishing the European Coal and Steel Community (ECSC), while the Treaty of Rome (1957) established the European Economic Community (EEC) and Euratom.[66] The European Communities were built 'around' a consensus for cooperation in three key sectors (coal, nuclear energy, and agriculture).[67] In this context, member states began to cooperate with each other in various forms and capacities as early as the 1950s, leading to the creation of CERN, ELDO, ESRO etc. Scientific cooperation provided fertile ground for extending or overcoming the national borders of the member states.

In the 1960s, the Organization for Economic Cooperation and Development (OECD) made an important remark. In particular, the OECD "…highlighted the crucial link between scientific research and economic growth."[68] Essentially, research was contextualizing as a means to achieve economic growth. Apart from this crucial link, the OECD also noted that the technological gap (and the economic lag) between Europe and the US could be remedied through research and, in particular through greater and/or further cooperation in research.[69,70]

---

[64] Veera Mitzner, *European Union Research Policy: Contested Origins*, Palgrave MacMillan (2020).

[65] Apart from her book, Mitzner has written the corresponding European research policy chapters in the Volume series "The European Commission 1958-2000: History and Memories of an Institution". In this Volume series, the emphasis is on the institutional changes of the European research policy.

[66] Having different structure and responsibilities, the (three) European Communities are the precursors of what is now the European Union.

[67] Following the Merger Treaty or Brussels Treaty (1967) the executive institutions of the European Communities merged, resulting in the establishment of the Commission of the European Communities. Prior to the Merger Treaty, the corresponding executive institutions were the following: the High Authority of the ECSC, the Commission of the EEC and the Commission of the Euratom. The Commission of the European Communities was officially renamed into European Commission following the ratification of the Treaty of Lisbon. Throughout the text we will be referring to the Commission of the European Communities as the European Commission or as the Commission to avoid confusion.

[68] Eric Bussiere and Arthe Van Laer, "Research and technology, or the 'six national guardians' for 'the Commission, the eternal minor', *in* The European Commission 1958-72: History and Memories of an Institution, Michel Dumoulin (eds.), Publications Office of the European Union (Luxembourg: 2014), p. 491.

[69] Eric Bussiere and Arthe Van Laer, "Research and technology, or the 'six national guardians' for 'the Commission, the eternal minor', *in* The European Commission 1958-72: History and Memories of an Institution, Michel Dumoulin (eds.), Publications Office of the European Union (Luxembourg: 2014), p. 491-506.

[70] There is a large literature covering different aspects of the 'technological gap'. Regarding aspects of the technological gap that directly relate to research policy, see: Luca Guzzetti, *A brief history of European Union Research Policy*, Office for Official Publications of the European Communities (Luxembourg: 1995).

Since the 1960s, the Commission had strived to expand its powers in research to other sectors not covered by the Treaties. Following the OECD's remarks, research has been understood since the 1960s as a means of achieving economic growth and supporting the European industry. However, the various initiatives proposed by the Commission always met with obstacles (e.g. European Council, disagreements between member state etc.).[71] 'Constrained' by the Treaties, the Commission could only (officially) launch research initiatives in three sectors (nuclear, agriculture and steel) until the mid-1980s.[72,73] Both the changes in the people behind the DGs and the crises the European industrial sectors faced, provided a renewed impetus to pursue research in more sectors.[74] An important driver for research policy to become a common policy of the European Commission was the Single European Act (SEA).

The vision for creating a Single European Market (SEM) was put forth (anew) when Jacque Delors became the President of the European Commission in 1985.[75] SEM concerned the free movement of goods, services, capital, and people and has been described by the European Commission as "one of the EU's greatest achievements."[76] The establishment and successful implementation of SEM was to be completed by 1992 and was based on the Single European Act (SEA).[77,78] With SEA, the EC acquired a stronger legal basis for the implementation of

---

[71] For more information on the obstacles see: The European Commission 1958-72: History and Memories of an Institution, Michel Dumoulin (eds.), Publications Office of the European Union (Luxembourg: 2014).; The European Commission 1973-86: History and Memories of an Institution, Éric Bussière, Vincent Dujardin, Michel Dumoulin, Piers Ludlow, Jan Willem Brouwer and Pierre Tilly (eds.), Publications Office of the European Union (Luxembourg: 2014).; The European Commission 1986-2000: History and Memories of an Institution, Vincent Dujardin, Éric Bussière, Piers Ludlow, Federico Romero, Dieter Schlenker and Antonio Varsori (eds.), Publications Office of the European Union (Luxembourg: 2019).

[72] Numerous efforts were made by the Commission to launching research initiatives since the 1960s. For various reasons these efforts were not always successful or welcomed. Detailed analyses are provided by: Luca Guzzetti, *A brief history of European Union Research Policy*, Office for Official Publications of the European Communities (Luxembourg: 1995).; The European Commission 1958-72: History and Memories of an Institution, Michel Dumoulin (eds.), Publications Office of the European Union (Luxembourg: 2014).; The European Commission 1973-86: History and Memories of an Institution, Éric Bussière, Vincent Dujardin, Michel Dumoulin, Piers Ludlow, Jan Willem Brouwer and Pierre Tilly (eds.), Publications Office of the European Union (Luxembourg: 2014).; The European Commission 1986-2000: History and Memories of an Institution, Vincent Dujardin, Éric Bussière, Piers Ludlow, Federico Romero, Dieter Schlenker and Antonio Varsori (eds.), Publications Office of the European Union (Luxembourg: 2019).

[73] We analyse the energy and renewable energy specific activities and programmes in a later section.

[74] For example, ESPRIT that was highly reinforced by Etienne Davignon, was a huge success. This legitimized both the capabilities of the Commission in doing research policy in a key sector (IT) and at the same time served as a model for the launch of more programmes.

[75] Jacques Delors was the President of the European Commission from 1985 to 1995.

[76] European Commission, *Single Market and Standards*, Europa, Available online: https://ec.europa.eu/growth/single-market_en, (accessed 19 April 2022).

[77] Commission of the European Communities, *Single European Act*, Office for Official Publications of the European Communities (Luxembourg: 1986).

[78] SEA comprised the first major revision of the Treaty of Rome. Moreover, the establishment of SEA had major political repercussions regarding the economic and monetary union of the European Communities. Essentially paving the way for the monetary union of the EU with the adoption of a single currency (Euro). An overall or full assessment of SEA cannot be made in a footnote. However, we do not aim at assessing SEA in its entirety as that

research policy beyond the three original sectors defined in the founding Treaties (coal and steel, nuclear energy and agriculture), as evidenced by the gradual extension of the sectors and areas covered by the Framework Programmes (FPs).[79] SEA provided the legal basis for the EC in extending its research policy to additional sectors and areas while at the same time, with SEA, research policy was explicitly addressed as a means to achieve economic growth and as part of completing the establishment of SEM. In this context, the FPs became the EC's main tool/instrument for research funding. In other words, the FPs became the concrete expression and manifestation of the research policy of the EC. The FPs were repeatedly challenged and contested for different reasons each time, but over time both the budget and the scope of the FPs grew.[80] The scattered research programmes and activities found a 'home' in the multi-annual research and development (R&D) programmes (FPs).[81,82]

As we analyse in detain in chapters 4 and 6, research policy in the first period was instrumentalized to serve industrial policy. This is not only true for PV and RES, but research was conceived as a means and/or as a tool to 'serve' industrial policy from the very beginning. However, research policy in the first period was also a means to create SEM and was understood as an important driver for economic competitiveness (by strengthening European industry).

> "**The rise of research policy was closely tied to the European Commission's single market initiative and the strong commitment to boosting the EC's economic competitiveness**. The Commission succeeded in convincing the governments of the Member States of the necessity of increased research cooperation and spending to create a powerful economic area, in response to accelerating technological change and intensifying worldwide competition in research and development (R & D). […] **Research policy was, in practice,**

---

transcends the aim of our undertaking. Rather, we aim to provide an overview of some of the major implications and changes SEA brought to/for European research policy.

[79] FP1 (1985-1988); FP2 (1988-1991); FP3 (1990-1994); FP4 (1994-1998); FP5 (1998-2002); FP6 (2002-2006); FP7 (2007-2013); Horizon 2020 (2014-2020).

[80] Regarding the reasons behind the budget contestations see: The European Commission 1973-86: History and Memories of an Institution, Éric Bussière, Vincent Dujardin, Michel Dumoulin, Piers Ludlow, Jan Willem Brouwer and Pierre Tilly (eds.), Publications Office of the European Union (Luxembourg: 2014).;

[81] FP1 (1985-1988); FP2 (1988-1991); FP3 (1990-1994); FP4 (1994-1998); FP5 (1998-2002); FP6 (2002-2006); FP7 (2007-2013); FP8 – Horizon 2020 (2014-2020); FP9 – Horizon Europe (2021-2027).

[82] The energy R&D programmes (1975-1984) were incorporated into FP1 as part of the non-nuclear energy (NNE) research activity of the EC.

> **subordinated to industrial policy and the creation of the single market**".[83] (emphasis added)

In the European context, research was seen as a means of aiding the international competitiveness of the European industry, by strengthening its scientific and technological basis, which was the main aim of the FPs in the first period.[84] The aim was thus to achieve economic objectives that would also contribute to the launch and/or completion of the single market initiative.

It should be noted that while most of the Commission's research initiatives and programmes were 'brought' together the umbrella of the FPs, there were still programmes that run separately. This is the case, for example, of the demonstration programmes for RES (Thermie programmes), which we analyse in chapter 4, APAS, VALOREN etc. These initiatives were overseen and executed by other DGs (i.e. not DGXII). The VALOREN programme, for example, was managed by DG XVI and targeted the "…improvement of energy supply of less privileged areas in Europe."[85]

With the Treaty of Maastricht (1992), "[t]he legal basis for the Community's research policy was further strengthened".[86] In addition, the Treaty of Maastricht "stipulated that all research and development activities should come within the framework programme."[87] This essentially called for all research activities (and programmes) to be placed under the umbrella of the FPs. At the same time, evaluation and assessment was suggested (even indirectly) with regard to possible duplication of efforts and a more 'efficient' organization of research efforts.[88]

---

[83] Veera Mitzner, "European research policy", *in* The European Commission 1986-2000: History and Memories of an Institution, Vincent Dujardin, Éric Bussière, Piers Ludlow, Federico Romero, Dieter Schlenker and Antonio Varsori (eds.), Publications Office of the European Union (Luxembourg: 2019), p. 322.

[84] These overarching aims pertain the FPs of the first period. The specific aims for RES (including PV) were aligned to the overall FP aims. A detailed analysis as to how these aims were 'translated' in the context of the PV research activities can be found in Chapters 4-6.

[85] W. Palz, R. van Overstraeten, G. Palmers, "PV-programmes of the European Commission", *in* Twelfth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Amsterdam, The Netherlands, 11-15 April 1994, R. Hill, W. Palz, and P. Helm (eds.), Vol II, H. S. Stephens & Associates (UK: 1994), p. 1444.

[86] Veera Mitzner, "European research policy", *in* The European Commission 1986-2000: History and Memories of an Institution, Vincent Dujardin, Éric Bussière, Piers Ludlow, Federico Romero, Dieter Schlenker and Antonio Varsori (eds.), Publications Office of the European Union (Luxembourg: 2019), p. 322.

[87] Luca Guzzetti, "Maastricht and the Nineties", *in* A brief history of European Union Research Policy, Office for Official Publications of the European Communities (Luxembourg: 1995), p. 159.

[88] Thermie, in particular, is analysed in Chapter 4. Through this analysis we trace similarities, 'potential overlaps', and follow the efforts made by the EC in merging the demonstration programme for RES (Thermie) with the R&D programme for RES (Joule) towards the end of the first period.

2.1.2 Research priorities and the role of RES and PV in the Framework Programmes

In this section, we analyse the trigger that led to the inclusion of renewables in EU (energy) research programmes, while at the same time examining the place of each renewable in EU research funding and the way in which each RES has been contextualized and framed.[89] We also establish a link between the previously analysed institutional changes and the changes in renewable energy research, with a focus on PV.

2.1.2.1 The start of renewable energy research: the trigger of the 1973 (oil) energy crisis

In October 1973, the countries of OPEC imposed an oil embargo that led to high crude oil prices and at the same time, pressure in several countries; both energy and economic.[90] In response to these challenges, the EC set out an energy policy strategy. The objectives of the strategy included measures to reduce oil dependence and ensure energy security and supply.[91] These objectives, which emerged in response to the 1973 oil crisis and were reinforced during the 1979 oil crisis, aimed to reduce the uncertainty, unease and urgency of securing the European Community's energy supply. In this context, the first EC energy R&D programme launched in 1975 to explore other potentially viable energy options such as RES.[92] However, the objective of the energy policy strategy of the EC to reduce imports of oil products in order to ensure security of the energy supply, was to be achieved primarily through nuclear energy and natural gas, not through RES.[93,94]

---

[89] Before the launch of FP1, the EC initiated two energy research programmes that included RES (and PV), which were then incorporated into the FPs.

[90] The pathways towards oil substitution varied, depending on cultural, geographical and political specificities, as well as on the availability of energy resources. For example, Germany opted for coal, and later for nuclear energy (Frank Laird and Christoph Stefes, "The diverging paths of German and United States policies for renewable energy: Sources of difference", *Energy Policy*, 2009, p. 2619-2629). France launched a massive nuclear energy programme in 1974, whereas Denmark prioritised coal in combination with natural gas (Miriam J. Boyle, M. E. Robinson, "French Nuclear Energy Policy", *Geography*, 1981, p. 300-303.; Mogens Rüdiger, "From import dependence to self-sufficiency in Denmark, 1945−2000", *Energy Policy*, 2019, p. 82-89.). Accordingly, the national R&D programmes on RES also had varying priorities. Germany, France and Italy dedicated funds both for PV and WE, whereas Denmark and the Netherlands prioritised WE (Maarten Wolsink, "Dutch wind power policy: Stagnating implementation of renewables", *Energy Policy*, 1996, p. 1079-1088).

[91] Council Resolution of 17 December 1974 concerning Community energy policy objectives for 1985, Official Journal of the European Communities, 9.7.1975.

[92] The first energy R&D programme run from 1975 to 1978. Accordingly, the second energy R&D programme run from 1979 to 1983.

[93] Council Resolution of 17 December 1974 concerning Community energy policy objectives for 1985, Official Journal of the European Communities, 9.7.1975.

[94] Council Resolution of 16 September 1986 concerning new energy policy objectives for 1995 and convergence of the policies of the Member States (86/C 240/01), Official Journal of the European Communities, 25.09.1986.

Alternative potential energy solutions such as RES were possible long-term options to be explored initially through the R&D programmes of EC in order to contribute to the energy grids in the 21st century. The R&D programmes were implemented and executed by DGXII.[95] In this context, the R&D programmes were tasked with providing long-term technological options that could help address the challenges created by the energy crises. The creation and establishment of the first energy R&D programme was thus directly related to the 1973 oil crisis and was one of EC's responses to the challenges posed by this crisis. Direct references to the close connection between renewable energy sources and solar photovoltaics in particular with the oil crisis can be found in a number of documents from this the period.[96] To be more precise:

> "**Given the energy supply situation of the Community, there is an obvious necessity for a special effort to develop new energy sources and the associated technologies**. **This is the reason why a first four year Energy Research and Development Programme of the European Communities had been approved** by the Council on 22 August 1975. **It constitutes one of the actions with which the Community replied to the challenge arising from the energy price crisis**."[97] (emphasis added)

The trigger for the establishment of a vision for the new energy sources, including RES, was a direct outcome of the 1973 oil crisis. Within this framework, RES was envisaged as a potential candidate for overcoming future energy problems, and their research (and technological development) became necessary as a result of the energy crisis. Moreover, Dr Günter Schuster, then Director General for Research, Science and Education of the EC, stated that both oil and gas would eventually be depleted. In this context, PV were seen as an important future energy source that could contribute roughly about 3-5% to the energy supply in the countries of the

---

[95] It is important to note that the RES activities and programmes were organized by the RES Unit within the DGXII. Not only was DGXII the only DG to have a dedicated RES Unit but it comprised of scientific (and not administrative) personnel.

[96] During the 1970s and 1980s, our actors, used the terms 'new energy sources', 'alternative energy sources' and in some cases the term 'renewable energy sources' was also employed. Moreover, this set of energies were classified as geothermal energy and solar energy; the latter included all other RES.

[97] Commission of the European Communities - Directorate-General for Research, Science and Education, *Energy Research and Development Programme: Second Status Report (1975-1978)*, Vol I, Martinus Nijhof Publishers (The Hague, Boston, London: 1979), p. 1.

EC by the year 2000.[98] For this vision to become reality several developments had to take place in the short, medium and long-term. The EC included this vision in its first energy R&D programme, in which solar PV had an important place in funding.[99] The second oil crisis of 1979 gave further impetus to R&D efforts for RES. In particular, as Günter Schuster said:

> "Now that we have become aware of the energy problem which lies ahead of us and endangers the future development of our economies, it has become most urgent to conserve energy and to diversify our energy resources. This can only be achieved by extensive research and development."[100]

Thus, DGXII established a close link between the 1979 oil crisis and R&D for other energy sources (including RES) in order to better embed the research policy of EC in the overall policy agenda and to reinforce related research activities and the research agenda. Given the continued pressure exerted by the second oil crisis, we see how the context became differentiated. The energy problem was explicitly understood and framed as a threat to the EC economies, justifying the urgency of further R&D action by EC's DGXII. With the oil crisis of 1979, the importance of RES and in particular PV was again brought to the fore. It is clear from the statements of various important actors from this period that the oil crisis and the development of new energies, especially photovoltaics, had an interchangeable relationship. Dr. Guido Brunner of the Commission of the European Communities stated in the opening speech of the 1979 European Conference:

> "**Roughly from the start of the next millenium, we can expect that solar energy, including photovoltaic conversion, will be making a significant contribution**. **In the year 2000**, according to our calculations, **solar energy and the various other alternative sources should provide 5% of the EC**

---

[98] Gunter Schuster, "Opening Address from the Commission of the European Communities", *in* Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Luxembourg, September 27-30, 1977, D. Reidel Publishing Company, (Dordrecht Holland, Boston USA: 1978), p. 26-28.

[99] PV had a prominent funding place among all other RES, ranking first in R&D funding from 1975 to 2002. See analysis in forthcoming section.

[100] G. Schuster, "The Future of Photovoltaics in Europe", *in* Third EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes France, 27-31 October 1980, W. Palz (eds.), D. Reidel Publishing Company, (Dordrecht: Holland/Boston: USA/London: England: 1981), p. 5.

> **total**. In oil-equivalent terms, this would represent almost 100 million tonnes/year."[101] (emphasis added)

From the above statement, it is clear that the contribution of RES was directly expressed in terms of tonnes of crude oil that they were to replace. Furthermore, the above statement confirms the importance given to solar energy, including PV, for the future energy supply of the Community. In this context, the role of the R&D efforts of EC was further strengthened, as evidenced by an increase in funding in both the second energy R&D programme and in FP1.[102] The energy challenges of the 1970s were crucial for the expansion of the research policy of the EC. Energy, as a theme, was crucial for the EC to develop a research policy that went beyond energy issues. Equally importantly, this was how the EC legitimised its R&D programmes and thus its ability to conduct research policy, and extended its powers to other sectors, thus extending its influence to more policy areas. All these powers were transferred to DGXII and enabled this DG to attain more power and more responsibilities, which in turn extended the powers and responsibilities of the EC.

2.1.2.1.1 The 'place' for each RES: defining the geographic boundaries and possible uses for each RES

RES were understood as locally sourced energies. In the early years of the R&D programmes, DGXII made geographical and, in some cases, country-specific references that linked each RES to respective uses and applications. Essentially, the EC mapped the geographical distribution of each RES and selected the corresponding applications. In relation to geothermal energy, for example, we see the following:

> "**By virtue of its geographical distribution** and the quantities of energy which could be tapped, the possible overall contribution of geothermal energy towards meeting Europe's future energy requirements is much smaller than that of solar energy, **but it will not be negligible on a local scale**. **As far as the Community is concerned, geothermal energy is exploited only in Italy** (electricity

---

[101] Guido Brunner, "Opening Address", *in* Second EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Berlin (West), 23-26 April 1979, R. Van Overstraeten and W. Palz (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1979), p. 9.

[102] It is worth noting that the energy R&D activities under FP1 received a little over 47% of the total programme budget. Energy was a critical driver for EC's research policy and had a core role within the R&D programmes.

> generation from steam) **and in France** (space heating with hot water)."[103] (emphasis added)

The above example about geothermal energy is an excellent example of how the EC understood RES and their potential contribution. Moreover, its shows that the EC had a clear strategy and vision for each RES, which was closely linked to their respective geographical distribution. For example, geothermal energy was limited to certain geographical locations (i.e. Italy and France), while solar thermal energy production through central heliocentric power plants was descibed as a 'promising technology for the Southern Community regions.'[104]

In contrast, PV was seen as the main source of energy for electricity production, in the Northern/Western European climates. In particular, for PV we see:

> "**Quite some emphasis is put on those methods particularly suitable for the relatively unfavourable climatic conditions of the Community countries**. For this reason, the largest single fraction of the programme is devoted to photovoltaic conversion."[105] (emphasis added)

As the above quote shows, the rationale for prioritising PV research in funding over all other RES was given by setting geographical boundaries. However, in this case, PV was seen as the dominant energy solution for the Northern/Western EC countries. Thus, climatic conditions also served as a means to justify and determine the distribution of R& among RES. Based on expected applications of PV in the North-Western EC countries, PV was given priority in R&D funding (until the 2000s).[106]

Geography combined with local climatic conditions played a role not only in favouring one RES over another, but also in selecting the dominant PV technology design. In particular, we see that the exclusion of the different PV design options was justified in the same way. While

---

[103] Commission of the European Communities - Directorate-General for Research, Science and Education, *Energy Research and Development Programme: Second Status Report (1975-1978)*, Vol II, Martinus Nijhof Publishers (The Hague, Boston, London: 1979), p. 738.

[104] Commission of the European Communities - Directorate-General for Research, Science and Education, *Energy Research and Development Programme: Second Status Report (1975-1978)*, Vol II, Martinus Nijhof Publishers (The Hague, Boston, London: 1979), p. 342.

[105] Commission of the European Communities - Directorate-General for Research, Science and Education, *Energy Research and Development Programme: Second Status Report (1975-1978)*, Vol II, Martinus Nijhof Publishers (The Hague, Boston, London: 1979), p. 342.

[106] Wolfgang Palz played a crucial role in steering the R&D funding towards PV. He had an explicit preference in PV and an influential role since he was the head of the DG XII RES Unit until the late 1990s.

the EEC enlargement to the South had already started, the R&D agenda changed. In particular, G. Schuster, the Director General of DGXII, at the European Solar Photovoltaic Energy Conference in 1980, stated:

> "The weather problem is not as critical for solar cells as for most other solar energy technologies because they convert diffuse light as efficiently as direct radiation. In Europe, however, and in particular in its Northern regions, solar radiation is very low in winter. Nevertheless, an electrical output up to a few per cent of the total European supply could be achieved relatively easy by integrating photovoltaic plants into the grid."[107]

The above statement illustrates the criteria used to explain and justify PV prioritisation. In contrast to all other RES, PV were considered suitable for the North-Western European climates because they could use both the diffused and direct solar radiation, the former being the typical Northern European radiation. Therefore, the property of (c-Si) solar cells to convert radiation into electricity in these climates became an argument for choosing PV over the other RES.

Each RES was assigned its 'best' uses (i.e. electricity generation or heating/cooling) as well as the scales envisaged for the respective technologies and the corresponding applications (i.e. grid-connected or stand-alone). In particular, geothermal energy was primarily to be used for the heating/cooling of residential buildings, while large-scale solar thermal was best suited electricity generation (grid-connected) and small-scale for the heating and cooling of residential and commercial buildings. Biomass was associated with its regional applications for (mainly) agriculture and the agricultural sector. The main vision of EC DGXII for electricity generation was focused on large-scale systems that would be connected to the electricity grid (see e.g. the examples of wind power and solar thermal below). This was the way in which RES would contribute to the electricity generation of the EC member states and this was the strategy that DGXII had outlined to overcome the energy problems and challenges created by the oil crises. Therefore, R&D was directed towards ever larger wind energy power plants and large solar thermal power plants. As EC expressed, the individual applications and uses of RES:

---

[107] G. Schuster, "The Future of Photovoltaics in Europe", *in* Third EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes France, 27-31 October 1980, W. Palz (eds.), D. Reidel Publishing Company, (Dordrecht Holland, Boston USA, London England: 1981), p. 6.

> "Solar electricity production, mainly by solar cells but also - **for certain geographic regions within Europe** - by power plants based on thermodynamic cycles and from biomass, is therefore high ranking in the proposed second energy R&D programme. There are good chances that within the **next ten years the prices of solar cells can be decreased to a level that makes them competitive with conventional equipment for power production**. Of course, the intrinsic lead times up to market introduction and the associated problems to be solved in the field of energy transport and storage will require some additional time before a substantial contribution to the energy supply can be expected."[108] (emphasis added)

In summary, RES were understood by the European Commission as a local and/or regional energy source. Given the way RES 'work', the specific climatic conditions were crucial for their installation. Therefore, these climatic conditions were used to map the geographical distribution of each RES. In this context, EC selected PV as its 'favoured' RES – in terms of R&D funding – and the geographical criteria were used as arguments to explain and/or justify said prioritisation (i.e. PV is best suited to the Western/Northern European climate and is prioritised in R&D funding). So, unlike all other energy sources, RES have been coupled with their "respective geographical conditions" given their nature and general requirements for selecting the installation site.

2.1.3 Formulating an EU research policy to promote the competitiveness of European industry

During the first period, research aimed to support the international competitiveness of the European industry. To this end, research was designed to strengthen the industry's scientific and technological basis. The R&D programmes aimed to provide a basis for cooperation between member states and their various actors (e.g. universities, research centres, industry). Research in energy technologies (including RES) should support the overall EC energy policy strategy goal to secure energy supply and reduce energy imports. EU-funded research in PV

---

[108] Commission of the European Communities, *Proposal from the Commission to the Council concerning a Second Year Energy Research and Development Programme*, COM (78) 388 final – Volume I, Brussels, 4 August 1978, p. 3.

was characterised by technological pluralism. EC research policy advocated the pursuit of different energy technologies, but with clear frontrunner in funding (e.g. in PV research on different cells, but with a clear dominance of crystalline Si cells).

Even though research on energy technologies (including RES) took place before the establishment of the FPs, the respective aims and objectives are consistent with those of the first period FPs.[109] Overall, the FPs set the overarching aim that governs the areas and/or activities covered. The objectives for the individual area are then set in the corresponding sub-programmes.[110] It is common for further clarifications and/or specifications to be made in the work programmes and calls for proposals.[111] This allowed a certain degree of flexibility in setting the specific objectives of the activities funded through the FPs. At the same time, this allowed for the inclusion of different objectives or activities so that research could better adapt to developments.

In the absence of a general – overarching – research policy framework for the two energy R&D programmes, we examine the objectives set under these two programmes separately. Both programmes were focused on the energy crises, as explained in an earlier section, and pursued the following objectives:

> "…save energy and to develop new energy sources, to foster international collaboration, to develop the technological level and the competitivity of European industry, to favour a more even distribution of research and development potentials in the Community, to improve social and economic development, etc."[112]

---

[109] From 1975 to 1983, the EC supported two energy R&D programmes that included gradually more RES. Solar energy (including PV) and geothermal energy were included in both programmes, whereas wind energy was incorporated in the second energy R&D programme of the EC (1979-1983). Under FP1, the term 'renewable sources of energy' was introduced, and the corresponding activities were incorporate to the non-nuclear energy programme (NNE). What is listed as 'objectives' in the Annex of the legislation adopting these sub-programmes is in fact a more detailed breakdown of the research supported. For example, for 'Solar energy' this included photovoltaic conversion, solar heat collectors etc.

[110] The FPs are implemented through sub-programmes. For example, under FP2 the Energy activity was sub-divided into three sub-programmes. One of these sub-programmes concerned non-nuclear energies and rational use of energy.

[111] The research supported for each activity was – sometimes – further 'delineated' in the calls for proposals. For example, in the case of PV more details were provided regarding the type of technologies and/or methods to be funded. For example, see: C14, Communication from the Commission regarding the energy research and development programme adopted by the Council of the European Communities on 22 August 1975, Official Journal of the European Communities, 21.1.1976, p. 2.

[112] Farinelli Ugo, Gelus M., Muus L. T., Rorsch A., Stocker H. J., *The evaluation of the Communities' energy conservation and solar energy R&D sub-programmes,* Office for Official Publications of the European Communities (Luxembourg: 1980), p. 48.

The first two energy research programmes were aimed at finding technological solutions to energy crises and promoting the (international) competitiveness through European-wide cooperation. Despite the lack of broader or specific objectives, the direction is similar to the rest of the first period. SEA established a new legal basis for Community R&D programmes and at the same time defined and specified the aim to be pursued by the FPs. In particular, the Article 130f notes:

> "The Community's aim shall be to strengthen the scientific and technological basis of European industry and to encourage it to become more competitive at international level."[113]

This aim became the 'guiding principle' of the R&D programmes. Essentially, the programmes were to provide the European industry with technological solutions that would in turn lead to industry becoming more competitive internationally. In other words, research was instrumentalized to serve industrial policy. In addition to this aim, the FPs were also intended to support the completion of SEA.

Under FP2, the Joint Opportunities for Unconventional or Long-term Energy supply (JOULE) programmes were introduced.[114,115] The objectives of the JOULE programmes were similar to those of the previous programmes for RES. In particular, research conducted within the framework of JOULE:

> "The objective of developing energy technologies is directly linked to the Community's energy strategy, the aim of which is to increase security of supply in the long term and to reduce energy imports to a reasonable cost, bearing in mind the environment. […] The development of advanced energy technologies should stimulate and improve industrial competitiveness, including that of small

---

[113] L. 169, *Single European Act*, Official Journal of the European Communities (29.06.1986), p. 10.

[114] They were the successor of the NNE programme, supported under FP1. The JOULE programmes comprised a long-lasting 'tradition' since they run for nearly ten years (1989-1998). We will be referring to three JOULE programmes as JOULE I (1989-1992) JOULE II (1990-1994) and JOULE III (1994-1998).

[115] From FP2 to FP4 RES research was supported under the Joint opportunities for unconventional or long-term energy supply (JOULE) sub-programmes. All these sub-programmes were organized, executed and overseen by the RES Unit withing DGXII, same as their predecessors.

> and medium-sized enterprises in the Community, and, as a consequence, help to enhance the economic and social cohesion of the Community."[116]

In line with the aim of SEA for research, the research (sub-)programmes for energy technologies (including RES) sought to serve industrial policy while adhering to the overall Community energy strategy goals. In addition, a number of projects were funded in line with the establishment of common standards.

The two energy R&D programmes that preceded the FPs, and the first period FPs were in fact effectively pursued the same goal. Despite minor changes, the first period research programmes (including the sub-programmes for RES) essentially pursued the same aim: to strengthen the scientific and technological base of the European industry to make it more competitive, internationally. This was the aim that pertained the research activities for PV.

2.1.3.1 Allocation of research funding in the energy sector

Energy, as a theme, received a just over 47% of the total budget of FP1. For the remainder of the first period, we see changes in funding for both energy as a theme in the FPs and for RES.[117] As illustrated in Figure 2.1 (below), non-nuclear energy (NNE) received a significant share of funding during FP1, highlighting the impact of the two oil crises; almost 50% of the total funding was allocated to NNE R&D.

In FP2 and FP3, NNE received a smaller share of funding compared to the funding allocated to nuclear energy, which clearly indicates the high priority given to nuclear energy. This significant increase in funding allocated to nuclear energy can be attributed to the Chernobyl nuclear disaster, which was the main trigger for the increase in funding for nuclear energy – especially for nuclear safety. Low crude oil prices – since 1986 and throughout the 1990s – did not help reignite interest in RES. The 'effect' that the low crude oil price had on R&D is already evident in FP2 and continues in FP3, where RES had a low funding share. In FP4, NNE funding was almost as high as nuclear energy funding. Thus, compared to the funding NNE received in the previous two FPs, NNE gained prominence during this period. At the same time, we

---

[116] L98, Council Decision of 14 March 1989 on a specific research and technological development programme in the field of energy – non-nuclear energies and rational use of energy – 1989 to 1992 (Joule), Official Journal of the European Communities, 11.4.1989, p. 15.

[117] Gradually, the IT became the recipient of the bulk of the R&D programmes' funding.

should note that in the 1980s and throughout the 1990s, public R&D funding for RES decreased worldwide.[118]

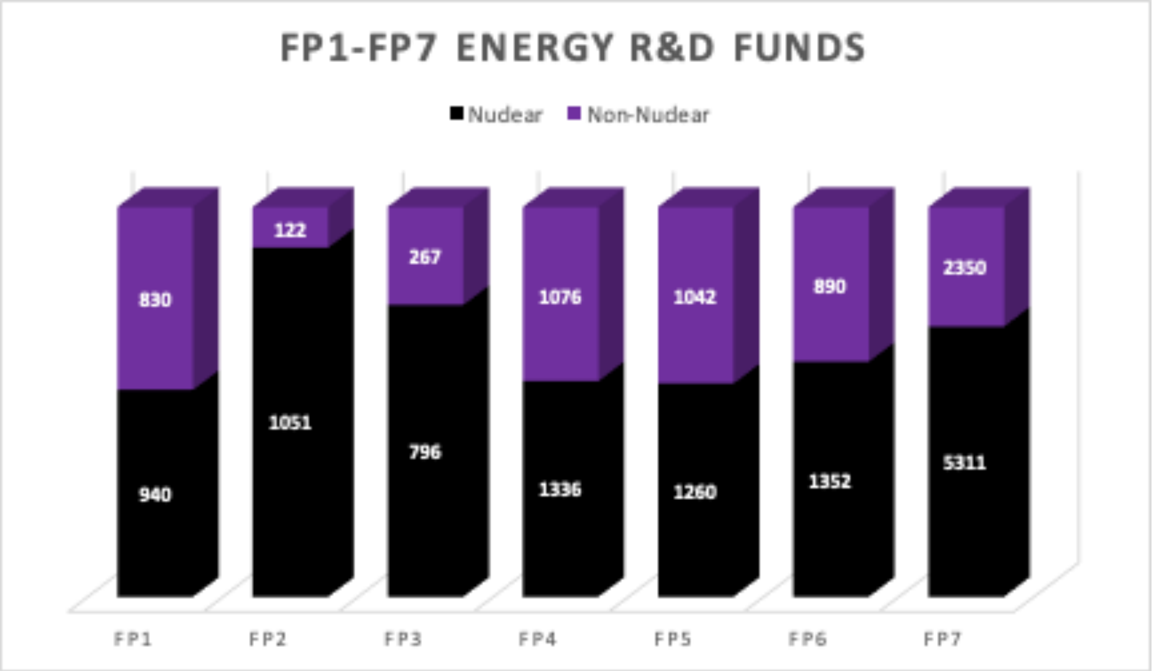


Figure 2.1. FP1-FP7 Energy R&D Funds (in EUR million). Adapted from: Vilma Radvilaite, *EU budget 2014–2020 deal: opportunities for wind energy*, European Wind Energy Association, 2013, p. 3.

Although energy research played an important role in the establishment of FP1, the share of energy research declined steadily thereafter.[119] Instead, other activities became the main funding recipients. One example is life sciences, which increased its share of funding with its many subcategories. The most notable example, however, is information technology (IT), which became the main funding recipient from FP2 onwards. We attribute this shift in funding to IT to its strategic role in the economy. This 'trend' continued in the second period, with the addition of some areas such as life sciences and biotechnology, and transport and nanoscience and nanotechnology.

---

[118] Breyer Ch., Birkner C, Kersten F., Gerlach A., Goldschmidt J. C., Stryi-Hipp G., Montoro Fraile D., Riede M., "Research and Development Investments in PV: a limiting factor for a fast PV diffusion?", 25th European Photovoltaic Solar Energy Conference / 5th World Conference on Photovoltaic Energy Conversion, Proceedings of the International Conference held in Valencia, Spain, 6-10 September 2010, G. F. de Santi, H. Ossenbrink and P. Helm (eds.), WIP Renewable Energies (Germany: 2010), p. 5385-5408.

[119] The energy research share dropped to nearly 22% in FP2, to approximately 14% in FP3, to a little over 9% in FP4. Accordingly, energy received nearly 8% under FP5, whereas its share dropped to nearly 5% under FP6 and then further dropped to 4,6% in FP7.

During FP4 and FP5, NNE funds were almost as high as those for nuclear energy. Thus, when compared to the funding received by NNE in the previous two FPs, NNE gained prominence during this period. The fluctuations in funding for NNE and nuclear energy between FP1 and FP5 appear to have been influenced by broader energy issues and pressures. Critical events such as the oil crises and the Chernobyl disaster were the driving force behind the changes in energy funding rather than the enlargements. In FP6, funding for NNE decreased, while in FP7, funding for NNE almost tripled and funding for nuclear energy almost quadrupled. In the 2004 and 2013 enlargements, several countries with nuclear power stations joined (Lithuania, Hungary and Bulgaria). The Kyoto Protocol required a reduction in greenhouse gas (GHG) emissions, sustainable energy production was among the energy priorities of the EC and the nuclear industry tried to rebrand nuclear energy as a safe and clean energy source.[120] The EC invested in both NNE and nuclear energy in its effort to balance energy security, energy efficiency and sustainable energy production. Global trends, competition with the USA and China, and the energy crises such as the gas conflict between Russia and Ukraine in January 2006 also spurred drove funding for NNE and nuclear energy in the last period of our study.[121]

2.1.3.1.1 The place of PV in research funding

Solar photovoltaics (PV) has always had a prominent place in R&D funding among all other RES. As we have seen in section 2.1.2.1.1, according to geographical criteria, PV was considered as the most important energy source (among all other RES) that could contribute to the energy needs of the North-Western Community countries. On the basis of this very criterion, its leading position in R&D funding was justified.

From FP1 to FP4, PV received substantial R&D funding, which in the first period accounted for about a quarter of the funding from RES.[122] The person responsible for the RES sub-programmes and research activities in DGXII (RES Unit), Dr Wolfgang Palz, played a key role

---

[120] Andrei Stsiapanau, Lithuania-Short Country Report, HoNESt Project, 2018; Mathew Adamson, Gábor Palló, Hungary-Short Country Report, HoNESt Project, 2017; Ivan Tchalakov, Ivaylo Hristov, Bulgaria-SCR, HoNESt, 2019.

[121] Frank Umbach, "Global Energy Security and the Implications for the EU", *Energy Policy*, 2010, p. 1229-1240.

[122] Calculated by mean/average funding for PV. In particular, PV R&D funding accounted for 16,27% of the RES funding under FP1, 30,75% under FP2, 24,87% under FP3 and 31,32% under FP4 (calculated by the author). For the calculations we have separated only the funding PV received in comparison to all other RES – not the entire NNE or JOULE programmes. Essentially, the above shares correspond to PV's R&D funding place among other RES. It should be noted that we have not included in the PV funding projects that do not correspond to electricity production as they do not comprise part of our analysis, nor have we included in the corresponding funding hybrid projects (i.e. PV in combination with another form of energy).

in prioritizing PV, as he held a strong position in determining the allocation of R&D funding.[123] Palz is a German physicist who wrote his doctoral thesis on CdS solar cells. In the early 1970s, he led the French PV Programme on behalf of the National Space Agency (CNES) and was involved in the design of the first EC RES programme as a French Delegate in 1974. Soon after, in 1977, he became Director of EC's DGXII RES Unit, where he remained until 1997 (until the end of the first period).

The PV's gradual descent from its R&D funding pedestal can be primarily attributed to Palz's departure from the DGXII RES Unit. In FP6 and FP7, bioenergy accounted for most of the R&D funding, while other activities (e.g. smart grids and energy efficiency) received significant research funding.[124] This resulted in PV losing its lead in R&D funding.

2.1.3.2 Low crude oil prices, the Chernobyl accident, and the climate change 'rescue'

Even though RES was the main 'priority' of the NNE R&D programmes and later the JOULE programmes, they still struggled to compete with the main energy sources and their powerful lobbies. As one EC Scientific Officer from DGXII RES Unit noted:

> "…the 90s was a period of low crude oil prices, because that had always been what the whole story depended on. In parallel, climate [change] had started to play a role but did not have a prominent role; it started in 1992 with the United Nations Rio Declaration […] this became, after a certain point, the main power for RES. So, this was the time when the crude oil prices were low […] DGXVII was not interested in RES. The(ir) priorities and interests were elsewhere. The interests are always there, it is obvious that the different lobbies at DGXVII were for natural gas, coal, nuclear energy etc. The RES lobby was very weak and not influential in DGXVII. It [the RES lobby] was powerful in DGXII

---

[123] Based on a written correspondence we had with Palz he confirmed that the DGXII's RES Unit had a strong say regarding the funding allocation and the corresponding research priorities, regarding the latter especially since the EC had the core task of drafting the programme proposals and its contents. Being the Director of the RES Unit, his central role in such decisions was confirmed by an interview with a former DGXII – RES Unit Scientific Officer.

[124] Geert van der Veen, Patrick Eparvier, Matthias Ploeg, Paola Trucco, *Evaluation of the impact of projects funded under the 6th and 7th EU Framework Programmes for RD&D in the area of non-nuclear energy*, Final Report (Version 4, 19 June 2013), Technopolis Group (2014), p. vi.

> because suddenly Palz was there, that was it! And he fought about it a lot, I've experienced this first-hand."[125]

The same reason that had sparked interest in RES became, in reverse, the reason for the 'waning' interest in RES in the late 1980s and throughout the 1990s. Essentially, it was the high crude oil prices of the 1970s that led to the establishment of an EC R&D programme that initiated research activities for RES. Accordingly, it was the low crude oil prices in the late 1980s and 1990s that impacted on the waning interest in RES. At the same time, the lack of a strong RES lobby in DGXVII and the strong presence of other dominant and influential energy lobbies contributed to 'delaying' an EC energy policy for RES.

In addition to the changed situation of the conventional sources, RES faced another problem. In particular, "[i]n the eighties and partially in the 90's the renewable energy sector was not taken seriously by most political authorities nor by the conventional energy sector".[126] RES were not seen as an actual, feasible, solution in the early to mid-1990s. For this reason, Professor Roger van Overstraeten, a key figure in the field of PV, founded the European Renewable Energy Research Centres (EUREC) Agency in 1991. As the name suggests, the EUREC Agency was founded as an association of the large European research centres for all RES. In a decade when interest in RES was steadily declining, Overstraeten created this association so that for research centres could play more impactful and/or influential role in setting the R&D priorities for RES.

In the absence of an EC energy policy for RES in the first period, left the efforts for PV research, the establishment of a European PV Community (both scientific and industrial) and the creation of a European PV market in the hands of research policy – implemented through the R&D programmes. Furthermore, the above tasks were left in the hands of the RES Unit of DGXII and its personnel and especially the person in charge of the RES programme, Wolfgang Palz. Palz remained in DGXII for twenty (20) years when he was transferred to another DG in 1997. As an EC Scientific Officer from DGXII remarked:

---

[125] Interview with former EC DGXII RES Unit Scientific Officer (via Skype), 14 May 2020, Athens, Greece.

[126] R. Mertens and G. Palmers, "Roger van Overstraeten – Professor, Manager and Entrepreneur: his work in photovoltaics", *in* Sixteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Glasgow, UK, 1-5 May 2000, H. Scheer, B. McNelis, W. Palz, H. A. Ossenbrink, and P. Helm (eds.), Vol I, James and James (London, UK: 2000), p. lvii.

> “Palz’s transfer significantly weakened DGXII. […] During Palz’s time, essentially, the policy for RES was done there [i.e. DGXII].”[127]

During these twenty years, DGXII was the only DG that had a research policy for RES. And this was largely due to Palz’s perseverance and active role. The fact that no one else seemed to be so interested in RES, as well as the fact that the powerful lobbies in DGXVII had other interests, enabled Palz to obtain and hold this strong and influential position.

As we have no further information regarding the reason(s) why Palz was removed from DGXII or transferred to another DG, we cannot draw any conclusions with absolute certainty. However, it is important to note that Palz was a central figure in DGXII RES research policy, particularly in the area of PV and that he left DGXII in the same year that EC began formulating an energy policy for RES. We return to the significance of Palz’s departure from DGXII in chapter 4, where we analyse the corresponding changing relationship between (EC’s) energy and research policies.

The 1990s were a difficult time for RES, including PV. As we have already seen, low crude oil prices diverted attention from RES. In the 1990s, however, the first steps towards a new vision for RES began to emerge, slowly gaining momentum in the late 1990s and especially in the second period.[128] To this end, the prevailing environmental policy challenges, especially climate change, helped gradually rekindle interest in RES.

In 1993, a common and centrally controlled EC energy policy began to shape and direct national energy policies.[129] Member states agreed to give up a (small) part of their sovereignty when they adopted the more-or-less binding common policy measures set out in EC regulations and directives. Within this framework, a common vision was created and energy policy was shaped by specific environmental challenges and problems. As we examine in depth in chapters 3-5, in the second period the EC promoted further energy production through RES and moved from indicative to binding targets for the share of RES in electricity generation. The three sets of EC policies—energy, environmental, and research—were aligned in that they pursued similar energy policy goals by promoting the further development and integration of RES technologies into the electricity grids. This synergy of energy, environmental and research

---

[127] Interview with former EC DGXII RES Unit Scientific Officer (via Skype), 14 May 2020, Athens, Greece.

[128] That is not to say that the vision was created to ‘serve’ or promote RES. However, the vision created/established to deal with and overcome the environmental problems largely benefited RES too.

[129] This did not include RES. As we have already explained an EU energy policy for RES started to take shape in the late 1990s, following the 1997 White Paper for RES.

objectives helped the EC to achieve its targets for GHS emissions and RES integration into the electricity grids and to enhance the sustainability of its energy policy.

2.2 Establishing an EU-wide research policy: narrowing the gap between research and market

In this section we analyse the main changes in EU research policy during the second period. These main changes that impacted research and research priorities are the following: the establishment of the European Research Area (ERA), the Lisbon agenda, the introduction of the Strategic Energy Technology Plan (SET-Plan) (for low carbon technologies, including RES) and the European Technology Platforms (ETPs).

2.2.1 The European Research Area: aligning member states research policies with those of the EU

The European Commissions' 2000 Communication proposed the establishment of the European Research Area (ERA).[130,131] The ERA was created to align EU and member state research activities, programmes, and policies. The ERA advanced alignment through joint research ventures under the EC R&D umbrella, accompanied by an increase in funding (3% of GDP target), to overcome fragmentation in Europe and between different countries.[132] As the then Director General of DGXII, Philippe Busquin, explained the ERA: "…should become in the research sector what the single market has been for commercial exchanges."[133] The ERA was to become the equivalent of the Single European Market (SEM), but for research; it was to create an integrated space for science and technology.

---

[130] Commission of the European Communities, *Communication from the Commission to the Council, the European Parliament, the Economic and Social Committee and the Committee of the Regions: Towards a European research area*, COM (2000) 6 final, Brussels, 18 January 2000.

[131] The idea behind the establishment of an/the ERA dates to the 1970s to Commissioner Ralf Dahrendorf. For a detailed take on the concept and a more in-depth analysis see: Luca Guzzetti, "The Seventies", *in* A brief history of European Union Research Policy, Office for Official Publications of the European Communities (Luxembourg: 1995), p. 35-70.; Veera Mitzner, "Conclusions and Further Thoughts", *in* European Union Research Policy: Contested Origins, Palgrave MacMillan (2020), p. 248-273.

[132] Thomas Banchoff, "Politic Dynamics of the ERA", *in Changing Governance on Research and Technology Policy: The European Research Area*, Jacob Edler, Stefan Kuhlmann, Maria Behrens (eds.), Edward Elgar (Cheltenham, U.K. and Northampton, Mass: 2003).

[133] Philippe Busquin, "Address at the Friedrich Ebert Foundation, Berlin, 18 January 2001", as cited in Thomas Banchoff, "Institutions, Inertia and European Union Research Policy", *Journal of Common Market Studies*, 2002, p. 14.

The ERA can best be understood as the recreation of a new geographical map of the EU, but for research. Without being material, like infrastructures or technologies, it contributed to the creation of an EU-wide research space and identity. The activities targeted for the creation of the ERA were research and innovation, human resources and mobility, research infrastructures and science and society.[134]

By raising questions about Europe's (worrying) situation in terms of growth, competitiveness and the global economy, and contrasting the examples of the USA and Japanese for R&D spending, the vision for the ERA was set in motion. By declaring the 21st century as the "century of science and technology" and in the context of fostering the transition towards a Knowledge-Based Economy (KBE), the Commission set the tone for the key drivers of the ERA.[135] Given the direct link between ERA and the transition to a KBE, which was a key element of the Lisbon agenda (2000), ERA was seen as a complementary means to achieve the goals of the KBE.

In the second period, research was (re)directed towards solving new problems. This led to a redefinition of its role and its use. R&D sought to foster economic development, sustainable development and at solving environmental and societal problems, while supporting the global competitiveness of the European industry. The systematic emphasis on economic development was directly in line with the Lisbon agenda (2000), which aimed to make the EU "the world's most competitive and dynamic knowledge economy."[136] Environmental targets, in particular CO_2 emission reductions, were linked to RES-related activities. Furthermore, *research was envisioned as the focal point of innovation and knowledge-production, and R&D programmes portrayed research as a means of achieving these economic objectives.* In this context, there was a constant effort to narrow the gap between research and the market and to promote the commercialisation of products that had emerged from research. This shift became evident as R&D programmes increasingly emphasized value and promoted innovation and commercial applications. In addition, energy policy was strongly focused to addressing environmental

---

[134] For a more detailed information on what these activities comprised of see: Decision No 1513/2002/EC of the European Parliament and of the Council of 27 June 2002 concerning the sixth framework programme of the European Community for research, technological development and demonstration activities, contributing to the creation of the European Research Area and to innovation (2002 to 2006), Official Journal of the European Communities: Luxembourg, 29.08.2002.

[135] Commission of the European Communities, *Communication from the Commission to the Council, the European Parliament, the Economic and Social Committee and the Committee of the Regions: Towards a European research area*, COM (2000) 6 final, Brussels, 18 January 2000.

[136] Decision No 1513/2002/EC of the European Parliament and of the Council of 27 June 2002 concerning the sixth framework programme of the European Community for research, technological development and demonstration activities, contributing to the creation of the European Research Area and to innovation (2002 to 2006), Official Journal of the European Communities: Luxembourg, 29.08.2002, p. 1.

problems. Energy policy thus had a clear impact on energy actions and activities of research policy. During this period, research shifted to industrial exploitation of near-market products and large-scale production, to solving connectivity problems that would facilitate the integration of RES technologies into the energy grids.

The importance of ERA is (also) reflected in FP6, which was designed to contribute to its creation.[137] To this end, new instruments proposed by the Commission have been introduced in FP6 onwards (i.e. Networks of Excellence and Integrated projects).[138]

2.2.2 The Strategic Energy Technology Plan and the European Technology Platforms

Another important change was introduced with the implementation of the Strategic Energy Technology Plan (SET-Plan) in 2007, which focused on low-carbon technologies and coordinated the criteria for research and innovation.[139] The SET-Plan called for better coordination and alignment between energy policy and research policy for RES technologies to achieve EU's energy policy goals.

With the SET-Plan, the EU sought to align energy and research policies (for energy technologies) to achieve energy policy goals, while ensuring synergy between the two policies. Directly targeting low-carbon technologies, such as RES, which are crucial to the EU's energy strategy.[140] Essentially, the SET-Plan can be understood as a bridge between the EU's energy and research policies by guiding research activities for energy technologies to be funded by the EU's research programmes. It is no coincidence that the SET-Plan was introduced in 2007, when the EU attained the legal basis for energy policy through the Treaty of Lisbon.[141]

In order to establish a concrete research agenda for the actions to be funded, the European Technology Platforms (ETPs) were launched in 2002.[142] Even before the creation of the SET-

---

[137] Evident already from the title of the Legislation establishing FP6 but also from the inclusion of ERA specific objectives, as well as the overall language and terms adopted.

[138] Many scholars have written about the ERA. Regarding the politics of the ERA see Thomas Banchoff, "The Politics of the European Research Area, ACES Working Paper 2002.3, August 2002, [working paper], Available online: http://aei.pitt.edu/8964/, p. 1-25. About the ERA establishment see: Thomas Banchoff, "Institutions, Inertia and European Union Research Policy, *Journal of Common Market Studies*, 2002, p. 1-21. Regarding the type of networks the ERA promotes see: Stefano Breschi and Lucia Cusmano, "Unveilling the texture of a European Research Area: emergence of oligarchic networks under EU Framework Programmes", *Int. J. Technology Management*, 2004, p. 747-772. Regarding an analysis of the vision of the ERA see: Dan Andrée, *Priority-setting in the European Research Framework Programmes*, VINNOVA Analysis VA – Swedish Governmental Agency for Innovation Systems (July 2009).

[139] As we analyse in Chapter 3, the SET-Plan was set in motion soon after the Treaty of Lisbon (2007) that provided the EU the institutional powers in setting up an EU-wide energy policy.

[140] We are referring to EU's short (2020) and long-term energy strategies (2050).

[141] Regarding this point, see Chapter 3.

[142] The ETPs are 'wide-ranging', clustered around areas or sectors such as energy, agriculture, and transport.

Plan, the ETPs had the same goal as today: establish a research agenda for their area/sector. The ETPs for low-carbon technologies were included in the SET-Plan when it was created.

The ETPs are industry-led fora that publish Strategic Research Agendas that link visions to challenges and propose responses to the latter by outlining research priorities that feed into and guide EC R&D priorities. The corresponding ETP for PV (ETP-PV) was established in 2004-5.[143,144] The creation of the ETPs was strongly supported by the European Commission. In a 2004 Commission report, the ETPs were defined as a response to the realisation of the ERA and its urgent challenges.[145] Essentially, the ETPs were seen as an instrument to implement the research priorities to be funded, embedding them in a concrete vision. In this context, each ETP published Strategic Research Agendas (SRAs), which included a vision and the corresponding research strategy for each area/sector.[146] The SRAs then form the basis for EU research funding priorities and enable the alignment of research priorities and activities in each area between interested parties from the different member states and the EU.

2.2.2.1 The Strategic Research Agenda(s) for PV

The first Strategic Research Agenda (SRA) for PV was published in 2007 and renewed/revised in 2011. The SRAs were prepared by the third Working Group "Science, Technology and Applications" of the ETP-PV. The members of ETP-PV WG3 were primarily composed of stakeholders from the European (PV) industry, major European research centres and to a lesser extent, universities.[147]

In Figure 2.2 we see the geographical distribution of actors involved in the establishment of the two SRAs for PV. Overall, there seems to be a concentration of actors from Western and Northern Europe, with Germany being more represented than other countries.[148] Accordingly, the Southern and Eastern EU member states seem to be underrepresented compared to the

---

[143] For more information on the ETP- PV see The European Technology and Innovation Platform for Photovoltaics, *Our Vision*, etip-pv. Available online: https://etip-pv.eu/about/our-vision/, (accessed 5 October 2019).

[144] Correspondingly ETPs for other RES were created (e.g. wind energy and geothermal energy). The ETPs were not restricted to RES.

[145] European Commission, *Technology Platforms: from Definition to Implementation of a Common Research Agenda*, Office for Official Publications of the European Communities: Luxembourg, 2004.

[146] The SRAs contain very detailed analyses of the respective field technologies and propose the direction of the future research priorities and activities.

[147] In the analysis of Chapters 4-6, we show that both the actors and the specific individuals comprising the WG3 were in fact active participants in the PV technoscientific research networks.

[148] The actors from Germany, when compared to the actors from any other country, are better represented. For example, in the first SRA we see five German actors participating, whereas only a single Spanish actor comprised part of the respective WG.

North-Western EU countries. Figure 2.2 lists the actors that have established the two SRAs for PV. There is an overwhelming presence of actors that had a prominent place in the technoscientific research networks for the dominant PV technology (c-Si), such as Fraunhofer ISE, University of Konstanz, imec, ECN, SINTEF, Photowatt, EniTechnologie etc.[149,150] In contrast, we see a limited inclusion or participation of representatives of the alternative design option (CPV) with UPM and BP Solar during the first SRA and ENEL during the second SRA. The SRAs aimed to guide FP7 PV R&D priorities and support the alignment of EU member states research priorities, activities, and programmes (i.e. concluding the establishment of the ERA).[151] To this end, the SRAs set specific priorities and targets for each PV technology. As noted in the second SRA: "The overall targets of the SRA are in line with the objectives of the Solar Europe Industry Initiative up to 2020."[152] The SRA targets were in line with the priorities of the Solar Europe Industry Initiative (SEII).[153] Essentially, these decision-making platforms – precisely because of their composition – enabled the promotion of national industry interests. Furthermore, through the establishment of the ETPs, the EC legitimized the role of the networks as the ones to set and steer the research agenda and priorities to be funded through the FPs, while allowing for the further promotion of corporate interests to steer the agenda.

One of the most important parts of the SRAs was the setting of specific timeframes for the corresponding targets. Within this framework, we see the division into short-, medium- and long-term research. Each category or sub-category was tasked with achieving specific targets.[154] Despite the timeframe, the overarching similarity was that research was mandated to achieve specific cost and efficiency targets. Given the timeframes defined in the SRAs, the objectives set for FP7 – and extended to 2016 with the second edition of the SRA – were

---

[149] See analysis of the c-Si technoscientific research networks, in chapters 4-5.

[150] Even though we make specific mentions in the analysis found in Chapters 4-6, it is worth noting that there is an overlap also in the individuals that set up the SRAs and who also participated in the technoscientific research networks.

[151] We explicitly mention the specific aims and targets of the SRAs throughout the empirical analysis of the PV technologies.

[152] Photovoltaic Technology Platform, *A Strategic Research Agenda for Photovoltaic Solar Energy Technology*, 2nd Edition, Office for Official Publications of the European Communities (Luxembourg: 2011), p. 17.

[153] SEII was one of the pillars comprising the SET-Plan, which is analysed in a previous section. SEII comprised of ETP-PV and EPIA.

[154] The specific timeframes for short-, medium- and long-term research in each SRA differ. This is explained given the year each SRA was published (i.e. 2007 and 2011). As such in the first SRA (2007) the timeframes were the following: (i) short-term, from 2008 to 2013, (ii) medium-term, from 2013 to 2020, (iii) long-term, from 2020 to 2030. Accordingly, the timeframes provided in the second SRA (2011) were the following: (i) short-term, from 2011 to 2016, (ii) medium-term, from 2016 to 2025, (iii) long-term, from 2025 to 2035.What remains constant is (a) the period each timeframe covers and (b) the short-term period is covered by the research activities of the corresponding FP.

defined as short-term. “**Short-term research should be fully dedicated to the competitiveness of the EU industry**.”[155]

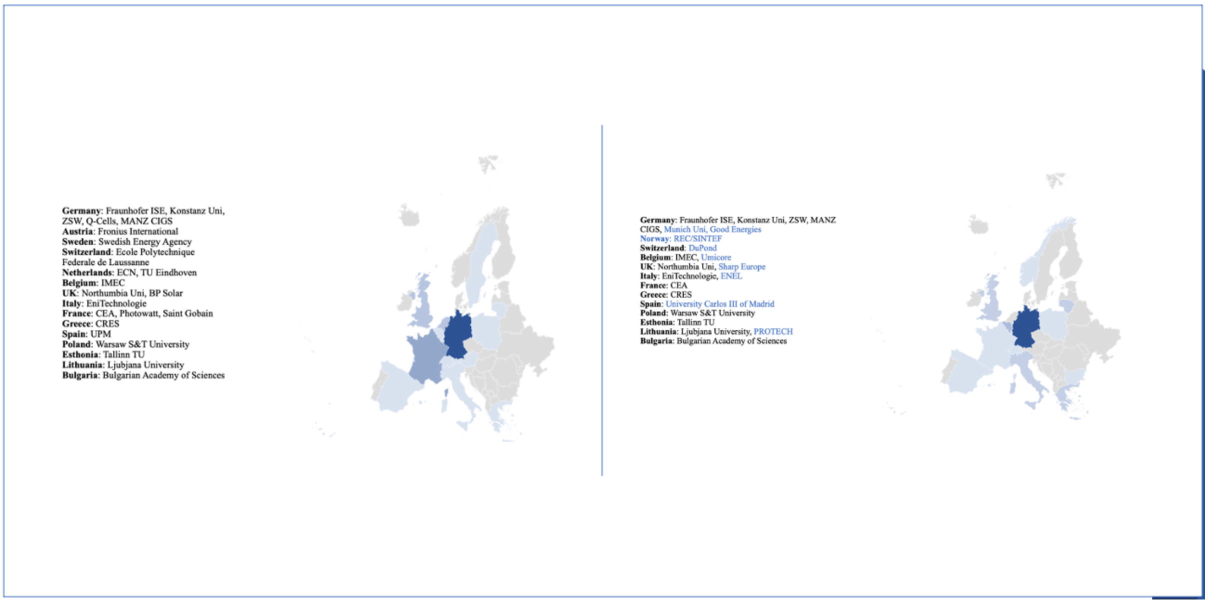


Figure 2.2 Actors setting-up the research priorities for PV listed by country and their respective geographical distribution (2007 SRA left, 2011 SRA right).

The last sentence provides a/the normative definition of what research should be and what role it should have. The research defined as short-term in the SRAs is the research covered and funded under FP7. Consequently, the funded research, and its objectives were defined by the SRAs and explicitly concerned industry competitiveness. This, in turn, corresponded to the different ways in which research was defined and used during the second period and the objectives it was intended to achieve; narrow the gap between research and market. Although the first SRA that clearly defined research supported under FP7 was published in 2007, both the role and character of research had already changed since FP5.

2.2.3 The second period Framework Programmes

During the second period, RES R&D was no longer supported under the JOULE programmes.[156] The RES R&D activities started to be coupled with sustainable development

---

[155] Photovoltaic Technology Platform, *A Strategic Research Agenda for Photovoltaic Solar Energy Technology*, Office for Official Publications of the European Communities (Luxembourg: 2007), p. 15; Photovoltaic Technology Platform, *A Strategic Research Agenda for Photovoltaic Solar Energy Technology*, 2nd Edition, Office for Official Publications of the European Communities (Luxembourg: 2011), p. 19.

[156] This could also be interpreted as a disassociation effort from the former ‘Palz era’.

and the environment. This signalled the beginning of a new era for RES, in which they became strongly linked to sustainable development and environmental challenges. Moreover, the aims and objectives of the FPs funded in the second period reflected this linkage by either directly making references to the Kyoto protocol objectives or to the White Paper objectives.[157]

In addition to environmental challenges, the FPs systematically prioritized the promotion of economic development, in line with the Lisbon agenda. Research was envisioned as **the** focal point of innovation and knowledge-production, and R&D programmes portrayed research as a means to achieve these economic goals. In this context, there were constant efforts to narrow the gap between research and the market and to promote the commercialisation of products that emerged (directly) from research.

For RES, research shifted to industrial exploitation of near-market products and large-scale production, to solving connectivity problems that would facilitate the integration of RES technologies into the energy grids.

The Fifth Framework Programme (FP5) had the overall aim of "strengthening the scientific and technological bases of the Community industry and encouraging it to become more competitive at international level".[158] Even though this appears to be similar to the aim of the first period FPs, as per the words of the European Commission:

> "The Fifth Framework Programme differs from its predecessors. It has been conceived to help **solve problems** and to respond to major **socio-economic challenges** facing the European Union."[159] (emphasis in the original text)

The inclusion of the 'socio-economic challenges' and thus the aims that FP5 sought to address is indeed a departure from the first period. The Lisbon agenda redefined the role of research and its relationship to economic goals. FP5 did not set specific targets for RES (or for PV). Rather, as we have noted, it is common for the specific objectives to be set by the sub-programmes targeting these activities, or for the respective objectives to be delineated in the

---

[157] For example, see: European Commission, *Energy, environment and sustainable development: sub-programme Energy Information package*, March 1999 edition and European Commission, *Work Programme: 6.1 Sustainable energy systems*, 2002.

[158] Decision No 182/1999/EC of the European Parliament and of the Council of 22 December 1998 concerning the fifth framework programme of the European Community for research, technological development and demonstration activities (1998 to 2002), Official Journal of the European Communities, 1.2.1999, p. 7.

[159] European Commission, *Energy, environment and sustainable development: sub-programme Energy Information package*, March 1999 edition, p. 4.

Work Programmes, calls for proposals etc. for each of the FP activities.[160] However, the FPs set the general guidelines for EU research policy in the respective sectors and areas and provide the overarching actions. For the area of 'energy', which includes RES, the following two key actions have been identified: (i) cleaner energy systems, including renewables and (ii) economic and efficient energy for a competitive Europe.[161]

Under FP5, RES were defined as the primary means of reducing environmental impacts, as opposed to fossil fuels. RES were grouped under the umbrella of **decentralized generation**, indicating the intended purpose and means of integrating these technologies into the energy systems.[162] Furthermore, the European Commission has set the following goal for the FP5 Energy sub-programme:

> "The **strategic goal** of this part of the programme **is to develop sustainable energy systems and services for Europe** and contribute to a more sustainable development world-wide, leading to increased security and diversity of supply, the provision of high-quality, low-cost energy services, improved industrial competitiveness and reduced environmental impact."[163] (emphasis added)

RES not only offered the possibility of decentralized integration into the energy system, but this type of system was also described as sustainable. In conjunction with the main energy policy aims (energy security and diversification of supply), RES were now part of energy policy and an important step towards achieving energy policy goals. Therefore, research policy had to respond to these goals and provide the scientific and technological means to achieve them.

The understanding of RES as the most important means to address and resolve the environmental challenges in the energy sector, and the corresponding goals set in the 1997 White Paper for RES became the main driving force for the research priorities of the second period. In the information package, published by the European Commission on the FP5 sub-programme 'Energy' sub-programme we find the following:

---

[160] This allows for an increased level of flexibility in the objectives and the research activities, especially since each FP is executed via a number of calls for proposals.

[161] Decision No 182/1999/EC of the European Parliament and of the Council of 22 December 1998 concerning the fifth framework programme of the European Community for research, technological development and demonstration activities (1998 to 2002), Official Journal of the European Communities, 1.2.1999.

[162] We analyse this point further in Chapter 3 where we discuss the different system integration options RES enable.

[163] European Commission, *Energy, environment and sustainable development: sub-programme Energy Information package*, March 1999 edition, p. 12.

> “**The Kyoto objectives**, which imply for the EU a reduction by 8%, compared to the 1990 level, of the greenhouse gas emissions (corresponding to approximately 600 million tons per year of CO2 equivalent) between 2008 and 2012, **are the driving force for the development of new technologies, innovation and associated measures**. Together with the Council Resolution on renewable energies of 8 June 1998, which seeks a **doubling of the share of renewables from 6% today to 12% in 2010**, they provide useful guidance for increased efforts at the Commission level as well as in Member States, (bearing in mind the need to reflect differing national circumstances), and set the objectives for the programme. Added to these, **the programme aims to provide Europe with a reliable, clean, efficient, safe and economic energy supply for the benefit of its citizens, the functioning of society and the competitiveness of its industry**.”[164] (emphasis added)

The incorporation of the White Paper and Kyoto targets into FP5 energy activities demonstrate (i) the changing relationship between energy and research policy, (ii) the changing character of research, (iii) the direction of the research agenda for energy, including RES.

The main focus of activities in ‘Energy’ has been reoriented to achieve “market exploitation and impacts within the short- and medium-term”.[165] We will explore in detail in chapters 4 and 6 how this reorientation of research activities was articulated and how it affected the character of research and the structure of the technoscientific research networks. However, the indirect exclusion of long-term research is an important difference from the programmes of the previous period. Research that could be transferred to market more quickly was promoted and the criterion for selecting projects became the proximity – or even usefulness – to market. For PV this meant that certain cost targets had to be met in order to achieve the goals set out in the White Paper:

> “**Cost efficient photovoltaic.** For **photovoltaic systems suitable for mass production system** cost targets are 7 €/Wp and 3 €/Wp for the short and

---

[164] European Commission, *Energy, environment and sustainable development: sub-programme Energy Information package*, March 1999 edition, p. 4-Part 2.

[165] European Commission, *Energy, environment and sustainable development: sub-programme Energy Information package*, March 1999 edition, Appendix 6, p. 15.

> medium term, respectively. For the long term the aim is a system cost <1 €/Wp and helping reach the White Paper target of 3GWp capacity in 2010."[166] (emphasis in the original text)

The cost and production targets as well as the suitability of the developments for mass production precisely defined and corresponded to different timeframes. Moreover, we can see how these targets were aligned with the achievement of the goals ser out in the 1997 White Paper for RES. Essentially, cost-specific research priorities were set based on timeframes to respond to EU energy policy goals. The energy policy goals were incorporated into the R&D programmes and were the main guide for what research had to achieve. This is one point of the directionality of energy to research policy, which was then also translated into specific cost targets to be pursued by the research programmes.

Similar aims and objectives for energy, including RES, were set in the next two FPs. In particular, a work programme of the sixth Framework Programme (FP6) states:

> "In the **short to medium term, the goal is to pave the way for the introduction of innovative and cost competitive renewable and energy efficiency technologies into the market as quickly as possible** through demonstration and other research actions aiming at the market, **thus supporting the future development and implementation of the EU Directives** on electricity from renewable energy sources and on the energy performance of buildings, as well as the proposed Directives on cogeneration (CHP) and the establishment of regulatory and fiscal measures for the promotion of liquid biofuels."[167] (emphasis added)

The rapid implementation of research and demonstration activities into the market was reinstated as a priority objective of the research funding programmes.[168] In conjunction with the supporting role this objective plays in the implementation of EU Directives (i.e. energy policy), the objectives and/or targets of the EU Directives (energy policy) for RES were

---

[166] European Commission, *Energy, environment and sustainable development: sub-programme Energy Information package*, March 1999 edition, p. 33.

[167] European Commission, *Work Programme: 6.1 Sustainable energy systems*, 2002, p. 2.

[168] The proximity and similarity of the activities undertaken by the two discrete programmes (i.e. R&D and Demonstration) is attributed to the attempts by the European Commission to 'merge' the programmes. We have analysed this point, in length, in a previous section.

included in each FP, further deepening the directionality of energy policy to research policy. Research projects had to demonstrate the economic feasibility of their activities, either by producing near-market products or by focusing on solving production issues. FP6 and the Seventh Framework Programme (FP7) further defined the role of research by explaining what was meant by short-, medium- and long-term research and by setting out the main objectives for each timeframe. FP6 defined medium- and long-term research and set out the objectives that research projects should support:

> "The medium to long term research objective is to develop new and renewable energy sources, and new carriers such as hydrogen which are both affordable and clean and which can be well integrated into a future sustainable energy supply both for stationary and transport applications. The **future large-scale development of these technologies will depend on significant improvements in their cost and other aspects of competitiveness against conventional energy sources**. The overall socio-economic and institutional context in which they are deployed will be covered in a synergetic approach, which takes account of energy and other related policies."[169] (emphasis added)

With a clearer definition of the role of short- and medium-term research, cost-driven research activities and their 'proximity' to the market are strengthened. It is clear that the role of research was reoriented and redefined in the second period. The SRAs legitimized the already changing role and character of research by setting clearer timeframes and linking them to cost-specific targets for the technologies. Even though medium- and long-term research was included in FP6, the main selection criterion was cost-dependent. This meant that projects had to prove their future potential in order to be funded, on the basis of economic criteria. The narrowing of the gap between research and the market was concretized and legitimized. The EU's efforts to narrow the gap between research and the market pertains the entire second period. They are still guided by energy aims and objectives set by energy policy, targeting their industrialization potential, but this rationale for research and the way a project is selected (i.e. the criteria) has changed.

---

[169] European Commission, *Work Programme: 6.1 Sustainable energy systems*, 2002, p. 3.

As we analyse in chapter 3, the Treaty of Lisbon (2007) gave the EU new institutional powers to centrally regulate energy policy (and set binding targets). These new EU instructional pertain the seventh Framework Programme (FP7). More specifically:

> "**The 7th Framework Programme** (FP7) of the European Community for research, technological development and demonstration activities **is an instrument for the realisation of a political vision, as expressed in the Lisbon Strategy**, of making the EU economy the most dynamic, competitive, knowledge- based economy in the world by 2010. It is conceived as a continuation of the previous 6th framework programme but with an even more ambitious and innovative character."[170] (emphasis added)

The EU's use of the FPs as instruments is not a novelty introduced by the FP7. Nor is the control of funding and the direction of the funding flows *a*political. However, the explicit inclusion of the Lisbon agenda (or strategy in the above quote) as a 'new' EU guiding political instrument deserves attention.[171]

> "The focus of the research and demonstration actions in FP7 will be on accelerating the development of cost-effective technologies for a more sustainable energy economy for Europe (and the rest of the world) and ensuring that European industry can compete successfully on the global stage."[172]

Alongside the above research 'focus', both FP6 and FP7 sought to incorporate and implement a number of other 'measures' (e.g. the establishment of the ERA, Lisbon agenda goals for KBE) that could accelerate and/or support the achievement of the above priorities.

Another important institutional change occured in 2007 with the establishment of the European Research Council (ERC).[173] Intended to fill the staggering gap in basic research funding and coupled with 'excellence', the ERC provided a complementary means (alongside the FPs) and an understanding of how the goals of the Lisbon agenda could be achieved. By targeting scientific personnel, scientific training etc. it provided a means to move away from

---

[170] European Commission, *Energy Research in the 7th framework programme*, 2007. p. 2.

[171] The Lisbon Strategy was mentioned in the FP6.

[172] European Commission, *Energy Research in the 7th framework programme*, 2007. p. 2.

[173] For a thorough and detailed analysis about ERC and its history, from a first-person account, see: Thomas König, *The European Research Council*, Polity Press (Cambridge-UK, Malden-USA: 2017).

technological development and infrastructures as the main pillars for a competitive economy and to achieve the goals of the Lisbon agenda.[174]

Horizon 2020 is a continuation of the second period in terms of the relationship between research and energy policies. The goals for RES were set by the Energy Union, while the SET-Plan ensured alignment between research activities and energy goals.[175] In addition, ERA and its strengthening under Horizon 2020 continued.

However, Horizon 2020 differs from all other FPs in terms of its institutional gravitas. In particular, Horizon 2020 is a regulation. As Horizon 2020 is a regulation, this means that it is: "'Binding in its entirety' […] 'Directly applicable in all Member States'".[176] This allowed the EU to set binding targets for research funding (3% of the GDP). Although it is not clear what the 'penalties' are for not meeting this target, this signals a change in the EU's institutional powers over member states' research spending and highlights the central organization of research policy by the EU.

While not an institutional change, it is worth noting that Horizon 2020 differs from previous FPs in at least one other respect. Horizon 2020 has incorporated the concept of 'responsible research and innovation' (RRI). The RRI concept was developed in the early 2010s and was intended to emphasize the need to align research and innovation (R&I) with societal needs while calling for more 'accountable' R&I to address and solve societal challenges (such as climate change).[177] In this framework, society and/or citizen engagement play a central role. Within this growing branch of RRI literature, the concept of 'Responsibility by Design' (RbD) was proposed. The authors proposed this concept "as a way to embed RRI into the governance and outcomes of research and innovation activities and to illuminate a dimension that the RRI community needs to address in more detail."[178] As the authors note, the RbD concept is not

---

[174] The idea on funding basic research had been contemplated and debated for many decades. Regarding the debates and the pre-historical precursors of the ERC see: Thomas König, *The European Research Council*, Polity Press (Cambridge-UK, Malden-USA: 2017).

[175] Regarding the first point (Energy Union) see analysis in Chapter 7.

[176] Neil Nugent, "European Union Law and the Courts", *in The Government and Politics of the European Union*, Neil Nugent (ed.), (6th Edition), Palgrave MacMillian (New York: 2006), p. 285.

[177] European Commission, Directorate-General for Research and Innovation, *Towards a Responsible Research and Innovation in the Innovation and Communication Technologies and Security Technology Fields*, Rene von Schomberg (eds.), Publications Office of the European Union (Luxembourg: 2011).; Rene von Schomberg, "A vision of responsible innovation", *in* Responsible Innovation, Richard Owen, John Bessant, Maggy Heintz (eds.), John Wiley (London: 2013), p. 51-74.; Stig-Erik Jakobsen, Arnt Fløysand, John Overton, "Expanding the field of Responsible Research and Innovation (RRI) – from responsible research to responsible innovation", *European Planning Studies*, 2019, p. 2329-2343.

[178] Bernd Carsten Stahl, Simisola Akintoye, Lise Bitsch, Berit Bringedal, Damian Eke, Michele Farisco, Karin Grasenick, Manuel Guerrero, William Knight, Tonii Leach, Sven Nyholm, George Ogoh, Achim Rosemann, Arleen Salles, Julia Trattnig & Inga Ulnicane, "From Responsible Research and Innovation to responsibility by design", *Journal of Responsible Innovation*, 2021, p. 176.

new. Its origins go back to an early evaluation of RRI activities in 2012, which stated that "Research should be "responsible by design" and thus account for societal risks, benefits and impacts right at the beginning'".[179]

2.3 Concluding remarks

Scientific cooperation comprises the backbone of EU research policy. Trans-European scientific cooperation – or the joining of 'powers' – in key sectors/areas formed the basis of consensus for several European countries soon after the end of the World War II.

In the 1960s, research policy was contextualized as a means to achieve economic development and underwent numerous changes. In the EU context, research was also seen as a possible means of overcoming the technological gap with the USA and Japan. As we have seen, although the European Commission did not 'technically' have the institutional powers to pursue research policy that went beyond the sectors covered by the founding Treaty sectors, it did launch an energy R&D programme that covered more energy sources (including RES). The Treaty of Maastricht legitimized the Commission's powers and at the same time led to the expansion of the European Commission's research policy activities. From the beginning, the Framework Programmes were instrumentalized for 'serving' industrial policy, which is evident from their main aim to strengthen the scientific and industrial base of the European industry on order to aid its international competitiveness. Furthermore, the Framework Programmes were intended to contribute to the creation and completion of the Single European Market. Thus, they are an inseparable part of the history of European economic integration.

The importance or 'place' of research policy was strengthened with the Lisbon agenda. In the second period (1999-onwards), research was envisioned as **the** focal point of innovation and knowledge-production, and R&D programmes presented research as a means to achieve economic goals, which were systematically highlighted in the Lisbon agenda. The launch of the ERA played a crucial role in EU research policy as it represented an effort to align national research activities, priorities, and programmes with those of the EU. In essence, the ERA was the equivalent of the SEM, but for research. During this period, research sought to narrow the gap with the market and the establishment of ETPs played a key role in directing research funding and setting research agendas. As industry-led fora, the ETPs enabled the promotion of corporate interests in steering the research agendas, which became the recipient of EU R&D funding.

---

[179] Technopolis & Fraunhofer, 2012, p. 29, as referenced in Stahl et al., 2021, p. 186.

The staggering funding gap in ‘basic research’ was filled – at least in part – with the establishment of the ERC, which also marked a departure from the understanding that development can be (only) technological. Essentially, the ERC provided a complementary way of understanding and achieving ‘development’.

Horizon 2020 is a regulation and represents a critical moment in the history of EU research policy. It is possible that the power of the EU to determine each member state’s share of research funding while controlling – at least in part – its direction can be seen as the beginning of a new ‘era’ for research policy.

RES represented provided a possible alternative to reduce the member states’ dependence on energy imports, the urgency of which emerged with the 1973 oil crisis. The Commission understood them as locally sourced energies and linked them to their respective uses and applications based on climatic conditions. These climatic conditions also played a detrimental role in the allocation of research funds, which consistently gave priority to solar photovoltaics, which was envisioned to become the main energy solution (among all other RES) for the Northern-Western Community countries. Although research on RES (technologies) was one of the Commission’s responses to the energy crisis, until the Treaty of Lisbon the Commission had no institutional or legislative powers to (formally) design energy policy. Let us now turn to the examination of the main events in the history of EU energy policy.

References

Adamson Mathew, Palló Gábor, Hungary-Short Country Report, HoNESt Project, 2017.

Andrée Dan, *Priority-setting in the European Research Framework Programmes*, VINNOVA Analysis VA – Swedish Governmental Agency for Innovation Systems (July 2009).

Banchoff Thomas, "The Politics of the European Research Area, ACES Working Paper 2002.3, August 2002, [working paper], Available online: http://aei.pitt.edu/8964/, p. 1-25.

Banchoff Thomas, "Institutions, Inertia and European Union Research Policy, *Journal of Common Market Studies*, 2002, p. 1-21.

Banchoff Thomas, "Politic Dynamics of the ERA", *in Changing Governance on Research and Technology Policy: The European Research Area*, Jacob Edler, Stefan Kuhlmann, Maria Behrens (eds.), Edward Elgar (Cheltenham, U.K. and Northampton, Mass: 2003).

Boyle Miriam J. and Robinson M. E., "French Nuclear Energy Policy", *Geography*, 1981, p. 300-303.

Breschi Stefano and Cusmano Lucia, "Unveiling the texture of a European Research Area: emergence of oligarchic networks under EU Framework Programmes", *International Journal Technology Management*, 2004, p. 747-772.

Breyer Ch., Birkner C, Kersten F., Gerlach A., Goldschmidt J. C., Stryi-Hipp G., Montoro Fraile D., Riede M., "Research and Development Investments in PV: a limiting factor for a fast PV diffusion?", 25th European Photovoltaic Solar Energy Conference / 5th World Conference on Photovoltaic Energy Conversion, Proceedings of the International Conference held in Valencia, Spain, 6-10 September 2010, G. F. de Santi, H. Ossenbrink and P. Helm (eds.), WIP Renewable Energies (Germany: 2010), p. 5385-5408.

Busquin Philippe, "Address at the Friedrich Ebert Foundation, Berlin, 18 January 2001", as cited in Thomas Banchoff, "Institutions, Inertia and European Union Research Policy", *Journal of Common Market Studies*, 2002, p. 1-21.

Bussiere Eric and Laer Arthe Van, "Research and technology, or the 'six national guardians' for 'the Commission, the eternal minor', *in* The European Commission 1958-72: History and Memories of an Institution, Michel Dumoulin (eds.), Publications Office of the European Union (Luxembourg: 2014), p. 491-506.

Caracostas Paraskevas and Muldur Ugur, *Koinonia: o anoichtos orizontas erevnas kai kainotomias* [Society: the open horizon of research and innovation], Ellinika Grammata (Athens: 2007).

Commission of the European Communities, *Proposal from the Commission to the Council concerning a Second Year Energy Research and Development Programme*, COM (78) 388 final – Volume I, Brussels, 4 August 1978.

Commission of the European Communities - Directorate-General for Research, Science and Education, *Energy Research and Development Programme: Second Status Report (1975-1978)*, Vol. I, Martinus Nijhof Publishers (The Hague, Boston, London: 1979).

Commission of the European Communities - Directorate-General for Research, Science and Education, *Energy Research and Development Programme: Second Status Report (1975-1978)*, Vol. II, Martinus Nijhof Publishers (The Hague, Boston, London: 1979).

Commission of the European Communities, *Energy Research and Development Programme: Second Status Report*, Vol. II, Martinus Nijhof Publishers (The Hague, Boston, London: 1979).

Commission of the European Communities, *Single European Act*, Office for Official Publications of the European Communities (Luxembourg: 1986).

Commission of the European Communities, *Communication from the Commission to the Council, the European Parliament, the Economic and Social Committee and the Committee of the Regions: Towards a European research area*, COM (2000) 6 final, Brussels, 18 January 2000.

Communication from the Commission regarding the energy research and development programme adopted by the Council of the European Communities on 22 August 1975, Official Journal of the European Communities, 21.1.1976.

Council Decision of 14 March 1989 on a specific research and technological development programme in the field of energy – non-nuclear energies and rational use of energy – 1989 to 1992 (Joule), Official Journal of the European Communities, 11.4.1989.

Council Resolution of 17 December 1974 concerning Community energy policy objectives for 1985, Official Journal of the European Communities, 9.7.1975.

Council Resolution of 16 September 1986 concerning new energy policy objectives for 1995 and convergence of the policies of the Member States (86/C 240/01), Official Journal of the European Communities, 25.09.1986.

Decision No 182/1999/EC of the European Parliament and of the Council of 22 December 1998 concerning the fifth framework programme of the European Community for research, technological development and demonstration activities (1998 to 2002), Official Journal of the European Communities, 1.2.1999.

Decision No 1513/2002/EC of the European Parliament and of the Council of 27 June 2002 concerning the sixth framework programme of the European Community for research, technological development and demonstration activities, contributing to the creation of the European Research Area and to innovation (2002 to 2006), Official Journal of the European Communities: Luxembourg, 29.08.2002.

European Commission, *Energy, environment and sustainable development: sub-programme Energy Information package*, March 1999 edition.

European Commission, *Work Programme: 6.1 Sustainable energy systems*, 2002.

European Commission, *Technology Platforms: from Definition to Implementation of a Common Research Agenda*, Office for Official Publications of the European Communities: Luxembourg, 2004.

European Commission, *Energy Research in the 7th framework programme*, 2007.

European Commission - Directorate-General for Research and Innovation, *Towards a Responsible Research and Innovation in the Innovation and Communication Technologies and Security Technology Fields*, Rene von Schomberg, (eds.), Publications Office of the European Union (Luxembourg: 2011).

European Commission, Europa, *Single Market and Standards*, Available online: https://ec.europa.eu/growth/single-market_en, (accessed 19 April 2022).

Farinelli Ugo, Gelus M., Muus L. T., Rorsch A., Stocker H. J., *The evaluation of the Communities' energy conservation and solar energy R&D sub-programmes*, Office for Official Publications of the European Communities (Luxembourg: 1980).

Guido Brunner, "Opening Address", *in* Second EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Berlin (West), 23-26 April 1979, R. Van Overstraeten and W. Palz (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1979), p. 4-10.

Guzzetti Luca, *A brief history of European Union Research Policy*, Office for Official Publications of the European Communities (Luxembourg: 1995).

Jakobsen Stig-Erik, Fløysand Arnt, Overton John, "Expanding the field of Responsible Research and Innovation (RRI) – from responsible research to responsible innovation", *European Planning Studies*, 2019, p. 2329-2343.

König Thomas, *The European Research Council*, Polity Press (Cambridge-UK, Malden-USA: 2017).

Laird Frank and Stefes Christoph, "The diverging paths of German and United States policies for renewable energy: Sources of difference", *Energy Policy*, 2009, p. 2619-2929.

Mertens R. and Palmers G., "Roger van Overstraeten – Professor, Manager and Entrepreneur: his work in photovoltaics", *in* Sixteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Glasgow, UK, 1-5 May 2000, H. Scheer, B. McNelis, W. Palz, H.A. Ossenbrink and P. Helm (eds.), Vol. I, James and James (London, UK: 2000), p. lvi-lvii.

Mitzner Veera, "European research policy", *in* The European Commission 1986-2000: History and Memories of an Institution, Éric Bussière, Vincent Dujardin, Michel Dumoulin, Piers Ludlow, Jan Willem Brouwer and Pierre Tilly (eds.), Publications Office of the European Union (Luxembourg: 2014), p. 321-334.

Mitzner Veera, *European Union Research Policy: Contested Origins*, Palgrave MacMillan (2020).

Nugent Neil, "European Union Law and the Courts", *in The Government and Politics of the European Union*, Neil Nugent (ed.), (6th Edition), Palgrave MacMillian (New York: 2006), p. 281-310.

Palz W., Overstraeten R. van, Palmers G., "PV-programmes of the European Commission", *in* Twelfth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Amsterdam, The Netherlands, 11-15 April 1994, R. Hill, W. Palz, P. Helm (eds.), Vol. II, H. S. Stephens & Associates (UK: 1994), p. 1441-1444.

Photovoltaic Technology Platform, *A Strategic Research Agenda for Photovoltaic Solar Energy Technology*, Office for Official Publications of the European Communities (Luxembourg: 2007).

Photovoltaic Technology Platform, *A Strategic Research Agenda for Photovoltaic Solar Energy Technology*, 2nd Edition, Office for Official Publications of the European Communities (Luxembourg: 2011).

Radvilaite Vilma, "EU budget 2014–2020 deal: opportunities for wind energy", *European Wind Energy Association*, 2013.

Rüdiger Mogens, "From import dependence to self-sufficiency in Denmark, 1945−2000", *Energy Policy*, 2019, p. 82-89.

Schomberg Rene von, "A vision of responsible innovation", *in* Responsible Innovation, Richard Owen, John Bessant, Maggy Heintz (eds.), John Wiley (London: 2013), p. 51-74.

Schuster G., "The Future of Photovoltaics in Europe", *in* Third EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes France, 27-31 October 1980, W. Palz (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1981), p. 4-9.

Schuster Gunter, "Opening Address from the Commission of the European Communities", in Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at

Luxembourg, September 27-30, 1977, D. Reidel Publishing Company, (Dordrecht Holland, Boston USA: 1978), p. 26-28.

Schuster G., “The Future of Photovoltaics in Europe”, *in* Third EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes France, 27-31 October 1980, W. Palz (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1981), p. 4-9.

Single European Act, Official Journal of the European Communities, 29.06.1986.

Stahl Bernd Carsten, Akintoye Simisola, Bitsch Lise, Bringedal Berit, Eke Damian, Farisco Michele, Grasenick Karin, Guerrero Manuel, Knight William, Leach Tonii, Nyholm Sven, Ogoh George, Rosemann Achim, Salles Arleen, Trattnig Julia, Ulnicane Inga, “From Responsible Research and Innovation to responsibility by design”, *Journal of Responsible Innovation*, 2021, p. 175-198.

Stsiapanau Andrei, Lithuania-Short Country Report, HoNESt Project, 2018.

Tchalakov Ivan, Hristov Ivaylo, Bulgaria-SCR, HoNESt, 2019.

The European Commission 1958-72: History and Memories of an Institution, Michel Dumoulin (eds.), Publications Office of the European Union (Luxembourg: 2014).

The European Commission 1973-86: History and Memories of an Institution, Éric Bussière, Vincent Dujardin, Michel Dumoulin, Piers Ludlow, Jan Willem Brouwer and Pierre Tilly (eds.), Publications Office of the European Union (Luxembourg: 2014).

The European Commission 1986-2000: History and Memories of an Institution, Vincent Dujardin, Éric Bussière, Piers Ludlow, Federico Romero, Dieter Schlenker and Antonio Varsori (eds.), Publications Office of the European Union (Luxembourg: 2019).

The European Technology and Innovation Platform for Photovoltaics, etip-pv, *Our Vision*, Available online: https://etip-pv.eu/about/our-vision/, (accessed 5 October 2019).

Umbach Frank, “Global Energy Security and the Implications for the EU”, *Energy Policy*, 2010, p. 1229-1240.

Veen Geert van der, Eparvier Patrick, Ploeg Matthias, Trucco Paola, *Evaluation of the impact of projects funded under the 6th and 7th EU Framework Programmes for RD&D in the area of non-nuclear energy*, Final Report (Version 4, 19 June 2013), Technopolis Group (2014).

Wolsink Maarten, “Dutch wind power policy: Stagnating implementation of renewables”, *Energy Policy*, 1996, p. 1079-1088.

Chapter 3. An EU energy policy history

> "'Energy is the daily bread of our nations' in the words of Fernand Spaak, Director-General of the Directorate-General for Energy from 1967 to 1975. A society without access to energy cannot function, survive or prosper because energy forms the basis of all industrial activity. Moreover, the development of the European economy is possible only thanks to a plentiful supply of low-cost energy."[180]

Energy has always been recognized as a basic requirement for the functioning of industry and society. Energy has become synonymous with contemporary or even modern societies associated with economic and societal welfare. Behind the assurance of adequate energy supply and energy security, which are the guiding principles of most energy policies, is the underlying precondition of securing energy resources. In other words, the energy raw materials or resources.

The foundations of today's EU rest on (at least) two important pillars. First, as we analysed in chapter 2, the European Communities were built 'around' a consensus for cooperation in three key sectors (coal, nuclear energy and agriculture). Scientific cooperation provided fertile ground for extending and/or overcoming the national borders of the member states. Scientific research and economic growth were already linked by the OECD in the 1960s. Although the European Commission was officially limited to these above-mentioned sectors, numerous attempts were made to broaden the spectrum of research policy even before the introduction of the Framework Programmes. In our case, most notably, it was the Energy R&D programmes that responded to the oil crises of the 1970s (see below for more on this point). Second, the importance of energy and energy resources, which we examine in this chapter.

3.1 Introduction

In this chapter we briefly analyse the history of EU energy policy, covering the period from 1973 to 2022. This aims of this chapter is to provide the reader(s) with a comprehensive understanding of the main events and/or landmarks of EU energy policy.[181] To this end, we

---

[180] Julie Cailleau, "Energy: from synergies to merger", *in* The European Commission 1958-72: History and memories of an institution, Publications Office of the European Union (Luxembourg: 2014), p. 471.

[181] We acknowledge that the topic has been extensively analysed and we do not intend on duplicating these efforts. Rather, the analysis of this Chapter is intended to provide the reader with a comprehensive understanding of the

examine the main events and how they have (re-)directed 'interest' from one energy source to another, focusing on the current and ongoing transition to RES.

In section 3.1.1 we analyse the main events and crises in the history of EU energy policy (1973-2022). Next (section 3.1.2), we provide a comprehensive analysis of the different types of electricity generation and consumption, the type of users they construct, and the scale of installations each type requires. Due attention is given to how the technologies of RES enable the reconfiguration of the energy system, particularly the electricity grid. This is complemented by a brief but comprehensive analysis of the beginnings of EU research into PV and 'alternative' electricity generation (and consumption), which the research networks promoted on the basis of the technologies they actively developed. In section 3.1.3 we trace the inaugural steps towards an EU-wide energy policy and the role played by RES. For this purpose, we analyse key documents (e.g. the White Paper for RES, RES Directives etc.) and the main proponents of RES. An important aspect of this analysis has been the European Commission's efforts to establish its place in energy policy-making. In section 3.1.4 we focus on the EU's changing powers in energy policy (through the Treaty of Lisbon), we analyse the EU's current long-term energy strategy and the ongoing energy crisis sparked by the war between Russia and Ukraine, and the EU's responses emphasizing the need to transition to RES (faster). We summarize the main findings and arguments in section 3.2.

3.1.1 An EU energy policy history: landmarks and energy crises

The founding of what is now the EU was largely based on a consensus among the member states that energy resources are of strategic importance, demonstrated by the establishment of the ECSC and Euratom (see chapter 2). Energy has thus always been at the heart of the EU and its predecessor organizations. However, energy policy and security of energy supply have always been a nation-state issue. As we will see in the following sections, the first (somewhat) successful efforts towards a common EU energy policy took place in the 1970s, when the European Commission developed an energy strategy to respond to the oil crises. Despite these efforts, member states pursued different routes to respond to the oil crises and tried to preserve their sovereignty in this area. In the following sections we trace and examine the main events in the history of EU energy policy from the 1970s until today.

---

main events and landmarks in EU energy policy. Our analysis focuses on electricity production by RES, especially PV. Thus, even though we provide an overview of the EU energy policy history, our focus is on electricity production, which comprises a part of European energy policy (e.g. the focus is not on heating, cooling etc.).

3.1.1.1 The first and second oil crises: the oil 'era' begins to crumble

The 1970s were – largely – marked by the two oil crises. Although both crises concerned (shortages of) oil, the triggers were different. The first oil crisis (1973/4) is be best described by rising crude oil prices and the subsequent oil embargo from OPEC on various countries.[182] The embargo was a political move by OAPEC (Organization of Arab Petroleum Exporting Countries) against Western counties to 'convince' them to take a pro-Arab position in the Yom Kippur War.[183] In contrast, the second oil crisis (1979) was triggered by a shortage of crude oil supply and a corresponding increase in oil prices as a result of the Iranian revolution.

In analysing the similarities and differences between the oil crises of the 1970s and the Russia-Ukraine gas incidents of the 2000s, Francis McGowan has noted the following:

> "It is true that, in both periods, the European Commission invoked both the immediate and longer term dimensions of the crises to reinforce the case for a common energy policy, highlighting energy security concerns as either the principal (1973/4) or one of the principal (2006/9) justifications for such a policy."[184]

As we analyse in a later section, until the Treaty of Lisbon, the EU had – officially – no legislative or institutional powers in energy policy-making.[185] However, similar to the case of research policy (chapter 2), there is a fine line between the official powers laid down in the Treaties, which define how the EU and each of its institutions operate and the powers that the EU has and what happens 'unofficially'.

The first objectives of the energy policy strategy of the EC were set to address the challenges arising from the 1973 oil crisis. In particular, the objectives included measures to reduce oil dependence and ensure energy security and supply.[186] These objectives, which emerged in response to the 1973 oil crisis and were further strengthened during the 1979 oil crisis, aimed

---

[182] For more information about the two oil crises in relation to the European Communities member states see: […]

[183] Frank Bösch and Rüdiger Graf, "Reacting to Anticipations: Energy Crises and Energy Policy in the 1970s. An Introduction*", Historical Social Research*, 2014, p. 7-21.

[184] Francis McGowan, "Putting Energy Insecurity into Historical Context: European Responses to the Energy Crises of the 1970s and 2000s", *Geopolitics*, 2011, p. 492. Francis McGowan has written extensively about EU policy-making and EU energy policy.

[185] Tonini has written about European energy policy and the EU's earlier attempts in establishing a common energy policy, alongside the EU's institutional 'transformation'. See: Alberto Tonini, "The EEC Commission and European Energy Policy: A Historical Appraisal", *in* European Energy and Climate Security, Rosella Bardazzi, Maria Grazia Pazienza, Albterto Tonini (eds.), Springer (Switzerland: 2016), p. 13-35.

[186] C. 153, Council Resolution of 17 December 1974 concerning Community energy policy objectives for 1985, Official Journal of the European Communities, 9.7.1975.

to reduce the uncertainty, unease, and urgency of securing Europe's energy supply. It was against this background of uncertainty that the first Energy R&D Programme was launched in 1975 to explore potentially viable energy options, such as RES. However, the goal of the EC's energy policy strategy to reduce imports of oil products in order to ensure security was to be achieved primarily through nuclear energy and natural gas, not through RES.[187,188] The pathways to substitute oil varied and depended on cultural, geographical and political characteristics, as well as on the availability of energy resources. Germany, for example opted for coal and later for nuclear energy.[189] France launched a big nuclear energy programme in 1974, while Denmark gave priority to coal in combination with natural gas.[190,191] Accordingly, national R&D programmes for RES had different priorities. Germany, France and Italy allocated funds both to PV and wind energy, whereas Denmark and the Netherlands prioritised wind energy.[192] From 1986 and throughout the 1990s, apart from the Chernobyl disaster that briefly boosted RES R&D efforts, public funding for RES declined worldwide.[193] Overall, the 1980s and 1990s can be characterized by low crude oil prices and a declining political support and/or attention to energy security issues.

3.1.1.2 Establishing a common European energy market: liberalization of the electricity market

Until 1993, the EU had no (concrete) common energy policy and lacked the institutional power to establish the necessary institutional, legislative and policy tools to implement an EU-wide common energy policy. Moreover, member states had conflicting interests that led them to

---

[187] C. 153, Council Resolution of 17 December 1974 concerning Community energy policy objectives for 1985, Official Journal of the European Communities, 9.7.1975.

[188] C. 241, Council Resolution of 16 September 1986 concerning new energy policy objectives for 1995 and convergence of the policies of the Member States (86/C 240/01), Official Journal of the European Communities, 25.09.1986.

[189] Frank Laird, Christoph Stefes, "The diverging paths of German and United States policies for renewable energy: Sources of difference", *Energy Policy*, 2009, p. 2619-2629.

[190] Miriam J. Boyle, M. E. Robinson, "French Nuclear Energy Policy", *Geography*, 1981, p. 300-303.

[191] Mogens Rüdiger, "From import dependence to self-sufficiency in Denmark, 1945−2000", *Energy Policy*, 2019, p. 82-89.

[192] Maarten Wolsink, "Dutch wind power policy: Stagnating implementation of renewables", *Energy Policy*, 1996, p. 1079-1088.

[193] Breyer Ch., Birkner C, Kersten F., Gerlach A., Goldschmidt J. C., Stryi-Hipp G., Montoro Fraile D., Riede M., "Research and Development Investments in PV: a limiting factor for a fast PV diffusion?", 25th European Photovoltaic Solar Energy Conference / 5th World Conference on Photovoltaic Energy Conversion, Proceedings of the International Conference held in Valencia, Spain, 6-10 September 2010, G. F. de Santi, H. Ossenbrink and P. Helm (eds.), WIP Renewable Energies (Germany: 2010), p. 5385-5408.

having opposing stances on energy policy issues and the means to address them.[194] What existed, therefore, were national energy policies – either fragmented or coherent – and an EU energy policy strategy.[195,196] The absence of a common energy policy was acknowledged by the European Commission. Only in a few areas, such as Energy R&D programmes, was there joint action (i.e. consensus among member states to conduct joint research at EU level).[197,198]

With the creation of the European Single Market (SEM) in 1992, a common energy policy slowly took shape. In addition, the European Commission was given more powers through SEM and contributed to the harmonization of energy policy in the member states.[199,200] The measures relevant to energy policy concerned the establishment of 'common rules for the internal market in electricity'.

A series of Directives aimed at creating and completing the liberalization of the (internal) electricity market (i.e. deregulation of the electricity market). The European Commission's first step towards the internal market in electricity was Directive 96/92/EC.[201] This Directed aimed at (and later achieved) important changes in the electricity sector, including the end of monopolistic (national) electricity companies, which were supposed to support the liberalization of the electricity market. Directive 96/92/EC was followed by Directive

---

[194] Alberto Tonini, "The EEC Commission and European Energy Policy: A Historical Appraisal", *in European Energy and Climate Security: Public Policies, Energy Sources, and Eastern Partners,* Rosella Bardazzi, Maria Grazia Pazienza, Alberto Tonini (eds.), Springer (New York, London: 2016), p. 13-35.

[195] Alberto Tonini, "The EEC Commission and European Energy Policy: A Historical Appraisal", *in European Energy and Climate Security: Public Policies, Energy Sources, and Eastern Partners,* Rosella Bardazzi, Maria Grazia Pazienza, Alberto Tonini (eds.), Springer (New York, London: 2016), p. 13-35.

[196] Both strategy and policy set targets to be achieved through objectives. The two terms are used to indicate the changes in the acquired institutional powers of the EC. Thus, we employ the term strategy to denote the lack of 'tools' required and/or presupposed to reinforce the necessary actions taken towards achieving the targets at an EC level (i.e. the EC did not have the institutional tools to implement the objectives in the member-states). In contrast, policy indicates that the required 'tools' for implementing the actions necessary exist (the EC acquires more powers that enable the implementation of the objectives in the member states).

[197] Nugent Neil, "Policies", *in The Government and Policies of the European Union*, Neil Nugent and William E. Paterson (eds.), Palgrave Macmillan (Basingstoke: 2006), p. 351-391.

[198] European Commission – Directorate General for Energy, *Energy in Europe: Energy policies and trends in the European Community*, Office for Official Publications for the European Communities (Luxembourg: 1989).

[199] Alberto Tonini, "The EEC Commission and European Energy Policy: A Historical Appraisal", *in European Energy and Climate Security: Public Policies, Energy Sources, and Eastern Partners,* Rosella Bardazzi, Maria Grazia Pazienza, Alberto Tonini (eds.), Springer (New York, London: 2016), p. 13-35.

[200] SEM was to create a unified European market by deregulating. It provided the EC with more powers and, along with the Single European Act, 'allowed' regulating energy policy.

[201] L. 27, Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity, Official Journal of the European Communities, 30.1.1997.

2003/54/EC and then Directive 2009/72/EC. [202,203] Each Directive sought to promote the completion of the internal market while establishing common rules for all the member states (i.e. harmonization).[204] An important change occurred with Directive 2009/72/EC, which mentioned smart grids and decentralized generation for the first time, while setting provisions for the roll-out of smart meters by 2020 (in line with the 20-20-20 targets, see analysis in section 3.1.4).[205] Following this Directive, the European Commission published a report tracing the progress made by the member states in the roll-out of smart meters.[206] There is an interesting interplay between the powers of EU-member states through this measure. For example, in France:

> "In 2016, the mandatory introduction of smart meters started and should be completed by 2021. This measure provides an indirect support measure for small self-consumption systems, because it removes the grid connection costs."[207]

With smart meters and smart metering, the Commission was essentially trying to encourage small-scale installations, but the sovereignty of the member states in setting the roll-out criteria was maintained.[208] This 'push' by the Commission was through market provisions and clearly favoured small-scale installations and user empowerment. In line with the EU's long-term energy strategy, further provisions for smart metering systems and smart grid roll-out were made adopted through Directive 2019/944.[209]

---

[202] L. 176, Directive 2003/54/EC of the European Parliament and of the Council of 26 June 2003 concerning common rules for the internal market in electricity and repealing Directive 96/92/EC, Official Journal of the European Union, 15.7.2003.

[203] L 211, Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC, Official Journal of the European Union, 14.08.2009.

[204] Typically, in these Directives specific provisions were made for their implementation by each member states, the timeframes varied.

[205] See L 211, Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC, Official Journal of the European Union, 14.08.2009, p. 58 (paragraph 27) and p. 91, respectively.

[206] European Commission, *Report from the Commission – Benchmarking smart metering deployment in the EU-27*, Final Report, COM(2014) 356 final, Brussels, 17.6.2014.

[207] Jäger-Waldau A., *PV Status Report 2018*, Publications Office of the European Union (Luxembourg: 2018), p. 15.

[208] European Commission – JRC, [last updated on 19 July 2022], *Europa*, Smart Metering deployment in the European Union, Available online: https://ses.jrc.ec.europa.eu/smart-metering-deployment-european-union, (accessed 20 July 2022).

[209] L. 158, Directive (EU) 2019/944 of the European Parliament and of the Council of 7 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EC (recast), Official Journal of the European Union, 14.06.2019.

3.1.1.3 The current energy crisis: shortages along the gas pipeline

As we analysed in an earlier section, the oil crises of the 1970s acted as a pressure to reconfigure and diversify the energy mix – in our case in Europe. Part of this diversification, which was also supported by the European Commissions' energy policy strategy, was to be achieved (mainly) through natural gas. Natural gas has been – and continues to be – at the centre of disputes and of an energy crisis (currently). For example, the disputes between Russia and Ukraine in 2006 and 2009 led to an increase in natural gas prices, which also affected EU member states.[210]

The current war between Russia and Ukraine has also led to an energy crisis affecting many EU member-states.[211] Once again, natural gas is at the centre of issues, which has led to an increase in energy prices affecting many EU households and businesses.[212] In the midst of the COVID-19 pandemic that has impacted the global economy (perhaps to an extent that is too early to fully grasp), the energy crisis continues to put pressure on EU economies.[213] As the EU is increasingly dependent on natural gas imports (see Figure 3.1 below), particularly from Russia, the current energy crisis has triggered the need to revisit the EU's long-term energy strategy. Within this context, RES and especially PV are envisioned to play an important role in the EU's energy future and drive the faster implementation of the transition to RES in the

---

[210] Regarding the 2006 and 2009 gas disputes see: Jonathan Stern, The Russian-Ukrainian gas crisis of January 2006, *Oxford Institute for Energy Studies*, 16 January 2006.; Jonathan Stern, "Natural Gas Security Problems in Europe: the Russian-Ukrainian Crisis of 2006", *Asia-Pacific Review*, 2006, p. 32-59.; Francis McGowan, "Can the European Union's Market Liberalism Ensure Energy Security in a Time of 'Economic Nationalism'?", *Journal of Contemporary European Research*, 2008, p. 90-106.; Frank Umblach, "Global energy security and the implications for the EU", *Energy Policy*, 2010, p. 1229-1240.; Francis McGowan, "Putting Energy Insecurity into Historical Context: European Responses to the Energy Crises of the 1970s and 2000s", *Geopolitics*, 2011, p. 486-511. For a run-down of all the everts (2006-2009) see: Reuters Staff, 11 January 2009, *Reuters*, TIMELINE: Gas crises between Russia and Ukraine, Available online: https://www.reuters.com/article/us-russia-ukraine-gas-timeline-sb-idUSTRE50A1A720090111, (accessed 10 June 2022). Regarding the history and politics of energy transitions see: Roger Fouquet and Peter J. G. Pearson, Editorial "Past and Prospective energy transitions: Insights from history", *Energy Policy*, 2012, p. 1-7.; Benjamin Sovacool, "The history and politics of energy transitions: Comparing contested views and finding common ground", WIDER Working Paper No. 2016/81, 2016, ISBN 978-92-9256-124-6, The United Nations University World Institute for Development Economics Research (UNU-WIDER), Helsinki, https://doi.org/10.35188/UNU-WIDER/2016/124-6.

[211] Prasanta Kumar Dutta, Samuel Granados and Michael Ovaska, 16 February 2022, *Reuters*, Ukraine crisis: Russian gas threat in Europe, Available online: https://graphics.reuters.com/UKRAINE-CRISIS/GAS/gdpzynlxovw/, (accessed 14 July 2022).

[212] Kate Abnett, 23 June 2022, *Reuters*, A dozen EU countries affected by Russian gas cuts, EU climate chief says, Available online: https://www.reuters.com/business/energy/russian-gas-cuts-have-hit-12-countries-eu-climate-chief-says-2022-06-23/, (accessed 30 June 2022).; Suzzane Twidale, 29 June 2022, *Reuters*, EU race to fill gas storage draws record supplies from Britain, Available online: https://www.reuters.com/markets/europe/eu-race-fill-gas-storage-draws-record-supplies-britain-2022-06-29/, (accessed 30 June 2022).

[213] Byomakesh Debata, Pooja Patnaik, Abhisek Mishra, "COVID-19 pandemic! It's impact on people, economy, and environment", *Journal of Public Affairs*, 2020, p. 1-20.; Ligang Song and Yixiao Zhou, "The COVID-19 Pandemic and Its Impact on the Global Economy: What Does It Take to Turn Crisis into Opportunity?", *China and World Economy*, 2020, p. 1-25.

EU (see related analysis in section(s) 3.1.4). However, as EU member-states seek to address the energy crisis, ensure energy security and relieve pressure on their economies, the reality diverges from the vision. To meet their immediate energy needs – also in the midst of a very hot summer – many member states are going 'back to basics' (i.e. fossil fuels and (potentially) nuclear energy).[214] It remains to be seen what the future holds, both for the energy crisis and for the transition to RES.

3.1.2 Different types of generating and consuming electricity: users, scale, and the infrastructures they require

Electricity production systems worldwide produce electricity from large-scale power plants. The dominant 'electricity production' paradigm in this respect is that of centralized electricity production with large-scale power plants distributing electricity across regions and larger areas. As has already been noted:

> "Today's grids are predominantly based on **large central power stations** connected to high voltage transmission systems which, in turn, supply power to medium and low-voltage local distribution systems. […] The overall picture is still one of **power flow in one direction** from the power stations, via the transmission and distribution systems, to the final customer. […] Traditional grid design has evolved through economies of scale in **large centralised generation** and the geographical distribution of generation resources (locations near coalfields, cooling water, hydro resources, etc)."[215] (emphasis in original text)

---

[214] Igor Todorović, 11 March 2022, *Balkan Green Energy News*, Europe switching on coal plants amid energy crisis, Available online: https://balkangreenenergynews.com/europe-switching-on-coal-plants-amid-energy-crisis/, (accessed 30 June 2022).; Angeliki Koutantou and Vassilis Triandafyllou, 16 June 2022, *Reuters*, In a Greek coal mine, stocks build up ahead of peak summer demand, Available online: https://www.reuters.com/business/energy/greek-coal-mine-stocks-build-up-ahead-peak-summer-demand-2022-06-16/, (accessed 30 June 2022).; Noah Browning and Nora Buli, 22 June 2022, *Reuters*, EU signals shift to coal, accuses Russia of 'rogue moves' on gas', Available online: https://www.reuters.com/business/energy/russian-gas-flows-europe-via-nord-stream-ukraine-unchanged-2022-06-22/, (accessed 30 June 2022).; Elisabeth Schumacher, 23 June 2022, *Deutsche Welle*, Available online: https://www.dw.com/en/will-germany-return-to-nuclear-power/a-62223935, (accessed 30 June 2022).; Reuters, 27 June 2022, *Reuters*, G7 leaders debate fossil fuel investments amid energy crisis, Available online: https://www.reuters.com/world/g7-leaders-debate-fossil-fuel-investments-amid-energy-crisis-sources-2022-06-26/, (accessed 30 June 2022).

[215] European Commission – DG for Research Sustainable Energy Systems, *European Smart Grids Technology Platform: Vision and Strategy for Europe's Electricity Networks of the Future*, Office for Official Publications of the European Communities (Luxembourg: 2006), p. 15.

Fossil fuels have shaped today's grids and energy infrastructure(s). These infrastructures lead to large-scale power plants that generate electricity centrally, which is then distributed through the grid. This results in a clear separation between producer(s) and consumer(s).

In contrast to the prevailing way of production mentioned above and moving away from these large, centrally regulated and organized infrastructures, renewable energy technologies offer at least two distinct possibilities. First, solar photovoltaic technologies offer a unique system integration option. Because small-scale PV systems can be mounted to rooftops, they enable the transition to a distributed form of electricity generation and consumption.[216] They are the only energy technology that can be integrated into the urban environment (e.g. on rooftops), enabling the reconfiguration of the electricity system while constructing different users (e.g. prosumers). PV enables the active participation of users in the reconfiguration of the energy system and empowers the role of consumers in the electricity market. In other words, without PV it would have been impossible to open-up energy policy to include smart grids, net-metering etc. (see analysis in forthcoming section). Given this unique option for system integration that PV offers, it is a crucial technology for the transition to RES and its implementation. A distributed electricity generation system is governed by technologies that generate electricity "at or near where it will be used".[217] With distributed electricity there is a proximity to where the electricity is being generated and consumed. Thus, users/consumers have control over the generation of electricity and are involved in this process. At the same time, this allows users/consumers to play a more active role in the electricity market, as they can sell the remaining electricity to the grid. This type of electricity generation enables the creation of smaller grids (microgrid(s)).

We distinguish between distributed and decentralized generation based on the scale of the systems and the energy market relationships they foster. Systems on rooftops, for example, are small-scale and generally serve to supply electricity to the installation site or to transfer the electricity that is not consumed into the grid. In contrast, decentralized generation often requires large-scale installations (e.g. solar farms, wind farms) that produce larger amounts of electricity, which is then fed into the grid at the location where it is consumed. Decentralized electricity generation is made possible by RES, while distributed electricity is made possible

---

[216] Historically there is confusion regarding the differences between distributed and decentralized electricity generation. These two terms are used at times interchangeably, like they are synonymous. They are primarily used to denote the more away from centrally regulated electricity generation.

[217] El Bassam Nasir, Maegaard Preben, Schlichting Marcia Lawton, Scope of the Book, *in* Distributed Renewable Energies for Off-Grid Communities, El Bassam Nasir, Maegaard Preben, Schlichting Marcia Lawton (eds.), 1st Edition, Elsevier (Oxford, UK: 2013), p. 1.

through solar PV installations. In both cases, the electricity is generated and consumed 'locally' and can minimize the transmission losses.[218]

The infrastructures required for the transition to a decentralized and distributed electricity production – distribution – and consumption need to be redesigned and reconfigured. At the same time, with the opportunities offered by these new infrastructures, consumers are seen as active actors in this system. The possibilities offered by RES empower the consumers to take control in the generation of electricity and become an incremental part of the electricity supply and the market.

The potential of distributed electricity generation through PV was recognized early on, also by (important) actors from the PV research networks.[219] During the first period (1975-1998), research aimed at aiding the international competitiveness of the European industry by strengthening its scientific and technological basis. This was the main aim of the Framework Programmes (FP), which were and still are the EU's main instrument for funding R&D.[220] To achieve this aim, (pan-European) cooperation between research centres, universities and the industry was sought. The PV research networks of this period explored the potential applications of different PV technologies and designs leading to technological pluralism (see chapters 4-6). It was these networks that determined the material possibilities of the technological choices and set the research priorities (hence, bottom-up research policy). Given the way the 'problem' was defined, the networks had a very clear mission (i.e. to respond to the energy crisis), at the same time they played a crucial role in developing new technologies that promoted the competitiveness of the industry (electronics background). On this basis,

---

[218] United States Environmental Protection Agency, (last updated 23 June 2022), *Distributed Generation of Electricity and its Environmental Impacts*, EPA, Available online: https://www.epa.gov/energy/distributed-generation-electricity-and-its-environmental-impacts, (accessed 25 June 2022).

[219] This is based on a series of papers presented in the EC Photovoltaic Solar Energy Conferences, organized by the European Commission. These international Conferences comprised a European-based hub for the scientific and industrial community of PV, as well as policy makers, politicians etc. The first references to PV and their potential for distributed electricity production, within the context of these Conferences, were made during the first Conference in 1977. Indicatively see some of the papers that focused specifically on this topic: G. J. Vachtsevanos, A. P. Meliopoulos, B. K. Paraskevopoulos, "Distributed photovoltaic system impact upon utility load/supply management practices", *in* Fifth EC Photovoltaic Energy Conference, Proceedings of the International Conference held at Kavouri, Athens, Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 383-392.; J. Schmid, "Photovoltaic System Design", *in* Fifth EC Photovoltaic Energy Conference, Proceedings of the International Conference held at Kavouri, Athens, Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 410-416.; S. I. Firstman and G. J. Vachtsevanos, "Distributed Photovoltaic Systems: addressing the utility interface issues", *in* Fifth EC Photovoltaic Energy Conference, Proceedings of the International Conference held at Kavouri, Athens, Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 424-431.

[220] These overarching aims pertain the FPs of the first period. The specific aims for RES (including PV) were aligned to the overall FP aims.

research focused on the development of a single system component: the solar cell. In this context, the politics of the networks, which directed research towards distributed electricity production, gave a clear technological frontrunner at the end of the first period: c-Si flat plate PV.

3.1.2.1 RES reconfiguring the electricity grid: smart grids, smart meters, and net metering

RES are not only 'alternative' sources of energy. Rather, the materiality of RES technologies enables new and unique options for system integration while providing the possibility for to reconfigure the electricity grid. The options enabled by RES technologies, as analysed in the previous section, have led to the reconceptualization of the electricity grids and how they work (smart grids and smart meters), the introduction of new policy measures and billing mechanisms (e.g. FiT and net metering), the way the electricity market works and the construction of new users (prosumers). In 2005, the ETP-SmartGrids was established and published its vision and strategy in 2006. It was envisioned that:

> "*SmartGrids will use revolutionary new technologies, products and services to create a strongly user-centric approach for all customers.*"[221] (italics in original)

New services, new products and technologies are some of the new 'features' that make smart grids 'smart'. Perhaps more importantly, however, smart grids are made 'smart' by the role the that users/consumers play in the grid.[222] The reconfiguration of electricity grids described as

---

[221] European Commission – Directorate General for Research Sustainable Energy Systems, *European SmartGrids Technology Platform: Vision and Strategy for Europe's Electricity Networks of the Future*, Office for Official Publications of the European Communities (Luxembourg: 2006), p. 7.

[222] Recently there has been a growing body of literature studying the (in)justices and (in)equalities deriving from this ongoing energy transition. This body of work draws from the analytical framework of energy justice and its three tenets, namely distributional justice, recognition justice, and procedural justice (Benjamin K. Sovacool and Michael H. Dworkin, "Energy justice: Conceptual insights and practical applications", *Applied Energy*, 2015, p. 435-444.; Kristen Jenkins, Darren McCauley, Raphael Heffron, Hannes Stephan, Robert Rehner, "Energy justice: A conceptual review", *Energy Research & Social Sciences*, 2016, p. 174-182.). Originally rooted to the examination of the injustices and inequalities deriving from the insofar fossil fuel (and nuclear energy) systems the literature has recently grown to examine and problematize the inequalities deriving from the RES transition (Florian Hanke, Rachel Guyet, Marielle Feenstra, "Do renewable energy communities deliver energy justice? Exploring insights from 71 European cases", *Energy Research & Social Sciences*, 2021, 102244.; Jesse Hoffman, Megan Davies, Thomas Bauwens, Philipp Spath, Maarten A. Hajer, Bleta Arifi, Amir Bazaz, Mark Swilling, "Working to align energy transitions and social equity: An integrative framework linking institutional work, imaginaries and energy justice", *Energy Research & Social Sciences*, 2021, 102317.; Stephen Knox, Matthew

‘user-centric’, would not have been feasible without the possibilities offered by RES. Smart grids, in turn, enable the full potential of RES to be realized and the transition to distributed and decentralized electricity generation and consumption. Essentially, smart grid is the reconfiguration of the electricity grid through the generation, transmission and consumption options offered by RES. Smart grids include a range of new services and operations and construct active users.

Storage is another important component of the RES transition and smart grids. Batteries, allow electricity generated at a given time to be consumed throughout the rear, as well as at different times within a day. Another important component of smart grids, in addition to RES and storage, are the smart meters. These are electronic devices that ‘collect’ information about electricity consumption and supply when electricity is generated and/or consumed. Smart meters allow different electricity prices to be applied depending on when and/or season what time of year electricity is produced. Complementing these important options enabled by RES technologies, especially PV, net metering is an electricity policy (tool) that concerns billing. Net metering is aimed at small producers and enables them to:

> “… reduce their electric bills by offsetting their consumption with PV generation, independent of the timing of the generation relative to consumption—in effect, selling PV generation to the utility at the customer’s marginal retail electricity rate”[223]

This billing mechanism was enabled and perceived through the options enabled by RES and PV in particular.[224] So we see how RES technologies resulted in the creation of new policy and billing mechanisms. In turn, these policies and mechanisms, much like the grid reconfiguration, enable the full potential offered by RES technologies to be realized. Thus, RES not only

---

Hannon, Fraser Stewart, Rebecca Ford, “The (in)justices of smart local energy systems: A system review, integrated framework, and future research agenda”, *Energy Research & Social Sciences*, 2022, 102333.

[223] Naim R. Darghouth, Galen Barbose, Ryan Wiser, “The impact of rate design and net metering on the bill savings from distributed PV for residential customers in California”, *Energy Policy*, 2011, p. 5243.

[224] For more detailed analyses of net metering policies see: Cherrelle Eid, Javier Reneses Guillén, Pablo Frías Marín, Rudi Hakvoort, “The economic effect of electricity net-metering with solar PV: Consequences for network cost recovery, cross subsidies and policy objectives”, *Energy Policy*, 2014, p. 244-254.; Rodolfo Dufo-Lopez and Jose L. Bernal-Agustin, “A comparative assessment of net metering and billing policies. Study cases for Spain”, *Energy*, 2015, p. 684-694.; Georgios C. Christoforidis, Ioannis P. Panapakidis, Theofilos A. Papadopoulos, Grigoris K. Papagiannis, Ioannis Koumparou, Maria Hadjipanayi and George E. Georghiou, “A Model for the Assessment of Different Net-Metering Policies”, *Energies*, 2016, p. 1-24.; Stephen Comello and Stefan Reichelstein, “Cost competitiveness of residential solar PV: The impact of net metering restrictions”, *Renewable and Sustainable Energy Reviews*, 2017, p. 46-57.

reconfigure the electricity infrastructures, but also reconfigure and/or enable policies and billing mechanisms. Essentially, RES are simultaneously actively transforming the electricity grid and market and how they work – or rather, how they can work. Smart grids, smart meters and net metering would not have been possible without the unique options offered by RES technologies. At the same time, to realize the full potential of RES they 'need' all the former.

3.1.3 The role and place of RES in EU's energy policy

At the end of the first period, in 1997, the European Commission put RES on the energy policy map. The establishment of an EU energy policy for RES impacted the relationship between EU energy policy and research policy. In the following sections, we analyse key events and developments on the way to the establishment of an EU energy policy for RES, as well as key legislative material. Although some of the developments we analyse took place in the 1990s (e.g. the Kyoto Protocol, the White Paper for RES etc.), we include them in the analysis of the second period because they materialized during this period. Essentially, the impact of these developments was realised in the second period and impacted the relationship between EU energy and research policy in the second period.

3.1.3.1 The inaugural steps towards an EU-wide energy policy: the role of RES and RES entanglers

The 1992 Rio Summit was the first step in putting RES on the energy policy map. As soon as crude oil prices fell in 1986, R&D funds for RES started to decrease worldwide. Therefore, a new vision for RES was needed, a vision that would/could link RES to specific (and new) challenges that could rekindle interest to RES. This new vision for RES came from environmental policy. Both the Rio Summit of 1992 and the World Climate Conference of 1995 were important for linking RES with/to environmental challenges.

On 11 December 1997, the Kyoto Protocol was adopted, which was to enter into force in 2005.[225] It comprised an agreement between different countries on the need and their respective commitment to reduce greenhouse gas (GHG) emissions. In preparation for the Kyoto Conference on Climate Change, the European Commission published two Communications. The first concerned the positions to be negotiated during the Kyoto Conference and the second

---

[225] United Nations Climate Change, *United Nations Climate Change*, What is the Kyoto Protocol?, Available online: https://unfccc.int/kyoto_protocol%26from%3D, (accessed 10 June 2019).

a common EU-wide strategy for RES, which included the European Commission's positions on GHG emission reductions.[226,227] The latter is known as the 1997 White Paper for RES.[228,229,230] In line with the Commission's proposals for the Kyoto Conference, the environmental challenges were included in the RES strategy and became the main driver for the EU's energy policy for RES. With the inclusion of RES in energy policy, the European Commission has essentially succeeded in acquiring powers in energy policy.

The first step towards creating an EU energy policy for RES began in 1997 with the White Paper for RES and was followed by a series of Directives. Most importantly, Directive 2001/77/EC, which was the first Directive for RES. Both documents represented a global novelty and served as the 'baseline document' for the development of other regional energy policies for RES. Upon discussing with a former EC official and key-author of the 1997 White Paper for RES about these two documents, their importance and impact, they stated:

> "…it is the first Directive – globally – for RES. **These [documents] comprise European global novelties, both the White Paper and the Directive**. You have a legislation concerning RES with targets etc. **Until then that did not exist anywhere**. **It is introduced by the European Union** […] Until then, and even the first Directive for electricity, despite that it did not include any binding targets, played a catalytic role globally […] In 2003-4, China was preparing a policy for RES. The main reference was Europe and the Directive for RES. There was nothing else in the world."[231,232] (emphasis added)

---

[226] European Commission, "Communication from the Commission Climate Change – The EU Approach to Kyoto", COM (97) 481 final, 1 October 1997.

[227] Commission of the European Communities, *Communication from the Commission ENERGY FOR THE FUTURE: RENEWABLE SOURCES OF ENERGY White Paper for a Community Strategy and Action Plan*, COM (97) 599 final, Brussels, 26.11.1997.

[228] Commission of the European Communities, *Communication from the Commission ENERGY FOR THE FUTURE: RENEWABLE SOURCES OF ENERGY White Paper for a Community Strategy and Action Plan*, COM (97) 599 final, Brussels, 26.11.1997.

[229] In the White Paper of 1997, the guidelines for the member states to initiate their own, national, programmes for RES (including PV) were incorporated. It is crucial to note that the European Commission had made another attempt to 'push' towards what was essentially an EU-wide energy policy also in 1995 (see: Commission of the European Communities, "White Paper: An Energy Policy for the European Union", COM (95) 682 final, Brussels, 13.12.1995). In this attempt the European Commission had already linked RES with environmental policy.

[230] Aside from the EU member-states, such initiatives were also adopted in other regions like Japan and in the USA. We will briefly analyse them too. For the purposes of our analysis, we look into and examine this type of initiatives for solar photovoltaics. This however does not mean that similar initiatives were not adopted for other RES and/or did not apply for the development of other RES too.

[231] Interview with former EC DGXII RES Unit Scientific Officer (via Skype), 14 May 2020, Athens, Greece.

[232] The words in brackets are explanatory, to complement what the interviewee means.

This EU novelty put RES on the energy policy map. Until then, RES had neither been envisaged nor been part of any country's energy policy. Moreover, these documents served as the basis for RES policy making (e.g. in China). Perhaps more importantly, these documents, also in light of what came after, shed light on how an institution like the European Commission accumulates power. The 1997 White Paper for RES was the first document to set comprehensive goals for RES. It was in the context of the 1997 White Paper that the first vision for sustainability and a RES transition was formulated.

> "More recently, the EC has published its White Paper on Renewable Energy Sources. This sets out for the first time a comprehensive strategy and action plan designed to achieve, by 2010, an ambitious but realistic goal of doubling from 6 to 12% the share of renewable energies in the total energy demand of the EU. This **White Paper recognises that unless the EU succeeds in supplying a significantly higher share of its energy demand from renewables over the next decade, it will miss an important market development opportunity**. At the same time, it will become increasingly difficult for the EU to comply with its commitments to environmental protection and emissions reductions both at European and international level."[233] (emphasis added)

From the above quote we see how RES were also understood as a market and about their market development potential. The key actions proposed in the 1997 White Paper suggested a certain number of installations for PV, wind energy and biomass. The 1997 White Paper proposed the installation of 1.000.000 PV systems, 10.000 MW large wind farms and 10.000 MW_{th} biomass.[234] The proposed figured signalled the industrialization of these sectors by scaling up the production to meet 'demand'. It is interesting to see how PV was understood in the 1997 White Paper:

> "Photovoltaics (PV) is a high technology with **strong export potential in a very competitive global market and fierce competition with Japan and the USA**. There is a very motivated **PV industry in Europe** which **should be**

---

[233] DGXVII, "Thermie-Altener Renewable Energy Report", Office for Official Publications of the European Communities (Luxembourg: 1998), p. 8.

[234] For more details see: Commission of the European Communities, *Communication from the Commission ENERGY FOR THE FUTURE: RENEWABLE SOURCES OF ENERGY White Paper for a Community Strategy and Action Plan*, COM (97) 599 final, Brussels, 26.11.1997.

> **supported in its effort to bring domestic and export markets off the ground**."[235] (emphasis added)

Against the backdrop of global markets and global competitiveness, EU support for the PV industry was deemed necessary. This understanding of global markets and placing PV in the context of global competition impacted the direction of research. As we will see in detail in the forthcoming analysis (chapters 3 and 5), the targets for PV installations set in the 1997 White Paper redirected PV research activities in the second period, namely: in response to the looming silicon crisis in PV and by reorienting research on (mass) production and production line issues. The 1997 White Paper for RES would not have materialise had it not found political support. One person who helped confirm and strengthen the interest in RES at the EU level was Mr. Christos Papoutsis. Papoutsis was at the time European Commissioner for Energy and as such the face and voice of EC for Energy. He was a supporter of RES and a key figure in achieving the goals of White Paper for RES.[236] Despite Papoutsis' efforts, Dr Hermann Scheer's involvement and contribution was a catalyst for the advancement of RES policy. Equally important was the (general) role of Germany and its place in the EU. We turn to these last two points later.

Two years before the 1997 White Paper for RES, Mrs Tachmintzis stated on behalf of Mr Papoutsis during the welcome address at the 1995 European Solar Photovoltaic Conference:

> "In the past, **the renewable energy industry has suffered from government indifference and subsidized electric utilities using fossil and nuclear fuels**. Now **this is changing, as the foundations of energy strategy are also changing**. With more emphasis on market forces, sustainability and the costs of environmental damage, at least some of the constraints that have hindered the growth of renewable energy are being removed."[237] (emphasis added)

---

[235] Commission of the European Communities, *Communication from the Commission ENERGY FOR THE FUTURE: RENEWABLE SOURCES OF ENERGY White Paper for a Community Strategy and Action Plan*, COM (97) 599 final, Brussels, 26.11.1997, p. 27.

[236] Christos Papoutsis (Χρήστος Παπουτσής) was a Greek politician who served under different roles when the Panhellenic Socialist Movement (PASOK) was the majority party. Additionally, he was a member of the European Parliament and served as the European Commissioner for Energy under the Santer Commission (1995-1999). The Santer Commission's term was cut short due to corruption allegations.

[237] Joanna Tachmintzis of Mr Papoutsis' Cabinet on behalf of the European Commissioner for Energy, Christos Papoutsis, "Welcome Address", Thirteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Nice, France, 23-27 October 1995, W. Freiesleben, W. Palz, H. A. Overstraeten, P. Helm (eds.), Vol I, H. S. Stephens & Associates (UK: 1995), p. xxxvi.

The above quote confirms – once again – the turbulent years that the RES sector experienced until the 1990s. Moreover, it illustrates that the (national) electric utilities played an important role in their ‘struggles’, which, as soon as the prices for conventional energy sources dropped, made a ‘U-turn’ and essentially lost interest in RES. Furthermore, the above quote also makes clear that the 1990s signalled a – slow but promising – shift for RES, including PV. The increasing emphasis on environmental challenges in the reorientation of energy policy was detrimental. It was only by linking RES to environmental challenges that the European Commission stepped up the efforts to RES. The EU established a vision for RES to address the environmental challenges. In this way, the European Commission succeeded in including RES on the energy policy map. Most importantly, RES were the medium through which the EU acquired powers in energy policy through the single market for electricity.

> “The **development of renewable energy as a significant energy resource is a central aim of the European Commission's energy policy**. The EC's Energy Policy White Paper identified three key aims with respect to the present and future energy policy for the EU: to ensure security of supply, to protect the environment and to encourage the development of commercially-viable energy technologies. **Renewable energy clearly has an important role to play in the EC's energy policy.** Because renewable energy is a non-fossil source of energy, **its use instead of fossil fuel sources can contribute significantly to reducing carbon dioxide emissions**. Increasing the share of renewable energy in the energy balance contributes to improved sustainability in energy supplies. It also helps to improve the security of energy supply by reducing the Community's growing dependence on imported energy sources. **Renewable energy is mainly local energy**. Its development can create new businesses, bring employment and encourage economic and social cohesion in regions that otherwise lack industrial development. This local expertise can also be translated into opportunities to exploit the considerable and growing export potential from renewable energy technologies, particularly in the developing world.”[238] (emphasis added)

---

[238] DGXVII, “Thermie-Altener Renewable Energy Report”, Office for Official Publications of the European Communities (Luxembourg: 1998), p. 5.

In the above quote we see how RES were linked to 'traditional' energy policy aims, complemented by their coupling to overcoming environmental challenges. Essentially, it was about reframing an energy policy vision through the lens of contemporary goals related to environmental challenges, centred on RES. We also see how RES were the core for the development of an EU energy policy. In other words, RES were at the forefront of the formulation of a – centrally regulated – EU energy policy.

As noted in the quote above, 'renewable energy is mainly local energy'. This understanding and classification of RES is not new, but dates back to the first R&D efforts for RES. At that time, RES were placed at the local level and understood in strict geographical terms. This time, however, the 'local' element of RES was linked to the benefits (economic and social) that the development of the RES business would/could bring. These benefits reflected the Treaty goals of the EC.

There were several actors who promoted this linkage and who supported RES. Most of these actors came from the PV sector. One key figure was Dr Hermann Scheer. Scheer held many important positions that enabled him to further promote and support the implementation of RES. As we will see, Scheer was a key figure for the implementation of RES and especially for the rapid growth of PV in the second period. Among the many important positions Scheer held, we will focus on two: (a) he was a member of the German parliament (Social Democratic Party) and (b) he was the president of the European Association for Renewable Energies (Eurosolar).[239,240]

As Scheer remarked in his welcome speech during the European Photovoltaic Solar Energy Conference in 1995:

> "**The European energy tax, first time promised in 1989, was postponed from year to year**. The European Energy charter was signed, which leads to lower conventioned energy process. The **contemporary plans for a European energy market are supporting the economic behavior of ignoring social costs of energy consumption.** All **these decisions are not a progress, but a**

---

[239] In 1988, Dr Scheer founded Eurosolar, which is a non-profit, non-governmental association aimed at excreting political influence towards replacing conventional energy sources by RES and most prominently PV; essentially in assisting the RES transition. For more information on Eurosolar see: The European Association for Renewable Energy, *Our mission & history*, Eurosolar. Available online: https://www.eurosolar.de/en/index.php, (accessed 15 January 2020).

[240] For more information on Dr Scheer and his publications, see: Hermann Scheer, 2014, *About Hermann Scheer*, Hermann Scheer. Available online: http://www.hermannscheer.de/en/, (accessed 10 January 2020).

> **regress for ecological energy alternative-decisions motivated by the will to promote the European industrial place in global economic competition**. The gap between friendly words about renewables and insufficient or counteracting acts shows the inability to leave the dispose of old shoes and indicates a short sighting conscious of our economic experts in industrial representatives."[241] (emphasis added)

Using the above quote, Scheer essentially criticized the political postponement of aid to the PV and RES market. He attributed this political inaction to the vested interests of industrial lobbies, which influenced and directed governmental priorities to other areas (e.g. other energy sources, but also different sectors like aviation). As he explained, the PV programme proposed by Eurosolar (100.000 PV roof and façade) was "…not supported by the industrial representatives."[242]

A major trigger behind a common energy policy was climate change.[243,244] The objective of reducing CO_2 emissions played an important role in the (re)definition of European energy policy and its objectives. The Kyoto Protocol and 1997 White Paper, for example, called for a reduction in greenhouse gas (GHG) emissions and set specific reduction targets expressed as percentage relative to the 1990 baseline year (for the EC, 8% reduction of the six GHGs within the first commitment period 2008-2012).[245] This overall target was divided into country-specific targets via an EU burden-sharing agreement. The country-specific targets varied greatly from country to country and depended on the prosperity of each country and its previous energy efficiency and emission reduction measures. These GHG emission reductions were accompanied by EC policies and measures to be taken to achieve the targets. Similar targets regarding the RES share of energy consumption have been included in EU legislation (see analysis of RES Directives).

---

[241] Hermann Scheer, "Welcome Address", *in* Thirteenth European Solar Energy Conference, Proceedings of the International Conference held at Nice, France, 23-27 October 1995, W. Freiesleben, W. Palz, H. A. Ossenbrink and P. Helm (eds.), Vol I, H. S. Stephens & Associates (UK: 1995), p. xxxii.

[242] Hermann Scheer, "Welcome Address", *in* Thirteenth European Solar Energy Conference, Proceedings of the International Conference held at Nice, France, 23-27 October 1995, W. Freiesleben, W. Palz, H. A. Ossenbrink and P. Helm (eds.), Vol I, H. S. Stephens & Associates (UK: 1995), p. xxxii.

[243] L. 27, Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity, Official Journal of the European Communities, 30.1.1997.

[244] Jegen Maya, "Energy policy in the European Union: The power and limits of discourse", *Les cahiers européens de Sciences Po*, n°2, 2014.

[245] Commission of the European Communities, *Communication from the Commission ENERGY FOR THE FUTURE: RENEWABLE SOURCES OF ENERGY White Paper for a Community Strategy and Action Plan*, COM (97) 599 final, Brussels, 26.11.1997.

3.1.3.1.1 The relationship between the EU-member state priorities: the role of Germany

With the 1997 White Paper, the RES sector was given the green light for becoming industrial (in terms of production) for the first time in two decades. A concrete strategy for RES's share in the EU energy system was the proof of EC's political commitment to RES. In a sense, the White Paper was just that. However, despite the vision these efforts could not have been realised without political support. It is therefore crucial to shed light on the role of key actors in securing political support for RES. It is equally important to better understand the dynamics between the EU and its member states. When we spoke to a former EC official about the relationship between EU and national (research) priorities, we asked about the dynamics between the two and which side has more influence in setting priorities in relation to RES. Our interviewee replied:

> "Look, essentially **there were no national priorities [for RES]** with the exception of two-three member states that did have RES as one of their priorities. […] For example, there were the Danes, which were overall pioneers in this field, that had put an effort regarding the wind turbines that interested them. This was because they had started to build an industry and so in this sense, they were promoting it. So, you have some examples of this kind. But there weren't many such examples, isn't that so? The Germans started to slowly enter, then, and Hermann Scheer had played a role. He was a Parliament member of SPD, and he played a decisive role regarding RES in Germany and, by extension, also then in Europe – **given the role that Germany plays in Europe and has insofar played**. […] Germans have a procedure that they do not use very often. The Government was against the Law, but they have a procedure that [a Law] can pass from the Parliament. This was set-up by Scheer. And he did what is usually done in the European Parliament. Essentially, he got some people from CDU, which supported them, and passed it from the Parliament without their Government wanting it. This is how the first Legislation started in Germany, it was done in this way, and it was decisive. […] **Scheer played a catalytic role**. So, Germany that appears to start supporting RES – Germany always had a sensitivity in environmental issues and always comprised a

> pioneer in environmental legislation – at this time the Greens also started to rise […] and priority was given to RES. Great support was given to RES under the coalition government of 2000 between the Greens and the Social Democratic party. This was, obviously, the take-off of RES, politically speaking. And to a great extent this was continued by Merkel, it was a policy that she followed. **So, Germany has obviously played a catalytic role in the EU. Because of the gravity that Germany has in the EU. It is different when Denmark supports RES and when Germany supports RES**. So, what I want to say is that **there were some national priorities but essentially the policy priorities were determined by the EU**. **This is the reality regarding research**. In essence, **the European Commission and the (then) DG for Research played a role in determining the priorities for research in Europe**. Because the member states – except for Germany and the large member states – were simply marginal in essence in this sector. They had some groups/teams, but **the smaller member states were counting on EU funding entirely**. So then, what do you do? **In order to get funding, you need to 'enter' by following the priorities of the Union's programmes.** […] So, in this sense **the Commission played a catalytic role regarding what the priorities will be, during the 1990s**. **Later, things changed because of the entrance of the industries – the largest portion/share goes to the industry**."[246] (emphasis added)

Not all member states had research priorities for RES. We would argue that many member states did not have explicit general research policies until the 2000s or even later. Only a few of the larger member states had priorities for RES, but again, research priorities and strategy were set by EC and DG for Research.[247] The remaining member states, which also comprise the majority, depended on EC programmes to fund their research. The answer our interviewee confirms two things: (i) that the majority of the member states were fully dependent on EC for funding their research, (ii) that the EC and DG for Research were responsible for setting the research priorities. Moreover, the influence of EC in determining which research to fund was crucial for the character of the resulting technologies and for the structure of the networks (i.e. also for who was relevant and influential and who remained 'outside').

---

[246] Interview with former EC DGXII RES Unit Scientific Officer (via Skype), 14 May 2020, Athens, Greece.

[247] Regarding the role of the EC and DG for Research in determining the research priorities and in setting-up the research strategy see the corresponding section in chapter 4.

According to what our interviewee told us, Hermann Scheer played a catalytic role for RES in Germany. As the interviewee explained, given the role Germany had and still has in the EU, Scheer's role was important for the development of RES in the EU as a whole. Scheer succeeded in establishing a Law for RES (i.e. the first feed-in-tariff law), despite the German government's opposition in passing a Law for RES.[248] Essentially a policy instrument that allowed RES to enter the electricity market, which was a novelty and helped RES to take off – especially wind energy in the 1990s.[249] The opposition Scheer faced was also confirmed by Palz.[250] Palz described the political atmosphere in Germany as more favourable to conventional energy sources (e.g. coal) and especially nuclear power. He wrote: "The Parliament was not a frank supporter of solar energy either […] the defenders of nuclear power were more numerous and they were a lot more aggressive."[251]

Despite the political opposition to RES in Germany, Scheer's persistence and determination in supporting RES was victorious. Not only that, but this was of great importance for the future of RES. In this way, RES gained political support. We should note, however, that Scheer's views were also met with opposition from the electric utilities, who "went to the highest courts in Germany and the EU to complain, but without success."[252] They not only took legal action (e.g. lawsuits), but also tried to prevent the FiT law from coming into force. Basically, the utilities resisted RES every step of the way.[253] It was in this context of opposition and contestation that Scheer revolutionized the German energy scene – starting in Germany and reaching the globe.

In the 1990s and before the liberalization of the electricity market, which took place in the most member states in the 2000s, national electricity utilities were fully responsible for the generation, distribution, and transmission of energy. In addition, the utilities used electricity from conventional energy sources.

---

[248] We are referring to the "electricity feed law" (StromEinspG).

[249] Based on Palz's account the German Law was inspired by the Danes, which were the pioneers of such a policy instrument for wind energy and had developed a similar instrument to help boost the wind market in the late 1970s. For more information see Palz's book: Wolfgang Palz, The Triumph of the Sun: The Energy of the New Century, Wolfgang Palz (eds.), Pan Stanford Publishing (Singapore: 2018).

[250] The two men were good friends and knew each other since the 1980s. They were both strong proponents and supporters of PV. Palz dedicated his book in Scheer's memory who passed away in 2010.

[251] Wolfgang Palz, "The Solar Revolution of the Year 2000", *in* The Triumph of the Sun: The Energy of the New Century, Wolfgang Palz (eds.), Pan Stanford Publishing (Singapore: 2018), p. 59.

[252] Wolfgang Palz, "The Solar Revolution of the Year 2000", *in* The Triumph of the Sun: The Energy of the New Century, Wolfgang Palz (eds.), Pan Stanford Publishing (Singapore: 2018), p. 60.

[253] The opposition described by the utilities was not a phenomenon met only in Germany. As we will see in other major European countries the electric utilities followed a similar, hostile, path towards RES.

Scheer had been very active politically since his time at the university.[254] Even in his early days in the German Parliament (Bundestag), from 1980, he was a strong advocate of nuclear disarmament.[255] Scheer wrote "I was not only against nuclear weapons, but against nuclear power plants as well."[256] He was also not satisfied with fossil fuels. He was determined to find another alternative. So it was that he became interested in RES. Despite the very pessimistic view that scientists and politicians alike held for RES, Scheer was convienced that living in a world powered by RES was possible. This belief led Scheer to dedicate his life to this cause and this vision.

These ideas and ideals shaped Scheer's understanding and vision for the energy sector. Furthermore, his path explains why PV were central to his vision and more importantly, how he envisioned PV in relation to energy production. Unlike the utilities that opted for centralized power generation through large-scale installations of RES, Scheer had a different vision, and this explains why he was a strong proponent of PV particularly. PV not only offered a more environmentally friendly and less polluting energy option, but also, in Scheer's view, according a means by which people could become independent of the large (monopolistic) energy companies. His vision for PV was to turn users into 'independent producers', and this was precisely why the German energy companies were against PV (i.e. they would lose their supply monopoly).[257] For Scheer, PV offered a unique option for both users and the producers of electricity. For him a decentralized way of generating electricity was synonymous with autonomy and freedom and enabled energy independence for its users.

In addition to his political post in the German government, he was also President of the European Association for Renewable Energy (EUROSOLAR), which he founded in 1988, and Chairman of the World Council for Renewable Energy (WCRE). With EUROSOLAR, Scheer gathered all supporters of RES under one roof. The association included members from the political, scientific etc. scene who covered a broad spectrum. Through this association, Scheer succeeded in gaining the support of members of Parliament from the opposing parties in Germany – who also supported RES – and in passing the electricity feed law (StromEinspG)

---

[254] For a summary of Scheer's University days see: Hermann Scheer, "Initiating a Solar Revolution in Germany", *in* Solar Power for the World, Wolfgang Palz (eds.), Pan Stanford (US: 2014), p. 287-300.

[255] He authored an influential book (Die Befreiung von der Bombe), published in 1986, and served as the Chairman of the Arms Control and Disarmament Committee (1990-3).

[256] Hermann Scheer, "Initiating a Solar Revolution in Germany", *in* Solar Power for the World, Wolfgang Palz (eds.), Pan Stanford (US: 2014), p. 291.

[257] Regarding the users Scheer spoke of see: Hermann Scheer, "Initiating a Solar Revolution in Germany", *in* Solar Power for the World, Wolfgang Palz (eds.), Pan Stanford (US: 2014), p. 287-300.

of 1990.[258] This law was essentially the precursor of what we known today as the feed-in-tariff scheme. It obliged utilities to buy the electricity generated by RES at a fixed price. The law was supplemented by the first roof programme (i.e. 1000 Roofs Photovoltaic Programme), which aiming to stimulate the PV market.[259] This programme became a reality after Scheer's campaign for PV, which resulted in solar energy becoming a priority in the national R&D programme. According to Scheer, he gave speeches and campaigned for PV throughout the year. Central to his campaign was the idea of acquainting people with PV and its possibilities and gaining supporters along the way. Through this route, he gained the support of grassroots organisations.

Almost a decade later, in the late 1990s, Scheer managed to launch another programme for RES. We are talking about the 100.000 roofs photovoltaic programme, which together with a new FiT law (Renewable Energy Law (EEG)), helped the PV market to take-off and made Germany the world leader both in production and installation of PV systems worldwide. At the time, RES and PV found support from the coalition government in Germany (SPD and Greens). When Scheer first drafted and presented the 100.000 Roofs Photovoltaic Programme in 1993, it was met with disbelief. Not only his colleagues thought it was unrealistic, but the major actors in the PV industry (i.e. Siemens Solar) shared this disbelief. The 100.000 roofs photovoltaic programme launched on 1 January 1999, a date Scheer described as "…the date of birth worldwide of industrial mass PV production".[260] Despite discussion of similar programme in other regions (e.g. Clinton's 1.000.000 roofs programme) or the eagerness of the EU to pursue a similar programme, Scheer wrote that "…none of these initiatives were ever implemented in practice".[261]

However, these initiatives were not welcomed by all. This time the opposition came from the EC, which filed a lawsuit before the European Court of Justice. The justification for this action was that the Act "would violate the EU's market-rules, and it was not compatible with European law."[262] As we understand it, EU market rules refer to the way a free market works. This means that the Act was seen and understood as a breach of the according to which the

---

[258] At the time SPD was not the majority party. Even though Scheer was the architect of the Law, it was passed under the conservative party, that was the majority party at the time.

[259] The Law proved beneficial for wind energy, not so much for PV. The PV sector was still very young at the time, in contrast to the wind energy sector.

[260] Hermann Scheer, "Initiating a Solar Revolution in Germany", *in* Solar Power for the World, Wolfgang Palz (eds.), Pan Stanford (US: 2014), p. 296.

[261] Hermann Scheer, "Initiating a Solar Revolution in Germany", *in* Solar Power for the World, Wolfgang Palz (eds.), Pan Stanford (US: 2014), p. 296.

[262] Hermann Scheer, "Initiating a Solar Revolution in Germany", *in* Solar Power for the World, Wolfgang Palz (eds.), Pan Stanford (US: 2014), p. 297.

market operates under the provisions of the European Single Market Act and the corresponding complementary provisions regulated by the governing EU Treaties. Based on the Court's ruling, the case was dismissed. In the following years, the electric companies continued their lawsuits and their efforts to circumvent and not implement the legal provisions. But this time PV took-off. Palz credits Scheer the 'architect of the solar revolution'.[263]

The path to establishing a new market, in our case for an energy technology, was met with opposition. The biggest opponent of RES was the electric companies (i.e. utilities), which had vested interests in other energy sources. Moreover, at a time when the liberalization of the electricity market had not yet been completed, these interests also collided with the interests in the (monopolistic) supply of the system.

The PV installations envisaged in the 1997 White Paper, meant the upscaling of c-Si production and the corresponding actors. The German programmes were also based on this technology. C-Si had emerged as the dominant PV technology since the first period. The importance of EC in terms of research policy should not be downplayed, as it provided the technological option on which the PV take-off was to take place. The targets for PV set out in the 1997 White Paper were based on c-Si flat plate PV. In this context, research policy directed energy policy. The research policy of the EC's provided the technological basis for shaping energy policy. Based on the technological options offered by research policy, the various options for energy policy were determined.

PV are the only energy technology for electricity generation that offers another option for system integration. They are the only energy technology that can be integrated into the urban environment (e.g. on rooftops), allowing the reconfiguration of the electricity system while constructing different users (e.g. prosumers). More importantly, this represents a shift away from the dominant centralized electricity generation towards decentralized generation. In turn, this new social order both enables and challenges the current transmission system(s). In other words, without PV, it would have been impossible to open-up energy policy to include smart grids, net-metering etc. Given this unique option for system integration that PV offers, it is a crucial technology for the transition to RES, as well as for the implementation of the transition to RES.

3.1.3.1.2 The RES Directives: from indicative to binding targets

---

[263] Wolfgang Palz, "The Solar Revolution of the Year 2000", *in* The Triumph of the Sun: The Energy of the New Century, Wolfgang Palz (eds.), Pan Stanford Publishing (Singapore: 2018), p. 51-64.

The White Paper for RES was followed by Directives. As word itself suggests, Directives provide a *direction*: they express the EU's intention and at the same time provide some some general guidelines for the materialization of the stated goals and/or targets.[264] Unlike regulations, Directives offer different timeframes for achieving the goals and are not binding. As such, they offer flexibility to the member states in terms of when and how the goals are to be achieved.

Directive 2001/77/EC was the first Directive to set indicative targets for electricity generation from RES. More specifically, the target was set the achieve a 22.1% share of electricity from RES by 2010.[265] Each member-state had the task of establishing a national plan to achieve this target. In contrast to Directive 2001/77/EC, Directive 2009/28/EC was the first EU legislative document to set binding targets for member states to promote RES (i.e. the 20% RES target).[266] The EU's ability to set binding targets stems from the institutional powers acquired by the Treaty of Lisbon.[267] Apart from the binding targets resulting from the new institutional powers of the EU due to the Treaty of Lisbon, the 2009 Directive had another novelty: integrating RES in buildings.

> "**Member States must embed**, in their building regulations and codes, **appropriate measures** in order **to increase the share of RES in the building sector**. Through these measures, by the end of 2014, a minimum amount of energy from RES in new buildings and in existing buildings that are subject to major renovation will be obligatory (especially RE technologies that achieve a significant reduction in energy consumption like heating and cooling systems). **RE technologies' integration in buildings is one of the major pillars towards the nearly zero-energy buildings concept which will be implemented from 2018 onwards**."[268] (emphasis added)

---

[264] This type of legislative document – in contrast to Regulations – is not binding, rather it is meant to be indicative. The member-states are given a timeframe to introduce the measures proposed in the Directives, whereas it was common to provide different timeframes for different member states. Following the publication of a Directive, the member states need to 'pass' a corresponding – national – legislative measure (e.g. Law) in the Parliament that introduces the measures stated in the Directive(s).

[265] Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market, Official Journal of the European Communities, 27.10.2001.

[266] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending the subsequently repealing Directives 2001/77/EC and 2003/30/EC, Official Journal of the European Union, 5.6.2009.

[267] The Treaty of Lisbon was signed in 2007 and came into effect in 2009.

[268] M. Kanellakis, G. Martinopoulos, T. Zachariadis, "European energy policy: A review", *Energy Policy*, 2013, p. 1023.

With a timeframe for implementation from 2018, this Directive sets a vision and a concrete target for RES technologies. The directive's vision for building-integrated RES technologies which goes beyond the previously centralized way of generating electricity and rooftop installations (for PV), aims to make the building sector an integral part of energy policy and the (future) RES transition. The inclusion of RES in the building sector, in turn, allowed energy policy another option for energy integration and constructed another market for RES technologies. This was made possible by PV technologies and their unique characteristics. They can be installed on rooftops and integrated into buildings.

Essentially, PV (flat plate) technologies not only provided a unique system integration option for energy policy, but they also expanded the areas of energy policy by allowing the building sector to become part of energy policy through the options that PV technologies provide. One of the most prominent proponents of rooftop PV was Scheer. He explicitly linked rooftop PV to a vision for decentralized and distributed electricity generation. He wrote in 2007:

> "Many agree that renewable energy is the future. I would submit that we should make a rapid transition to renewable sources of energy and distributed, decentralized energy generation. This is a model that has been proven, technologically, commercially and politically, as has now been comprehensively demonstrated."[269]

The significance of these developments goes beyond setting EU energy policy for RES. Rather, their significance lies in how the EU has managed to acquire powers in regulating energy policy and how this acquisition of powers has also led to a shift in the relationship between DG XII and DG XVII. Finally, but equally important, is how the inclusion of RES in energy policy and the use of policy instruments for RES have helped to industrialize the sector.

The 2001 Directive set a target for an indicative share of 22.1% electricity from RES by 2010.[270] The 2009 Directive set an overall binding target of 20% share of RES energy in the final energy consumption by 2020, followed by national binding targets for each member

---

[269] Hermann Scheer, "Foreword" *in* Feed-in Tariffs: Accelerating the Deployment of Renewable Energy, Miguel Mendonca, Earthscan (UK and USA: 2007), p. x.

[270] L. 283, Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market, Official Journal of the European Communities, 27.10.2001.

state.[271] These targets in EU legislation and policy were influenced by environmental concerns, especially in the 2000s. These legislative changes, which facilitated further integration of RES into national electricity grids, drew attention to RES. During this period, financial incentives were adopted to facilitate the integration of RES into electricity grids. For example, feed-in-tariffs were introduced in several countries such as Germany, France, Greece, Italy, and the UK.[272] These incentives were accompanied by programmes such as the German 100.000 roofs programme of 1998 and the Italian 10.000 rooftops programme of 2001.[273]

Therefore, in 1993, a common and centrally controlled EC energy policy began to shape and guide national energy policies. Member states agreed to relinquish a (small) part of their sovereignty when they adopted the more-or-less binding common energy policy measures set out in EC regulations and directives. Within this framework, a common vision was created and energy policies were shaped by specific environmental challenges and problems. From 2001, the EC promoted further energy production through RES, moving from indicative to binding targets for the share of RES in electricity generation. These binding targets helped to steer development towards energy policy goals, particularly in relation to RES and emission reductions. At the same time, as we will see in the following analysis (chapters 4-6), the character of EU research policy became less experimental and exploratory, and more focused on the integration of RES technologies into electricity grids. At the EU level, this shift was accompanied by environmental concerns (e.g. climate change, reduction of GHS emissions), which provided political legitimacy for public policies that supported the investments in RES technologies.[274] Energy and environmental policies were thus moving in the same direction, both calling for the further integration of RES technologies into electricity grids. It was assumed that this could be achieved through supportive research policies.[275] The three areas of EU policies—energy, environmental, and research—were aligned in that they pursued similar

---

[271] L. 140, Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, Official Journal of the European Union, 5.6.2009.

[272] Luigi Dusonchet and Enrico Telaretti, "Comparative economic analysis of support policies for solar PV in the most representative EU countries", *Renewable and Sustainable Energy Reviews*, 2015, p. 986-998.

[273] Ahmad Zahedi, "Solar photovoltaic (PV) energy; latest developments in the building integrated and hybrid PV systems", *Renewable Energy*, 2006, p. 711-718.

[274] Climate change became a policy priority soon after the Kyoto Protocol (see: Tim Rusche, "The European climate change program: An evaluation of stakeholder involvement and policy achievements", *Energy Policy*, 2010, p. 6349-6359), and the same applies for GHG emission reductions (see: European Commission, *Report from the Commission to the European Parliament and the Council Progress Towards Achieving the Kyoto and EU 2020 Objectives*, COM(2014) 689 final, Brussels, 28.10.2014.

[275] Research, both for PV and WTs, was supporting the integration of RES into the electricity grids (e.g. through funding problems that addressed the resolution of connectivity issues). Such research themes can be traced already from the first pilot projects but it was-especially-in the late-1990s that such topics gained prominence in the R&D programmes.

energy policy goals by promoting the further development and integration of RES technologies into the electricity grids. This synergy of energy, environmental, and research objectives helped the EC to achieve its targets for GHS emissions and RES integration into the electricity grids and to enhance the sustainability of its energy policy.

3.1.3.1.3 The establishment of the European Renewable Energy Council

Three years after the publication of the 1997 White Paper for RES, the European Renewable Energy Council (EREC) was founded in 2000.[276] The aim of the EREC was to influence EU energy policy for RES. It consisted of a consortium of the main European industry associations for all RES, including a scientific association, and acted as their 'voice' in Brussels.[277,278,279] When asking a former EC DGXII RES Unit Scientific Officer about the reasons for the creating of EREC and the identification of the possible gap(s) EREC was meant to fill, they replied:

> "**There was not a voice for RES**, what existed were the associations that – each and every one would say their own things – and **the creation of EREC was strongly supported** – not financially – **by the Commission**. Essentially, the Commission said 'look, I want someone to talk with' […] Therefore, **through this need, which was an actual need, that is for a voice for RES to exist, which means to go through the processes to reach certain positions – to do that internally and not just do so when one is 'opposite' of the other towards the Commission, do you understand?** […] The initial idea already existed back in 1996 and the European Export Council was established then. So, **the need was established, when you want to go beyond Europe to have something like an industrial lobby, which will be able to go.** This is something the Americans had, and it worked a lot. And as such, the initial idea was the European Export Renewable Council – the association was actually established. Therefore, **when the White Paper was published and the**

---

[276] EREC was dissolved in 2014.

[277] The founding members of EREC were the following: European Photovoltaic Industry Association (EPIA), European Wind Energy Association (EWEA), European Small Hydropower Association (ESHA), European Solar Thermal Industry Federation (ESTIF), European Biomass Association (AEBIOM) and EUREC.

[278] Given that EREC dissolved in 2014 and its website is no longer working attaining information about EREC was particularly difficult. However, the information regarding (1) EREC's founding members, (2) how it emerged, (3) other primary sources published by EREC, where provided through an interview with a former EC DG XII, RES Unit officer.

[279] Gradually, other RES associations joined: European Biomass Industry Association (EUBIA), European Geothermal Energy Council (EGEC) and European Renewable Energies Federation (EREF).

> **discussion about the directives started etc., that is when the need for its establishment derived**. And it was not something easy, … it happened with a lot of arguing initially because everyone had…. So, **it materialised under difficult circumstances, and therefore its dissolvement was – to a large extent – a reverse course in the sense that throughout this 14-year period, when it was established, everyone was 'small'. When it ended there were two big ones and all the rest where small**."[280] (emphasis added)

From the above quote we can see that the need for the creating of EREC derived is due to two complementary factors. First, the European Commission's request for a 'united' voice from RES, a representative interlocutor. Second, the need for a RES industry lobby representing the EU and the corresponding European industrial interests.

When asked if the creation of EREC was meant to influence the corresponding (EU) priorities in research and energy policy, the interviewee replied:

> "The **energy policy priorities mainly**. EREC's reference is policy. That is when – after the White Paper – Europe's energy policy started to be established and configured. It did not exist until that point. So, what **EREC tries to** do is exactly to **intervene in the configuration of – primarily – energy policy**. **Secondly, and primarily through EUREC is the part that concerns research**. And so that EUREC defines, let's say, the priorities etc. EREC then takes it as EREC now its interest is – because that what is then configured is the energy policy and the Directives. […] On this [EREC] played a catalytic role, especially in the 2000s."[281] (emphasis added)

Both the establishment of the EREC and its aims impacted, albeit unintentionally, on the relationship between DGXVII and DGXII and further legitimised the transfer of powers from DGXII to DGXVII. By establishing a united RES voice that would primarily influence EU energy policy, this simultaneously meant that the 'arena' was transferred to DGXVII and away from DGXII already weakened by the removal of Palz. Energy policy thus became the area of primary focus, the area where direction was decided.

---

[280] Interview with former EC DGXII RES Unit Scientific Officer (via Skype), 14 May 2020, Athens, Greece.

[281] Interview with former EC DGXII RES Unit Scientific Officer (via Skype), 14 May 2020, Athens, Greece.

3.1.4 The Treaty of Lisbon: towards an EU-wide, common, energy policy?

The Treaty of Lisbon was signed in 2007 and came into force in 2009. At least two changes are significant for energy policy. First, energy was included in the Treaty and was defined "[…] as an area of priority action by primary (i.e. treaty) law […]".[282] Essentially, the EU – after many failed attempts in the past was given the official powers to shape energy policy.[283] However, based on the Treaty of Lisbon:

> "Such measures shall not affect a Member State's right to determine the conditions for exploiting its energy resources, its choice between different energy sources and the general structure of its energy supply, without prejudice to Article 175(2)(c)."[284]

It is clear from the above quote that while the Treaty extended the competences of the EU in energy policy, it also restored the sovereignty of the member-states. The member states retained their right to decide on their energy supply. The second important change involved a shift of power within the EU. For the first time in history of the EU, the role and powers of the Council of the European Union and the European Parliament were strengthened.[285] Essentially, these changes strengthened the role of the member states officially elected representatives in the EU.

A key moment in EU energy policy was the endorsement of the strategy "An energy policy for Europe", published shortly before the signing of the Treaty of Lisbon.[286] As has already been noted, it "… marks the beginning of a more integrated European energy policy …".[287] The basis of this common European energy policy was three grand challenges (i.e. sustainability,

---

[282] Jale Tosun, Sophie Biesenbender, Kai Schulze (eds.), *Energy Policy Making in the EU: Building the Agenda*, Springer (London: 2015), p. 22.

[283] Susanne Langsdorf, *EU Energy Policy: From the ECSC to the Energy Roadmap 2050*, Green European Foundation, December 2011.; Francis McGowan, "Putting Energy Insecurity into Historical Context: European Responses to the Energy Crises of the 1970s and 2000s", *Geopolitics*, 2011, p. 486-511.; M. Kanellakis, G. Martinopoulos, T. Zachariadis, "European energy policy – A review", *Energy Policy*, 2013, p. 1020-1030.

[284] C 306, "Treaty of Lisbon amending the Treaty on European Union and the Treaty establishing the European Community", Official Journal of the European Union, 17.12.2007, p. 88. Available online: http://publications.europa.eu/resource/cellar/688a7a98-3110-4ffe-a6b3-8972d8445325.0007.01/DOC_19

[285] For a detained analysis about the changing dynamics between the European Commission's and Councils', see: Philipp Thaler, "The European Commission and the European Council: Coordinated Agenda setting in European energy policy", *Journal of European Integration*, 2016, p. 571-585.

[286] Commission of the European Communities, *Communication from the Commission to the European Council and the European Parliament – An Energy Policy for Europe*, COM(2007) 1 final, Brussels, 10.1.2007.

[287] Susanne Langsdorf, *EU Energy Policy: From the ECSC to the Energy Roadmap 2050*, Green European Foundation, December 2011, p. 6.

security of energy supply and competitiveness), which were to be realized through the 20-20-20 targets.[288]

3.1.4.1 The EU's long-term energy strategy and the ongoing energy crisis: the role of RES

Following the Paris Agreement, the European Commission proposed a series of measures to respond to the climate change crisis, resulting in the European Green Deal.[289] Most notably, the EU committed to reducing the GHG emissions by at least 55% by 2030, while under the EU's long-term energy strategy, the goal is to become carbon-neutral by 2050.[290] In this context, it was envisaged that RES should account for 20% of final energy consumption (in 2020). For the climate-neutral strategy by 2050, a new target of 32% share of RES by 2030 has been set, in which PV is a main pillar:

> "The clean energy transition should result in a system in which **the largest share of the EU's primary energy supply comes from renewable energy sources**, thereby improving the security of supply and fostering domestic jobs, as well as reducing emissions."[291] (emphasis added)

As the EU's vision of becoming carbon-neutral by 2050 is gaining prominence and acts as an economic driver, EU research policy has been placed as the focal point of innovation and knowledge-production (see Lisbon agenda, 2000).[292] EU energy and research policies converged in the second period and the gap between the two was minimized. During Horizon

---

[288] Susanne Langsdorf, *EU Energy Policy: From the ECSC to the Energy Roadmap 2050*, Green European Foundation, December 2011.; M. Kanellakis, G. Martinopoulos, T. Zachariadis, "European energy policy – A review", *Energy Policy*, 2013, p. 1020-1030.

[289] For more information about the Paris Agreement and the European Green Deal see: UN, "Paris Agreement", 2015 (https://unfccc.int/sites/default/files/english_paris_agreement.pdf).; European Commission, "The European Green Deal", Brussels, 11.12.2019, COM (2019) 640 final. Regarding EU's commitments and long-term strategy see: European Commission, *A Clean Planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*, COM (2018) 773 final, Brussels, 28.11.2018.

[290] Regarding EU's commitments and long-term strategy see: European Commission, *A Clean Planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*, COM (2018) 773 final, Brussels, 28.11.2018.

[291] European Commission, Directorate-General for Climate Action, *Going climate-neutral by 2050 : a strategic long-term vision for a prosperous, modern, competitive and climate-neutral EU economy*, Publications Office of the European Union (Luxembourg: 2019), p. 9.

[292] Efi Nakopoulou and Stathis Arapostathis, "Reconfiguring Technologies by Funding Transitions: priorities, policies, and the renewable energy sources in the European Community funding schemes", *Journal of Energy History/Revue d'Histoire de l'Énergie* [Online], n°4, published 27 July 2020.

2020, this gap was further narrowed. Horizon 2020 is directly linked to the EU's energy policy goals as formulated in the 'Roadmap for moving to a competitive low-carbon economy in 2050'.[293] The research activities for RES (including PV) pursued under Horizon 2020 were initiated by the SET-Plan. The SET-Plan, launched in 2007, essentially comprises the EU's strategy for European energy technology policy and has been formulated to support the EU's energy and climate goals through research.[294] The SET-Plan has been characterised as follows:

> "…**a key stepping-stone to boost the transition towards a climate neutral energy system through the development of low-carbon technologies** in a fast and cost-competitive way."[295] (emphasis added)

In other words, the SET-Plan bridges the gap between the EU's energy and research policies and seeks to direct the EU's research activities so that they respond to energy policy objectives. In setting research priorities for the technologies that will comprise the new 'climate-neutral' energy system envisaged by the EU, RES are at the heart of the new energy system, while PV are an important pillar.[296]

The current and ongoing energy crisis has further increased the pressure for the rapid implementation of the RES transition. As Kadri Simson, the EU Commissioner for Energy Commissioner, noted:

> "By 2030 … solar energy in power production capacities should double from the current level of 33% to 67%. And **by then solar energy will also be the largest electricity source in the EU with more than half coming from rooftops**."[297] (emphasis added)

---

[293] Regarding the Roadmap see: European Commission, *A Roadmap for moving to a competitive low carbon economy in 2050*, COM (2011) 112 final, Brussels, 8.3.2011..; Regarding its incorporation to Horizon 2020 for RES research, see: L 347, Regulation (EU) No 1291/2013 of the European Parliament and the Council of 11 December 2013 establishing Horizon 2020 – the Framework Programme for Research and Innovation (2014-2020) and repealing Decision No 1982/2006/EC, 20.12.2013, Official Journal of the European Union, p. 104-173.

[294] We have already analysed the SET-Plan in Chapter 2.

[295] European Commission, *Strategic Energy Technology Plan*, Europa, Available online: https://energy.ec.europa.eu/topics/research-technology-and-innovation/strategic-energy-technology-plan_en#european-technology-and-innovation-platforms, (accessed 14 March 2022).

[296] SET-Plan TWP PV Implementation Plan – Final Draft (Approved by TWG members), 18 October 2017.

[297] EcoGreen Energy, Solar Energy Deployment in EU 2030, Available online: https://www.eco-greenenergy.com/solar-energy-deployment-in-eu-2030-global-energy-crisis/, (accessed 1 June 2022).

PV is an important pillar of the EU's long-term strategy. The 32% share of RES has increased to 45%, due to the energy crisis triggered by the ongoing war between Russia and Ukraine.[298] The climate crisis put pressure on the reconfiguration of the energy system, while the current and ongoing energy crisis adds to this urgency. The decisions taken give a clear priority to RES and especially to PV.[299]

3.1.4.1.1 The place of RES in the EU electricity generation mix

As we can see from Figure 3.1, electricity generation (in EU-28) from oil has declined steadily since 1990. From a share of 8,64% of the gross electricity generation in 1990, the EU's oil dependency has fallen to 1,87% in 2013. Conversely, the share of natural gas has steadily increased from 1990 to 2008-9, while the corresponding share of natural gas has declined since 2010. The share of coal and lignite fluctuates but follows a – mostly – declining trend (i.e. 31,26% in 1997 and 26,38% in 2013). The situation is similar for nuclear energy, whose share fluctuated between 32,82% in 1997 and 26,8% in 2013.

In contrast to all the above-mentioned energy sources, the share of RES gross electricity generation in EU-28 has risen steadily. With a small setback in 2002-3, when the share of RES slightly decreased (from 15,27% in 2001 to 13,63% in 2003), the share of RES is an exception compared to all other energy sources. Overall, the share of RES has doubled from 12,61% in 1990 to 27,16% in 2013. In 2020, electricity generation from RES reached a new record, accounting for over 38% of total electricity generated in the EU.[300] The 2020 target was surpassed, as RES accounted for 22,1% of the energy consumed in the EU.[301]

Hydropower has traditionally accounted for the largest share of electricity generation by RES, followed by wind energy. Solar energy (including thermal, photovoltaic, and concentrated) is considered the 'fastest-growing energy source'.[302] Despite the fact that PV are not reported

---

[298] SolarPower Europe, 14 July 2022, *pv-magazine*, Key European Parliament Committee says Yes to 45% RES!, Available online: https://www.pv-magazine.com/press-releases/key-european-parliament-committee-says-yes-to-45-res/, (accessed 15 July 2022).

[299] EcoGreen Energy, 27 May 2022, *EcoGreen Energy*, Solar Energy Deployment in EU 2030, Available online: https://www.eco-greenenergy.com/solar-energy-deployment-in-eu-2030-global-energy-crisis/, (accessed 1 June 2022).

[300] Please note that RES's share was calculated for EU-27 and not EU-28. The data were drawn from: Agora Energiewende and Ember, "The European Power Sector in 2020: Up-to-Date Analysis on the Electricity Transition", 2021.

[301] Eurostat, (January 2022), *Renewable energy statistics*, Europa. Available online: (https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics) (accessed 18 March 2022).

[302] Eurostat, (January 2022), *Renewable energy statistics*, Europa. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics, (accessed 18 March 2022).

separately, based on the actual market growth and projected growth, electricity generation from PV is expected to increase in the EU.[303]

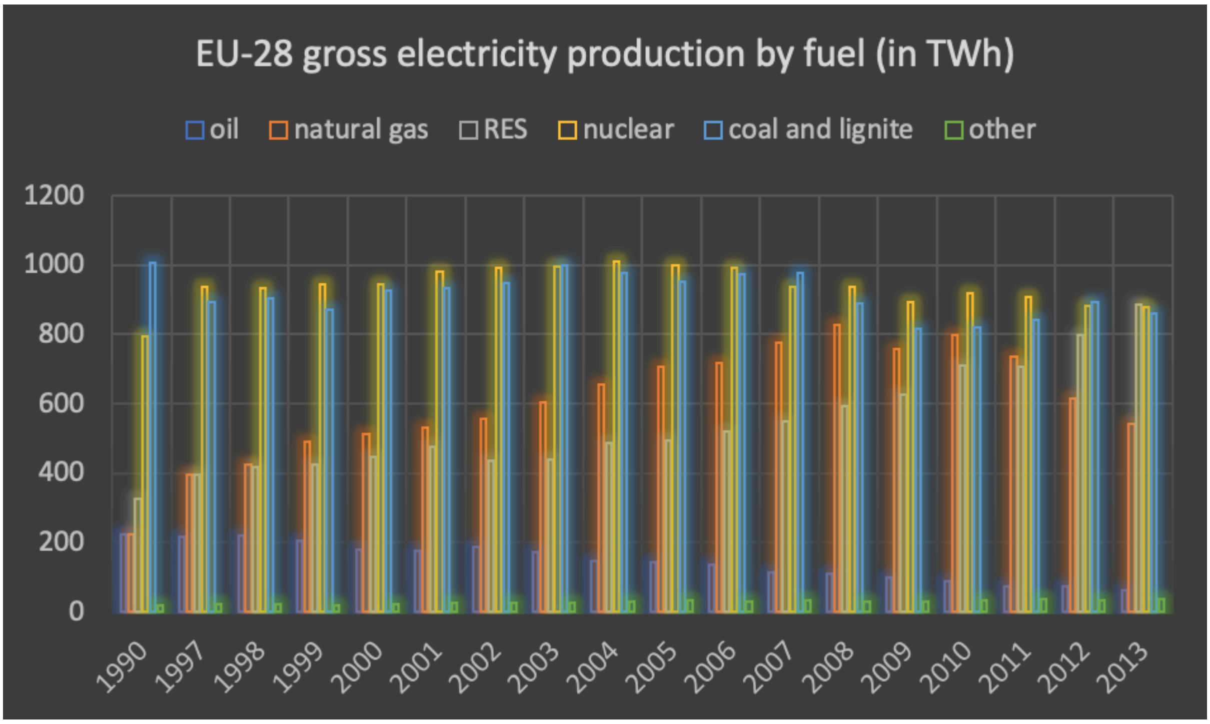


Figure 3.1 EU-28 gross electricity production (in TWh) per fuel, 1990-2013. (Adapted from: European Environment Agency, (archived 15 December 2016), "*Indicator Assessment: Overview of electricity production and use in Europe*", EEA Europa. Available online: https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-1/assessment, (accessed 15 November 2021).[304]

However, as we analyse in chapter 7, not all member states have 'embraced' or 'seized' the full potential of PV (small-scale installations). It therefore remains to be seen how individual member states will react to the current energy crisis, also in terms of the type of PV installations they will promote.

3.2 Concluding remarks

Energy and energy resources have always been at the heart of the EU and its predecessors. Energy crises have, overall, been impactful in redirecting 'interest' from one energy source to another. The oil crises of the 1970s sparked the need to reduce dependence on oil and paved the way for (further) diversification of the energy mix of member states, with each member

---

[303] Data on the PV market growth, actual and expected see: Jäger-Waldau Arnulf, *PV Status Report 2021,* Publications Office of the European Union (Luxembourg: 2021).
[304] Natural and derived gas.

state making a different choice (e.g. natural gas, nuclear energy etc.). As the EU is increasing dependent on natural gas imports, especially from Russia, the current energy crisis has led to the need to rethink the EU's long-term energy strategy. In this context, RES and in particular PV are expected to play an important role in the EU's energy future driving the faster implementation of the transition to RES in the EU.

The European Commission has made several attempts to attain more powers in energy policy and to design an EU-wide common energy policy. The European Commission has instrumentalized its capacities and powers in environmental policy and the internal market (smart metering) for this 'goal'. Crises – whether energy or environmental – have provided fruitful 'moments' in which the European Commission has been active (and to some extent successful) in acquiring more powers. One such 'moment' was in the 1970s, when the European Commission designed an energy policy strategy in response to the oil crises and called for a disentanglement from oil dependency. Another critical moment was in 1997 with the White Paper for RES. This White Paper was followed by a series of Directives that first set indicative targets for RES and, after the Treaty of Lisbon, binding targets for RES. This White Paper gave the European Commission more powers in energy policy-making. It comprised an extension of the European Commission's powers in energy policy through the successful linking of RES technologies in response to an environmental crisis (climate change). This successful 'linkage' (RES technologies and environmental policy) enabled the European Commission to gain powers in energy policy. Essentially, environmental policy and RES formed the medium for the European Commissions' expanded role in energy policy. The role of certain actors was crucial, without political support, the goals of the White Paper would not have been achieved. Furthermore, RES gained legitimacy within the energy policy map with the White Paper. At the same time, with the White Paper, the European Commission gave the sector of RES the green light to become industrial (in terms of production). With the Treaty of Lisbon, the EU competences in the field of energy policy were expanded. However, this happened at a time when the role of the Commission was minimized compared to the Parliament and the Council, while the sovereignty of member-states was restored; member states retained their right to decide on their energy supply.

RES technologies allow energy policy to move beyond the current (and dominant) centralized electricity generation. They offer the possibility to transition to distributed and decentralized electricity generation and consumption. They have the potential to actively reconfigure the electricity grid(s) and the functioning of the electricity market, while constructing new users (prosumers). Without these technologies, it would not have been possible to develop the current

EU long-term energy strategy in which users/consumers are envisioned to play an important and active role in transforming the energy system as a whole. Although RES technologies offer the possibility to move towards distributed and decentralized generation and consumption, which is advocated by the EU, their potential is not being fully realised. This is especially true for small-scale PV systems, which pave the way to distributed generation and consumption. Member states' sovereignty in this area (i.e. energy policy) seems to lead to different paths, as national energy policy, traditions and interests lead to different choices.

The climate crisis put pressure on the reconfiguration of the energy system, while the current and ongoing energy crisis adds to this urgency. The decisions taken, especially by the EU, give a clear priority to RES and especially to PV. However, while member-states seek to address the energy crisis, ensure energy security and relief their economies, the reality is parting ways from the vision. To meet their immediate energy needs – also in the midst of a very hot summer – many member states 'go back to basics' (i.e. fossil fuels and (potentially) nuclear energy). It remains to be seen what the future holds, both for the energy crisis and for the transition to RES.

References

Abnett Kate, 23 June 2022, *Reuters*, A dozen EU countries affected by Russian gas cuts, EU climate chief says, Available online: https://www.reuters.com/business/energy/russian-gas-cuts-have-hit-12-countries-eu-climate-chief-says-2022-06-23/, (accessed 30 June 2022).

Agora Energiewende and Ember, *The European Power Sector in 2020: Up-to-Date Analysis on the Electricity Transition*, 2021.

Bösch Frank and Graf Rüdiger, "Reacting to Anticipations: Energy Crises and Energy Policy in the 1970s. An Introduction*", Historical Social Research*, 2014, p. 7-21.

Boyle Miriam J. and Robinson M. E., "French Nuclear Energy Policy", *Geography*, 1981, p. 300-303.

Breyer Ch., Birkner C, Kersten F., Gerlach A., Goldschmidt J. C., Stryi-Hipp G., Montoro Fraile D., Riede M., "Research and Development Investments in PV: a limiting factor for a fast PV diffusion?", 25th European Photovoltaic Solar Energy Conference / 5th World Conference on Photovoltaic Energy Conversion, Proceedings of the International Conference held in Valencia, Spain, 6-10 September 2010, G. F. de Santi, H. Ossenbrink and P. Helm (eds.), WIP Renewable Energies (Germany: 2010), p. 5385-5408.

Browning Noah and Buli Nora, 22 June 2022, *Reuters*, EU signals shift to coal, accuses Russia of 'rogue moves' on gas', Available online: https://www.reuters.com/business/energy/russian-gas-flows-europe-via-nord-stream-ukraine-unchanged-2022-06-22/, (accessed 30 June 2022).

Cailleau Julie, "Energy: from synergies to merger", *in* The European Commission 1958-72: History and memories of an institution, Publications Office of the European Union (Luxembourg: 2014), p. 471-490.

Christoforidis Georgios C., Panapakidis Ioannis P., Papadopoulos Theofilos A., Papagiannis Grigoris K., Koumparou Ioannis, Hadjipanayi Maria and Georghiou George E., "A Model for the Assessment of Different Net-Metering Policies", *Energies*, 2016, p. 1-24.

Comello Stephen and Reichelstein Stefan, "Cost competitiveness of residential solar PV: The impact of net metering restrictions", *Renewable and Sustainable Energy Reviews*, 2017, p. 46-57.

Commission of the European Communities, *White Paper: An Energy Policy for the European Union*, COM (95) 682 final, Brussels, 13.12.1995.

Commission of the European Communities, *Communication from the Commission ENERGY FOR THE FUTURE: RENEWABLE SOURCES OF ENERGY White Paper for a Community Strategy and Action Plan*, COM (97) 599 final, Brussels, 26.11.1997.

Commission of the European Communities, *Communication from the Commission to the European Council and the European Parliament – An Energy Policy for Europe*, COM(2007) 1 final, Brussels, 10.1.2007.

Council Resolution of 17 December 1974 concerning Community energy policy objectives for 1985, Official Journal of the European Communities, 9.7.1975.

Council Resolution of 16 September 1986 concerning new energy policy objectives for 1995 and convergence of the policies of the Member States (86/C 240/01), Official Journal of the European Communities, 25.09.1986.

Darghouth Naim R., Barbose Galen, Wiser Ryan, "The impact of rate design and net metering on the bill savings from distributed PV for residential customers in California", *Energy Policy*, 2011, p. 5243-5253.

Debata Byomakesh, Patnaik Pooja, Mishra Abhisek, "COVID-19 pandemic! It's impact on people, economy, and environment", *Journal of Public Affairs*, 2020, p. 1-20.

DGXVII, *Thermie-Altener Renewable Energy Report*, Office for Official Publications of the European Communities (Luxembourg: 1998).

Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity, Official Journal of the European Communities, 30.1.1997.

Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market, Official Journal of the European Communities, 27.10.2001.

Directive 2003/54/EC of the European Parliament and of the Council of 26 June 2003 concerning common rules for the internal market in electricity and repealing Directive 96/92/EC, Official Journal of the European Union, 15.7.2003.

Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, Official Journal of the European Union, 5.6.2009.

Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC, Official Journal of the European Union, 14.08.2009.

Directive (EU) 2019/944 of the European Parliament and of the Council of 7 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EC (recast), Official Journal of the European Union, 14.06.2019.

Dufo-Lopez Rodolfo and Bernal-Agustin Jose L., “A comparative assessment of net metering and billing policies. Study cases for Spain”, *Energy*, 2015, p. 684-694.

Dusonchet Luigi and Telaretti Enrico, “Comparative economic analysis of support policies for solar PV in the most representative EU countries”, *Renewable and Sustainable Energy Reviews*, 2015, p. 986-998.

Dutta Prasanta Kumar, Granados Samuel and Ovaska Michael, 16 February 2022, *Reuters*, Ukraine crisis: Russian gas threat in Europe, Available online: https://graphics.reuters.com/UKRAINE-CRISIS/GAS/gdpzynlxovw/, (accessed 14 July 2022).

EcoGreen Energy, 27 May 2022, *EcoGreen Energy*, Solar Energy Deployment in EU 2030, Available online: https://www.eco-greenenergy.com/solar-energy-deployment-in-eu-2030-global-energy-crisis/, (accessed 1 June 2022).

Eid Cherrelle, Guillén Javier Reneses, Marín Pablo Frías, Hakvoort Rudi, “The economic effect of electricity net-metering with solar PV: Consequences for network cost recovery, cross subsidies and policy objectives”, *Energy Policy*, 2014, p. 244-254.

El Bassam Nasir, Maegaard Preben, Schlichting Marcia Lawton, Scope of the Book, *in* Distributed Renewable Energies for Off-Grid Communities, El Bassam Nasir, Maegaard Preben, Schlichting Marcia Lawton (eds.), 1st Edition, Elsevier (Oxford, UK: 2013), p. 1-6.

European Commission – Directorate General for Energy, *Energy in Europe: Energy policies and trends in the European Community*, Office for Official Publications for the European Communities (Luxembourg: 1989).

European Commission, *Communication from the Commission Climate Change – The EU Approach to Kyoto*, COM (97) 481 final, 1 October 1997.

European Commission – DG for Research Sustainable Energy Systems, *European Smart Grids Technology Platform: Vision and Strategy for Europe’s Electricity Networks of the Future*, Office for Official Publications of the European Communities (Luxembourg: 2006).

European Commission, *A Roadmap for moving to a competitive low carbon economy in 2050*, Brussels, 8.3.2011, COM (2011) 112 final.

European Commission, *Report from the Commission – Benchmarking smart metering deployment in the EU-27*, Final Report, COM(2014) 356 final, Brussels, 17.6.2014.

European Commission, *Report from the Commission to the European Parliament and the Council Progress Towards Achieving the Kyoto and EU 2020 Objectives*, COM(2014) 689 final, Brussels, 28.10.2014.

European Commission, *A Clean Planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*, COM (2018) 773 final, Brussels, 28.11.2018.

European Commission, Directorate-General for Climate Action, *Going climate-neutral by 2050: a strategic long-term vision for a prosperous, modern, competitive and climate-neutral EU economy*, Publications Office of the European Union (Luxembourg: 2019).

European Commission, *The European Green Deal*, COM (2019) 640 final, Brussels, 11.12.2019.

European Commission – JRC, [last updated on 19 July 2022], Europa, *Smart Metering deployment in the European Union*, Available online: https://ses.jrc.ec.europa.eu/smart-metering-deployment-european-union, (accessed 20 July 2022).

European Commission, Europa, *Strategic Energy Technology Plan*, Available online: https://energy.ec.europa.eu/topics/research-technology-and-innovation/strategic-energy-technology-plan_en#european-technology-and-innovation-platforms, (accessed 14 March 2022).

European Environment Agency, (archived 15 December 2016), EEA Europa, "*Indicator Assessment: Overview of electricity production and use in Europe*", Available online: https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-1/assessment, (accessed 15 November 2021).

Eurostat, (January 2022), Europa, *Renewable energy statistics*, Available online: (https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics) (accessed 18 March 2022).

Firstman S. I. and Vachtsevanos G. J., "Distributed Photovoltaic Systems: addressing the utility interface issues", *in* Fifth EC Photovoltaic Energy Conference, Proceedings of the International Conference held at Kavouri, Athens, Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 424-431.

Fouquet Roger and Pearson Peter J. G., Editorial "Past and Prospective energy transitions: Insights from history", *Energy Policy*, 2012, p. 1-7.

Hanke Florian, Guyet Rachel, Feenstra Marielle, "Do renewable energy communities deliver energy justice? Exploring insights from 71 European cases", *Energy Research & Social Sciences*, 2021, 102244.

Hermann Scheer, 2014, *About Hermann Scheer*, Hermann Scheer. Available online: http://www.hermannscheer.de/en/, (accessed 10 January 2020).

Hoffman Jesse, Davies Megan, Bauwens Thomas, Spath Philipp, Hajer Maarten A., Arifi Bleta, Bazaz Amir, Swilling Mark, "Working to align energy transitions and social equity: An integrative framework linking institutional work, imaginaries and energy justice", *Energy Research & Social Sciences*, 2021, 102317.

Jäger-Waldau A., *PV Status Report 2018*, Publications Office of the European Union (Luxembourg: 2018).

Jäger-Waldau Arnulf, *PV Status Report 2021,* Publications Office of the European Union (Luxembourg: 2021).

Jegen Maya, "Energy policy in the European Union: The power and limits of discourse", *Les cahiers européens de Sciences Po*, n°2, 2014.

Jenkins Kristen, McCauley Darren, Heffron Raphael, Stephan Hannes, Rehner Robert, "Energy justice: A conceptual review", *Energy Research & Social Sciences*, 2016, p. 174-182.

Kanellakis M., Martinopoulos G., Zachariadis T., "European energy policy: A review", *Energy Policy*, 2013, p. 1020-1030.

Knox Stephen, Hannon Matthew, Stewart Fraser, Ford Rebecca, "The (in)justices of smart local energy systems: A system review, integrated framework, and future research agenda", *Energy Research & Social Sciences*, 2022, 102333.

Koutantou Angeliki and Triandafyllou Vassilis, 16 June 2022, *Reuters*, In a Greek coal mine, stocks build up ahead of peak summer demand, Available online: https://www.reuters.com/business/energy/greek-coal-mine-stocks-build-up-ahead-peak-summer-demand-2022-06-16/, (accessed 30 June 2022).

Laird Frank N. and Stefes Christoph, "The diverging paths of German and United States policies for renewable energy: Sources of difference", *Energy Policy*, 2009, p. 2619-2629.

Langsdorf Susanne, *EU Energy Policy: From the ECSC to the Energy Roadmap 2050*, Green European Foundation, December 2011.

McGowan Francis, "Can the European Union's Market Liberalism Ensure Energy Security in a Time of 'Economic Nationalism'?", *Journal of Contemporary European Research*, 2008, p. 90-106.

McGowan Francis, "Putting Energy Insecurity into Historical Context: European Responses to the Energy Crises of the 1970s and 2000s", *Geopolitics*, 2011, p. 486-511.

Nakopoulou Efi and Arapostathis Stathis, "Reconfiguring Technologies by Funding Transitions: priorities, policies, and the renewable energy sources in the European Community funding schemes", *Journal of Energy History/Revue d'Histoire de l'Énergie* [Online], n°4, published 27 July 2020.

Nugent Neil, “Policies”, *in The Government and Policies of the European Union,* Neil Nugent and William E. Paterson (eds.), Palgrave Macmillan (Basingstoke: 2006), p. 351-391.

Palz Wolfgang, *The Triumph of the Sun: The Energy of the New Century*, Wolfgang Palz (eds.), Pan Stanford Publishing (Singapore: 2018).

Regulation (EU) No 1291/2013 of the European Parliament and the Council of 11 December 2013 establishing Horizon 2020 – the Framework Programme for Research and Innovation (2014-2020) and repealing Decision No 1982/2006/EC, 20.12.2013, Official Journal of the European Union, p. 104-173.

Reuters, 27 June 2022, *Reuters*, G7 leaders debate fossil fuel investments amid energy crisis, Available online: https://www.reuters.com/world/g7-leaders-debate-fossil-fuel-investments-amid-energy-crisis-sources-2022-06-26/, (accessed 30 June 2022).

Reuters Staff, 11 January 2009, *Reuters*, TIMELINE: Gas crises between Russia and Ukraine, Available online: https://www.reuters.com/article/us-russia-ukraine-gas-timeline-sb-idUSTRE50A1A720090111, (accessed 10 June 2022).

Rüdiger Mogens, “From import dependence to self-sufficiency in Denmark, 1945−2000”, *Energy Policy*, 2019, p. 82-89.

Rusche Tim, “The European climate change program: An evaluation of stakeholder involvement and policy achievements”, *Energy Policy*, 2010, p. 6349-6359.

Scheer Hermann, “Welcome Address”, *in* Thirteenth European Solar Energy Conference, Proceedings of the International Conference held at Nice, France, 23-27 October 1995, W. Freiesleben, W. Palz, H. A. Ossenbrink and P. Helm (eds.), Vol. I, H. S. Stephens & Associates (UK: 1995), p. xxxvii-xxxviii.

Scheer Hermann, “Foreword” *in* Feed-in Tariffs: Accelerating the Deployment of Renewable Energy, Miguel Mendonca, Earthscan (UK and USA: 2007), p. x-xii.

Scheer Hermann, “Initiating a Solar Revolution in Germany”, *in* Solar Power for the World, Wolfgang Palz (eds.), (Pan Stanford: US, 2014), p. 287-300.

Schmid J., “Photovoltaic System Design”, *in* Fifth EC Photovoltaic Energy Conference, Proceedings of the International Conference held at Kavouri, Athens, Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 410-416.

Schumacher Elisabeth, 23 June 2022, *Deutsche Welle*, Available online: https://www.dw.com/en/will-germany-return-to-nuclear-power/a-62223935, (accessed 30 June 2022).

SET-Plan TWP PV Implementation Plan – Final Draft (Approved by TWG members), 18 October 2017.

SolarPower Europe, 14 July 2022, *pv-magazine*, Key European Parliament Committee says Yes to 45% RES!, Available online: https://www.pv-magazine.com/press-releases/key-european-parliament-committee-says-yes-to-45-res/, (accessed 15 July 2022).

Song Ligang and Zhou Yixiao, "The COVID-19 Pandemic and Its Impact on the Global Economy: What Does It Take to Turn Crisis into Opportunity?", *China and World Economy*, 2020, p. 1-25.

Sovacool Benjamin K. and Dworkin Michael H., "Energy justice: Conceptual insights and practical applications", *Applied Energy*, 2015, p. 435-444.

Sovacool Benjamin, "The history and politics of energy transitions: Comparing contested views and finding common ground", WIDER Working Paper No. 2016/81, 2016, ISBN 978-92-9256-124-6, The United Nations University World Institute for Development Economics Research (UNU-WIDER), Helsinki, https://doi.org/10.35188/UNU-WIDER/2016/124-6.

Stern Jonathan, "Natural Gas Security Problems in Europe: the Russian-Ukrainian Crisis of 2006", *Asia-Pacific Review*, 2006, p. 32-59.

Stern Jonathan, The Russian-Ukrainian gas crisis of January 2006, *Oxford Institute for Energy Studies*, 16 January 2006.

Tachmintzis Joanna of Mr Papoutsis' Cabinet on behalf of the European Commissioner for Energy, Christos Papoutsis, "Welcome Address", Thirteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Nice, France, 23-27 October 1995, W. Freiesleben, W. Palz, H. A. Overstraeten, P. Helm (eds.), Vol. I, H. S. Stephens & Associates (UK: 1995), p. xxxvi-xxxvii.

Thaler Philipp, "The European Commission and the European Council: Coordinated Agenda setting in European energy policy", *Journal of European Integration*, 2016, p. 571-585.

The European Association for Renewable Energy, *Our mission & history*, Eurosolar. Available online: https://www.eurosolar.de/en/index.php, (accessed 15 January 2020).

Todorović Igor, 11 March 2022, *Balkan Green Energy News*, Europe switching on coal plants amid energy crisis, Available online: https://balkangreenenergynews.com/europe-switching-on-coal-plants-amid-energy-crisis/, (accessed 30 June 2022).

Tonini Alberto, "The EEC Commission and European Energy Policy: A Historical Appraisal", *in* Rosella Bardazzi, Maria Grazia Pazienza, Alberto Tonini (eds.), *European Energy and Climate Security: Public Policies, Energy Sources, and Eastern Partners* (New York, London: Springer, 2016), p. 13-35.

Tosun Jale, Biesenbender Sophie, Schulze Kai (eds.), *Energy Policy Making in the EU: Building the Agenda*, Springer (London: 2015).

Treaty of Lisbon amending the Treaty on European Union and the Treaty establishing the European Community, Official Journal of the European Union, 17.12.2007, Available online: http://publications.europa.eu/resource/cellar/688a7a98-3110-4ffe-a6b3-8972d8445325.0007.01/DOC_19

Twidale Suzzane, 29 June 2022, *Reuters*, EU race to fill gas storage draws record supplies from Britain, Available online: https://www.reuters.com/markets/europe/eu-race-fill-gas-storage-draws-record-supplies-britain-2022-06-29/, (accessed 30 June 2022).

Umblach Frank, "Global energy security and the implications for the EU", *Energy Policy*, 2010, p. 1229-1240.

United Nations, "Paris Agreement", 2015 (https://unfccc.int/sites/default/files/english_paris_agreement.pdf).

United Nations Climate Change, *United Nations Climate Change*, What is the Kyoto Protocol?, Available online: https://unfccc.int/kyoto_protocol%26from%3D, (accessed 10 June 2019).

United States Environmental Protection Agency, (last updated 23 June 2022), *Distributed Generation of Electricity and its Environmental Impacts*, EPA, Available online: https://www.epa.gov/energy/distributed-generation-electricity-and-its-environmental-impacts, (accessed 25 June 2022).

Vachtsevanos G. J., Meliopoulos A. P., Paraskevopoulos B. K., "Distributed photovoltaic system impact upon utility load/supply management practices", *in* Fifth EC Photovoltaic Energy Conference, Proceedings of the International Conference held at Kavouri, Athens, Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 383-392.

Wolsink Maarten, "Dutch wind power policy: Stagnating implementation of renewables", *Energy Policy*, 1996, p. 1079-1088.

Zahedi Ahmad, "Solar photovoltaic (PV) energy; latest developments in the building integrated and hybrid PV systems", *Renewable Energy*, 2006, p. 711-718.

Chapter 4. The PV sector was built on c-Si: the dominance of the Northern European semiconductor electronics industry

4.1 Introduction

In this chapter we analyse the EU funded R&D activities and technoscientific networks for flat plate c-Si during the first period (1975-1998).[305] The first network(s) emerged in the 1980s (FP1). Therefore, we analyse the previous programmes (separately) to trace continuities and discontinuities in the actors involved in the research activities.

The analysis of our empirical case-studies is divided into two periods. The criterion for this periodization is the changing relationship between EU research, energy and industry policy, focusing on how this relationship impacted the character of research, the research agenda and priorities. The first period begins in 1975 and ends in 1998 (this chapter). It marks the beginning of an EU-wide research policy and R&D efforts towards RES – including PV. During the first period, research policy was directed by industrial policy. Although an energy crisis was the trigger for initiating energy R&D programmes, the EC did not have the legislative powers to implement an EU-wide energy policy. Each member state designed its own energy policy and the EC developed an energy policy strategy to respond to the oil crisis.[306,307]

The goals of the EC energy strategy were to take measures to reduce oil dependence, to ensure energy security.[308] These objectives were reinforced during the 1979 oil crisis. It was in this context that the Commission launched the first Energy R&D Programme in 1975 to explore potentially viable energy options, such as RES. The immediate energy needs of the member

---

[305] The first period covers the following EU R&D programmes: first energy R&D programme (1975-1978), second energy R&D programme (1979-1983), first Framework Programme (FP1) (1985-1988), second Framework Programme (FP2) (1988-1991), third Framework Programme (FP3) (1990-1994), and fourth Framework Programme (FP4) (1994-1998). In Chapter 5 we analyse the second period (1999-2013).

[306] Tonini Alberto, "The EEC Commission and European Energy Policy: A Historical Appraisal", *in* Rosella Bardazzi, Maria Grazia Pazienza, Alberto Tonini (eds.), *European Energy and Climate Security: Public Policies, Energy Sources, and Eastern Partners*, Springer (New York, London: 2016), p. 13-35.; Nugent Neil, "Policies", *in The Government and Policies of the European Union*, Neil Nugent and William E. Paterson (eds.), Palgrave Macmillan (Basingstoke: 2006), p. 351-391.; Commission of the European Communities, *Energy in Europe: Energy policies and trends in the European Community*, Office for Official Publications of the European Communities (Luxembourg: 1989), p. 6.

[307] Both strategy and policy set targets to be achieved through objectives. The two terms are used to indicate the changes in the acquired institutional powers of the EC. Thus, we employ the term strategy to denote the lack of 'tools' required and/or presupposed to reinforce the necessary actions taken towards achieving the targets at an EC level (i.e. the EC did not have the institutional tools to implement the objectives in the member-states). In contrast, policy indicates that the required 'tools' for implementing the actions necessary exist (the EC acquires more powers that enable the implementation of the objectives in the member states).

[308] Council Resolution of 17 December 1974 concerning Community energy policy objectives for 1985 (C. 153), Official Journal of the European Communities, 9.7.1975.

states were not to be met through RES. Rather, mainly nuclear energy and natural gas were to satisfy the energy needs of the member states.[309,310] Each member state drew from their cultural and geographical specificities to replace oil. In this context, different choices were made (e.g. Germany coal and nuclear energy, France nuclear energy, Denmark coal and natural gas etc.).[311] The choices and priorities for RES were also different (Germany, France and Italy mainly PV and wind energy, Denmark and the Netherlands wind energy).[312] Since the mid-1980s and throughout the 1990s, public funding for RES witnessed a decline worldwide. The only exception that briefly boosted the R&D for RES was the Chernobyl disaster.[313]

We start our analysis with the main trigger for the initiation of R&D activities in PV and the relationship between research policy and industrial policy in setting research priorities and activities. As the first networks were formed in FP1, in sections 4.2.2-4.2.4 we examine and analyse the first ten years of PV research and the research actors separately. Next, in section 4.2.5, we analyse the research priorities and funding of FP1, which represents a break in terms of the technological prioritization of the whole first period. In this context, we analyse the events that led to this shift in FP1 and place them historically. From FP2 onwards and until the end of the first period (FP4), research funding ‘returned’ to c-Si, as the main technological frontrunner. In section 4.2.7, we analyse the reasons for this shift and the distribution of R&D funding for c-Si (both geographically and technologically), and elaborate on the actors that form the technoscientific research networks for c-Si. Before reaching our conclusions, we examine the relationship between research and energy policy during the first period by delineating the pilot, research, and demonstration components of the EU programmes.

---

[309] Council Resolution of 17 December 1974 concerning Community energy policy objectives for 1985 (C. 153), Official Journal of the European Communities, 9.7.1975.

[310] Council Resolution of 16 September 1986 concerning new energy policy objectives for 1995 and convergence of the policies of the Member States (86/C 240/01) (C. 241), Official Journal of the European Communities, 25.09.1986.

[311] Frank Laird, Christoph Stefes, “The diverging paths of German and United States policies for renewable energy: Sources of difference”, *Energy Policy*, 2009, p. 2619-2629.; Miriam J. Boyle, M. E. Robinson, “French Nuclear Energy Policy”, *Geography*, 1981, p. 300-303.; Mogens Rüdiger, “From import dependence to self-sufficiency in Denmark, 1945−2000”, *Energy Policy*, 2019, p. 82-89.

[312] Maarten Wolsink, “Dutch wind power policy: Stagnating implementation of renewables”, *Energy Policy*, 1996, p. 1079-1088.

[313] Breyer Ch., Kersten F., Gerlach A., Goldschmidt Jan, Stryi-Hipp Gerhard, Montoro D.F., Riede Moritz, “Research and Development Investments in PV: a limiting factor for a fast PV diffusion?”, *in* 25th European Photovoltaic Solar Energy Conference /5th World Conference on PV Energy Conversion, Proceedings of the International Conference held in Valencia, Spain, 6-10 September 2010, G. F. De Santi, H. Ossenbrink and P. Helm (eds.), WIP Renewable Energies: 2010, p. 5385-5408.

4.2 The initiation of PV research as a response to the energy crises: the directionality of the semiconductor electronics in selecting the dominant semiconductor

In direct response to the 1973 oil crisis, the first energy R&D programme was launched by the EC. The first energy R&D programme involved research into energy sources beyond the insofar reach of the EC (i.e. fossil fuels, renewables). Among all renewable energy sources (RES), PV enjoyed a favourable position in terms of funding; it ranked first until the start of FP6.[314] This prioritization of PV over all other RES is explained by how the EC understood this technology: as a technology best suited to the North-Western European climate.[315]

The research for PV included several semiconductors for the solar cell, but c-Si (flat-plate) always received the largest share of the EC R&D funds.[316] C-Si was the (funding) frontrunner of the EC PV R&D programmes from 1975 to 2002; the only exception was the temporary a-Si shift during FP1. Both the distribution of funding and the comments of EC officials show that the EU R&D programmes and the PV market were built around this semiconductor. This R&D 'trend' remained unchanged until the second period. C-Si is still the dominant technology with a market share of about 90%.[317]

In this section we analyse the research projects funded under the two energy R&D programmes.[318] Both programmes acted as the EC's response to the oil crises (i.e. the 1973 and 1979 oil crises). Furthermore, they cover the early stages of the development of the PV field in Europe and allow us to trace and identify the knowledge base on which European PV research was built. As we argue, actors from the semiconductor electronics field directed research for PV and actively shaped the research priorities for this newly created field. We follow the transfer of knowledge from the field of semiconductor electronics to the field of PV. This knowledge transfer has been instrumental in (a) defining and/or creating the knowledge base of the PV field, (b) determining the dominant material for PV solar cells/modules, (c) directing the research agenda for PV, and (d) constructing the market for PV. Moreover, the selection of semiconductors for the solar cell led to marginalization and exclusion, while this is similar for the prioritization of a particular PV design.

---

[314] Regarding this point see chapter 2.

[315] We analyse this point extensively in chapter 2.

[316] This gradually changed during the second period. We extensively analyse this point in a forthcoming section of the present chapter.

[317] Arnulf Jäger-Waldau, *PV Status Report 2019*, Publications Office of the European Union (Luxembourg: 2019).

[318] The pilot projects are analysed separately. Regarding the distinction between pilot-research-demonstration and the concurrent justification of their discrete analysis see corresponding section in this Chapter.

It was not until the second energy R&D programme (1980s) that the first transnational collaborative research networks emerged. These networks were the result of the first pilot programme, promoted by the EC, which aimed to construct a market for the actors. As we analyse in a forthcoming section, we distinguish between research and pilot projects. Although both are components of the R&D programmes, they differ in the way they pursue the R&D aim.

It should noted that although cooperation has been established since the first energy R&D programme, it took place at national level. It was not until FP1 that the first transnational collaborative research networks were formed. For this reason, we analyse the first two energy R&D programmes separately. FP1 signalled a significant shift in funding towards responding to Japanese competition. FP1 redirected R&D funding to a-Si, while for the remainder of the first period research turned back to the basics (i.e. funding prioritized c-Si). Therefore, FP1 is examined separately as the analysis reflects the shift in EC R&D funding.

4.2.1 Instrumentalizing research: the directionality of industrial policy in research policy

Throughout the first period, the R&D programmes aimed to strengthen the scientific and technological base of the European industry. In the case of c-Si this was achieved by conducting research that primarily pursued two interrelated objectives: increasing cell efficiency while decreasing the corresponding costs. This objective, which we analyse in detail in the corresponding section of the second period, comprises an industrial rationale. This rationale was incorporated into the research activities of the universities and research centres and comprised the point of directionality of the industrial policy towards research policy. To this end, various methods and techniques were researched, mainly originating from the electronics industry (e.g. ion implantation). In addition, the projects aimed to reduce the cost of PV by researching new processing steps (e.g. for the feedstock), simplification of manufacturing steps, development of cost effective (cell) manufacturing processes etc. While the universities and research centres dealt with the industrial process(es), the two 'spaces' remained separate.

During the first period, the majority of projects focused on solar cell research. Projects that had a different research focus (e.g. feedstock, wafer, ingot, module etc.) were – primarily – a response to the direct and urgent needs of the PV industry. For example, there were projects that conducted research on feedstock during the silicon feedstock shortage in the 1980s.[319] But it was only towards the end of the first period that the rare (two projects) inclusion of more parts of the PV system were researched in a single project. Research essentially distinguished the different components of the PV system and mainly focused on a single component of the PV system: the solar cell.[320]

The research on c-Si in the first period can be described as explorative. Even though the focus was on the development of different production steps and processes and the main objective of the projects was the cost-efficiency relationship, it included theoretical and experimental studies as well as the development of new and novel concepts – mainly for the solar cell. Thus, although research was directed by an industrial rationale, materializing through the cost-efficiency relationship, it remained exploratory. In this context, universities carried out studies, focused on obtaining data and collecting information, made measurements etc.

The majority of pilot projects involving actual PV installations were funded in the first ten years.[321] They involved either small scale (up to 5kW) or larger-scale systems (30-300kW).[322,323] Despite the lack of characterization of these systems, their applications and uses varied. From stand-alone to grid-connected PV systems, these installations ranged from powering a TV/FM transmitter to supplying electricity to villages.[324] These pilots were mostly coordinated by companies (76,2%), while research centres, universities and electric utilities also coordinated a smaller number of pilots.[325] The pilot projects, especially those funded under the second energy R&D programme, aimed as constructing a market for the European PV industry. In this way, research in the first period ‘approached’ the market.

The R&D programmes aimed to provide a basis for cooperation between member states and their various actors (e.g. universities, research centres etc.). The R&D programmes supported

---

[319] We analyse this event in depth in chapter 7.

[320] Other system components, such as inverters, converters, batteries etc. remained distinct. These system components received funding under the pilot projects. However, in these projects we see, again, that the focus is on a single system component.

[321] The following pilot projects were fewer in number and primarily consisted of either the continuation of the previous pilot projects (e.g. making improvements, follow-ups etc.) or studies based on the previously installed PV. This can be primarily attributed to the emergence of the demonstration programmes, which were overseen by the DGXVII.

[322] During the first energy R&D programme, a series of feasibility studies were conducted for the so-called ‘intermediate systems’. These systems ranged from 0,5-1MW, however such scale systems were never installed. Additionally, the 30-300kW systems were not characterised explicitly based on scale (i.e. large or small scale) but were referred to as power plants.

[323] The small-scale installations took place during the first energy R&D programme, whereas the larger scale projects were funded under the second energy R&D programme.

[324] We do not include in the analysis (or any of the calculations) projects that concerned the installation of hybrids (i.e. more than one power source) or that did not explicitly concern electrification (e.g. water pumping).

[325] The universities coordinated a smaller number of pilots (9,5%) like that of the electric utilities (9,5%), whereas the research centres accounted only for a marginal share (4,7%).

the international competitiveness of the European PV industry. This was done either by providing funds to strengthen the scientific and technological base of the PV industry or by redirecting funds to respond even more directly to competition. C-Si received most of the funding to strengthen the European PV industry and enable it to compete with its US and Japanese counterparts. During FP1, the EC redirected its R&D funds to a-Si, targeting Japanese competition. In this way, research supported the industry during the first period. Towards the end of the period, a small number of projects also conducted research related to standards (e.g. certification procedures for building integrated PV).[326]

4.2.2 Laying the foundations: the first ten years of PV research

In the first ten years of EC PV research, a total of forty-six (46) projects were funded for c-Si. Figure 4.1 (below) shows that c-Si funding was distributed among actors from eight countries. In particular, c-Si R&D funding was allocated to actors from France, the Netherlands, Belgium, Italy, Denmark, Germany, the United Kingdom, and Greece.[327,328] The French actors concentrated almost half of the c-Si R&D funding (44,1%), followed by the Dutch (19,3%), the Belgians (12,1%) and the Italians (9,5%). Together actors from these four countries accumulated more than three-quarters (85%) of the total c-Si funding, forming the core of c-Si research activities. In contrast, actors from Denmark, Germany, the United Kingdom and Greece – in that order based on the R&D funding they received – formed the c-Si periphery.

As we shall see in forthcoming sections, this picture is not surprising for Greece and Denmark. The Danes primarily relied on wind energy as a means to overcome the energy crises. Research efforts in PV remained limited. The Greeks also conducted PV research on a limited scale. The UK research activities were primarily focused on Si (mainly c-Si but also a-Si).[329] During the period covered here, national research activities were supported by the Department of Industry (DTI), the Science Research Council (SRC) and the EEC. Unlike most other national research programmes, the UK supported almost all PV research activities for different solar cells and

---

[326] All these projects were funded under FP4 and concerned measurements, tests, as well as pre-standardization activities.

[327] We should note that the geographical distribution changes if we take into consideration the pilot projects, all of which concerned the installation of flat-plate c-Si. This primarily concerns the position of Germany and Italy, both having large industrial actors from the field of the semiconductor electronics that were deeply involved in the (EC) PV activities.

[328] When referring to Germany, until the reunification of West and East Germany in 1990, we actually mean West Germany. But for reasons of coherency and simplicity we employ the term Germany throughout the text.

[329] Dollery A. A., "Photovoltaic Activities in the United Kingdom", *in* Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Luxembourg, 27-30 September 1977, D. Reidel Publishing Company (Dordrecht Holland, Boston USA: 1978), p. 522-531.

PV designs. In this context, the aim was to establish links between universities and industry to promote the transfer of research results to industry.

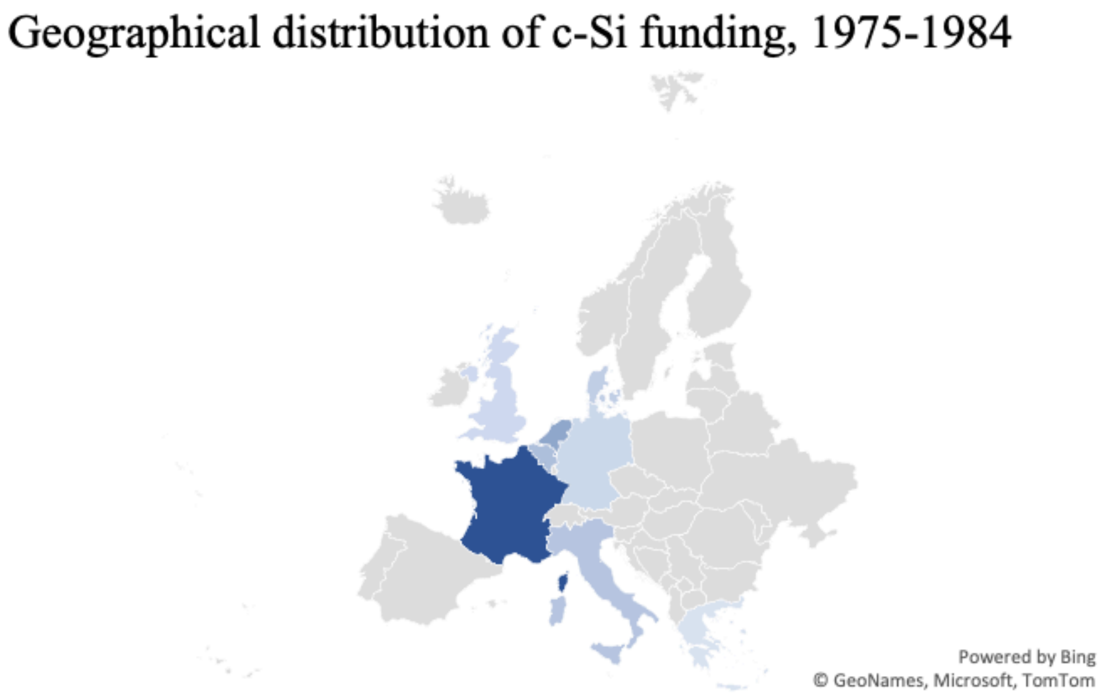


Figure 4.1 Geographical distribution of c-Si funding, 1975-1984.

UK actors had an active research interest in thin film development, which became the main priority of research policy in the second period. In the first ten years of PV R&D, thin film research was driven by UK actors mainly through the EC R&D programmes. This can be attributed to the fact that they had strong national funding for c-Si research and sought additional funding for their thin film research through the EC R&D programmes. Germany, France and Italy had launched national R&D programmes for PV and had a domestic semiconductor electronics industry.[330] The Netherlands prioritised solar thermal energy research over solar PV.[331] This explains the interest of Dutch actors in participating in the R&D programmes for PV funded by the EC. Essentially, it was a matter of advancing their PV

---

[330] As a matter of fact, the Italian semiconductor industry – during the period covered here – was partly German. Accordingly, the French semiconductor industry was also partly Dutch, as Philips had subsidiaries in France and elsewhere. For a more detailed account on the European and global semiconductor industry from the 1950s to the 2000s see: Morris P. R., *A History of the World Semi-conductor Industry*, The Institution of Engineering and Technology (London, United Kingdom: 2008), IET History of Technology Series 12, Series Editor B. Bowens.

[331] P. F. Sens, "The Dutch National Solar Energy and the International Energy Agency's Solar Heating and Cooling Programme", *in* First EC Conference on Solar Heating, Proceedings of the International Conference held at Amsterdam, April 30-May 4, 1984, C. Den Ouden (ed.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 7-10.

research (in this case for c-Si) through the EC R&D programmes, which ensured continuity of their PV research activities. Information on Belgian R&D programmes is limited.[332] Therefore, we do not know with certainty the extent of domestic R&D efforts for PV. However, based on the actors who conducted research on c-Si – domestically and in the R&D programmes of the EC – we can see that they had developed expertise on working in this material.

4.2.3 The actors that forged the basis of c-Si PV research: the semiconductor electronics industry structures the base of the PV field

As we have already mentioned, there were no transnational collaboration networks in the first ten years of EC R&D. Therefore, in this section we briefly analyse some of the main actors that were continuously involved in the c-Si research projects. Out of a total of forty-six projects, a total of six actors were continuously involved in c-Si research. These actors are the Katholieke Universiteit Leuven (KU Leuven), the Consiglio Nazionale delle Ricerche (CNR), Heliotronic GmbH, and the Stichting voor Fundamenteel Onderzoek der Materie (FOM). The two remaining actors that were continuously involved in the EC R&D programmes for PV entered through different companies and/or subsidiaries. These were in particular La Radiotechnique – Compelec (RTC) and La Laboratoires d'Electronique et de Physical Applique (LEP), both subsidiaries of Philips and the Italian multinational oil and gas company Eni.

Philips continued its entry into the programmes with the creation of Photowatt International, one of the first PV companies in France. The company was founded in 1979, as a joint venture between Compagnie Generale d'Electricite (CGE), Elf Aquitine, Moteur-Leroy Somer and RTC of Philips.[333,334] CGE was a major electrical and electronics company in France, whereas Elf Aquitine was a French petroleum company. Through this joint venture, PV research was moved to CGE's Laboratoire de Marcoussis, which was also participated the second energy R&D programme. Philips was the largest European manufacturer in 1979, while Photowatt rose to become one of the leading European PV producers in the 1980s. Dr. Emmanuel Fabre

---

[332] Most member states presented their national R&D programmes for RES – with a focus on PV, in the European Photovoltaic Solar Energy Conferences. This has been our main source of information on the member states' domestic research activities, priorities and research landscape. The Belgians comprised an exception as they never presented their national R&D programme and its contents. Based on papers Belgian actors presented in these Conferences we know there had national R&D programmes that included PV. However, even when searching for these programmes in Journal articles, books etc. the information was scarce.

[333] Science Applications Inc., *Characterization and Assessment of Potential European and Japanese Competition in Photovoltaics*, Solar Energy Research Institute (Colorado: 1979).

[334] Mark Newham, *Photovoltaics: The Sunrise Industry*, Financial Times Business Information (London: 1986).

was an important figure in the French PV research landscape, also continuously coordinating research projects in the programmes funded by the EC. Fabre originally started working on semiconductors at the RTC and dedicated a large part of his life to PV research.[335] He continued his research at Photowatt when RTC's PV business was transferred there.[336]

Eni entered the PV business through the establishment of joint ventures and subsidiaries. In the first energy R&D programme, Eni entered the programmes through Montedison, which had embarked on a joint venture with US-based Solarex Corporation to develop and manufacture Si. In the second energy R&D programme, Eni entered through both Heliosil and Instituto Guido Donegani (Gruppo Montedison). Heliosil was established to develop Si feedstock.[337] A key figure in Eni's PV business was Pr. Dr. Sergio Pizzini, Professor of Physical Chemistry at the University of Milan.[338] Pizzini started his career at JRC-Ispra and then moved to Petten in the Netherlands.[339] During his time at the University of Milan, he supported various R&D activities for Montedison and was the founder of Heliosil (1979), where he worked on the development of low-cost Si feedstock. Among Pizzini's many important positions, he was appointed by the Italian Ministry of Scientific Research to the EC's consulting group for PV.

The Italian National Research Council (CNR) is a major actor in the Italian research landscape, conducting research through its institutions. Together with ENEL and the Italian companies, the CNR pushed for the establishment of a national PV R&D programme.[340] The CNR had set up its own PV programme and funded research at universities and in industrial laboratories.[341] It thus acted as a link between research and industry within the Italian research landscape. The

---

[335] Philip R. Wolfe, "Who's Who: Profiles of Early PV Pioneers", *in* The Solar Generation: Childhood and Adolescence of Terrestrial Photovoltaics, John Wiley & Sons Inc. (Hoboken, New Jersey: 2018), p. 139-198.

[336] It is worth noting that we continue to see Fabre during the second period. He was one of the individuals responsible for setting the research agenda and priorities for PV under the first SRA (see Chapter 2).

[337] To be more accurate, Pragma, which was another ENI subsidiary, established Heliosil to develop low-cost Si feedstock. Philip R. Wolfe, "Photovoltaic Research", *in* The Solar Generation: Childhood and Adolescence of Terrestrial Photovoltaics, John Wiley & Sons Inc. (Hoboken, New Jersey: 2018), p. 47-76.

[338] We see Pizzini also in the second period's c-Si networks (Chapter 5), this time through his position at the Milan University.

[339] Sergio Pizzini, sergiopizzini, *Cirriculum Vitae*, Available online: http://www.sergiopizzini.eu/curriculum.html, (accessed 10 December 2020).

[340] ENEL was the national, publish, Italian electric utility. For more information regarding the origins and detailed contents of the Italian PV activities see: S. Pizzini, F. Califano, G. Soncini, "Italian Activities in Photovoltaics", *in* Second EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Berlin (West), 23-26 April 1979, R. Van Overstraeten and W. Palz (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1979), p. 1128-1134.

[341] S. Pizzini, F. Califano, G. Soncini, "Italian Activities in Photovoltaics", *in* Second EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Berlin (West), 23-26 April 1979, R. Van Overstraeten and W. Palz (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1979), p. 1128-1134.

CNR's PV research was conducted at LAMEL Institute.[342] With a background in microelectronics, the LAMEL team consisted of "physicists, chemists and electronic engineers".[343] The CNR programme clearly prioritized research on c-Si, but also included research on other Si-based cells (i.e. a-Si and c-Si for CPV) and other materials. However, the CNR was involved in Si-related research because of its expertise.

Heliotronic was established as a joint venture between Wacker Chemie and AEG Telefunken for material development. Wacker entered the EC R&D programmes through such joint ventures, while we see that AEG Telefunken entered first through the pilot projects. Both Wacker and AEG Telefunken were strong industrial actors in the German research landscape, conducting research on c-Si. In addition, the German programme aimed to transfer the research results to industry. At that time, AEG Telefunken was a pivotal company in c-Si, collaborating with several German universities in this field.[344] Wacker was one of the largest manufacturers of Si feedstock and heavily involved in the corresponding national R&D activities.[345]

A pivotal figure at KU Leuven and for the international and EC PV research activities in the field of c-Si, was Professor Roger van Overstraeten. The team at KU Leuven (Laboratory for Electronics, Systems Automation and Technology – ESAT) that specialized in c-Si was led by Overstraeten. Overstraeten was a central figure in the field of PV. He was the head of the Advisory Committee of the PV EC R&D programme and was active in c-Si research for space applications. In 1983 he founded the Interuniversity Microelectronics Centre (imec), a KU Leuven spin-off, and served as its director until his last days. Imec was established to "enable universities in Flanders to collaborate in semiconductor research, sharing costs and facilitating transfer of technology to industry."[346] This is a crucial point, especially with regard to the role of research centres like the imec and their place in future research. But we will come back this point in a later section.

---

[342] LAMEL originally stand for "Laboratory for Chemistry and Technology of Materials and for Components for Electronics", whereas it was later renamed to "Institute for Chemistry and Technology of Materials for Electronics".

[343] Institute for Microelectronics and Microsystems – National Research Council of Italy, IMM-CNR, *LAMEL History*, Available online: https://www.bo.imm.cnr.it/unit/history, (accessed 15 December 2020).

[344] R Koepke R., "Photovoltaic Research and Development Projects in the Federal Republic of Germany", *in* Second Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Berlin (West), 23-26 April 1979, R. Van Overstraeten and W. Palz (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London, England: 1979), p. 1120-1127.; Eisenbeiß G. and Batsch J., "The Photovoltaic Program of the Federal Republic of Germany", *in* Seventh EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Sevilla, Spain, 27-31 October 1986, A. Goetzberger, W. Palz and G. Willeke (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster, Tokyo: 1987), p. 1162-1169.

[345] See Chapter 6.

[346] Philip R. Wolfe, "Profiles of Early PV Companies and Organizations", *in* The Solar Generation: Childhood and Adolescence of Terrestrial Photovoltaics, John Wiley & Sons Inc. (Hoboken, New Jersey: 2018), p. 251.]

The last actor we see is the Dutch Foundation for Fundamental Research on Matter (FOM). FOM was founded in the Netherlands after World War II with a clear interest in atomic and molecular physics.[347,348] Within FOM, the AMOLF institute was founded by Pr. D. Jaap Kistmaker, who served as director until the early 1980s.[349] Kistmaker was an important figure in his field who was also interested in solar cell research.[350] This can be understood as an interest in other energy sources.

In the EC R&D programmes for PV we find all the (then) major European industrial actors from the semiconductor electronics field, both directly and indirectly (i.e. through subsidiaries, joint ventures etc.).[351,352] The industrial actors from the semiconductor electronics industry therefore coordinated and formed the core of the EC PV research.

Despite these continuities, it is important to note that large European semiconductor electronics companies such as Ferranti were also involved in c-Si research.[353,354] Furthermore, there are also the very first PV-specific companies. France Photon and Photowatt International were established in the late 1970s to manufacture PV solar cells. France Photon was established in 1978 as a joint venture between Moteurs-Leroy Somer and Solarex. Moteurs-Leroy Somer was a large French electrical specialist, whereas Solarex was a US company specializing in solar cells for space applications.[355] France Photon manufactured solar cells under the Solarex patent/license. In 1985 France Photon was absorbed by Photowatt International, which as we have already seen, some of its parent companies also came from the semiconductor electronics field.

The c-Si activities under the two energy R&D programmes were carried out by industrial actors from the semiconductor electronics field. Moreover, the European PV-specific companies

---

[347]Institute of Atomic and Molecular Physics, amolf *Short portrait of Jaap Kistemaker*, Available online: https://amolf.nl/wp-content/uploads/2016/03/Short-portrait-of-Jaap-Kistemaker_Impact-60-years-AMOLF.pdf, (accessed 20 October 2019).

[348] In 2013 FOM merged into NWO.

[349] Institute of Atomic and Molecular Physics, amolf, *Professor Jaap Kistemaker (1917-2010)*, Available online: https://amolf.nl/about/history-professor-jaap-kistemaker, (accessed 20 October 2019).

[350] Institute of Atomic and Molecular Physics, amolf, *History*, Available online: https://amolf.nl/about/history-of-amolf, (accessed 20 October 2019).

[351] Science Applications Inc, *Characterization and Assessment of Potential European and Japanese Competition in Photovoltaics*, Solar Energy Research Institute (Colorado: 1979).

[352] Prominent examples include Philips, who participated in the EC R&D programmes via its subsidiaries RTC and LEP. Additionally, AEG-Telefunken was collaborating with Wacker Chemie and together they had created Heliotronic, as a sister company, to support material development.

[353] Morris P. R., *A History of the World Semi-conductor Industry*, The Institution of Engineering and Technology (London, United Kingdom: 2008), IET History of Technology Series 12, Series Editor B. Bowens.

[354] In the pilot projects we also see other major/prominent actors from the semiconductor electronics participating (e.g. Siemens).

[355] Philip R. Wolfe, "Profiles of Early PV Companies and Organizations", *in* The Solar Generation: Childhood and Adolescence of Terrestrial Photovoltaics, John Wiley & Sons Inc. (Hoboken, New Jersey: 2018), p. 199-270.

established during this period were the result of joint ventures of companies from the semiconductor field; companies that had experience and expertise in working with c-Si. In the few cases where actors from another field were involved (e.g. Elf Aquitine), we should mention that it was 'common practice' to forge collaborations in the form of joint ventures to enter a new field. During this period, several oil companies entered the PV scene in this way, both in Europe and in the US. But it was not just a matter of them joining the PV scene. Rather, these oil companies represented a crucial investor for PV.[356] We must not forget that the oil companies had the capital during this period to support the (capital-intensive) research required for c-Si. The reason why several major US oil companies (such as Exxon and ARCO) supported PV was because they had a 'personal' experience with it. In the 1970s they started to use PV instead of non-rechargeable batteries especially on the oil platforms. The transport and disposal of the batteries, which weight about 500 pounds came to a halt in 1978 with the banning of EPA, which prohibited the disposal of batteries directly into the sea.[357] This in turn cleared the way for the wider use of PV at such sites, while convincing oil companies of the technology's potential. The European oil companies (e.g. ENI, BP Solar, Shell) also embarked on the PV business during this period. As these companies did not have the know-how to enter the field directly, they either forged collaborations with semiconductor electronics companies or with other oil companies that had bought up semiconductor electronics companies.

European industrial interests were explicitly focused on c-Si solar cells. Moreover, the European PV-specific companies that were established during this period were the result of joint ventures of companies from the semiconductor field; companies that had experience and expertise in working with c-Si. It was through this way that actors from semiconductor electronics were able to enter the energy market. Our analysis showed that, the scientific actors involved in c-Si research had similar backgrounds, expertise and experience in working with c-Si. Some were researching c-Si for space applications, while others were working on c-Si applications in telecommunications and electronics.

As can be seen from the above, several research centres, university spin-offs etc. on microelectronics were founded in the 1980s. This can be explained by the fact that the field of semiconductor electronics was understood as an area of strategic importance. Therefore, more funds were allocated R&D in the field of semiconductor electronics. This in turn led many universities and research centres to redirect their research or put even more emphasis on this

---

[356] Imamura M. S., Helm M. S. and Palz W., *Photovoltaic System Technology: A European Handbook*, Published by H. S. Stephens & Associates on behalf of the European Commission (Bedford, UK: 1992).

[357] John Perlin, *From Space to Earth: The Story of Solar Electricity*, AATEC Publications (Michigan: 1999).

field. A British Physics Professor recalls their experience in the 1980s, when they were still a postgraduate student:

> "… **GaAs is a very expensive material and it was our way in**, so **it was my postdoc supervisor's way in**, **to do solar research was to attach himself to this semiconductor electronics industry** (that had) active research activity, which was based very much on the III-V semiconductors."[358] (emphasis added)

Working on semiconductors, or in this case reorienting research on semiconductors, was one or the means to approach the semiconductor electronics industry that flourished in the 1980s. One entry point into this industry was PV research. Since the two sectors use the same semiconductors, knowledge could circulate freely. Since semiconductors were essentially the bridge between the two sectors, this enabled knowledge transfer. Moreover, the actors were able to continue pursuing their research by securing the necessary funding.

Having examined some of the key scientific and industrial actors involved in c-Si research, it is clear from both the large number of projects supported and the share of companies in the coordination of the c-Si projects that there was an explicit industrial interest in c-Si cell research, especially when comparing c-Si projects with other materials. Essentially, we see that the interests of industry were expressed primarily in the research for c-Si. Moreover, it was the industrial actors who conducted research for module development (for c-Si modules) and likewise it was the industrial actors who were interested in conducting pilot projects (again for c-Si cells and modules).

PV research activities supported by the EC R&D programmes were concentrated in those countries that had semiconductor electronics industry and well-established interests in c-Si. These actors, both from industry and academia, brought their know-how about c-Si. More importantly, it was their knowledge traditions and expertise that forged the knowledge base for the creation of the European field for PV.[359] In particular, specific methods and techniques such as ion implantation and chemical vapour deposition, which were well-established techniques for c-Si in the field of semiconductor electronics, were transferred to the field of

---

[358] Interview with Physics Professor at a UK university, specializing in the characterization of materials for PV, 21 November 2019, London, UK.

[359] We should note at this point that the influence of the semiconductor electronics in shaping the knowledge basis of the European PV field is pertinent throughout the first period.

PV. Both ion implantation and chemical vapour deposition were well-known processing methods/techniques used extensively in semiconductor electronics when working with c-Si.[360] Furthermore, the PV sub-programme of the second energy R&D programme, was structured based on well-known methods and techniques developed by and for the semiconductor electronics field. Even though the PV sub-programme under the first energy R&D programme was not structured in the same way as the successor programme, we see that the same methods and techniques are used by exactly the same actors when they conducted research for c-Si. A common 'trend' in both programmes was that these methods and techniques were used to make interventions and/or improvements on well-established processes in the manufacturing of c-Si cells. Thus, at least for the projects that were dealt exclusively with mono c-Si, we can argue that these projects – without this being directly mentioned anywhere – also aimed to support the field of semiconductor electronics. To be precise, the knowledge attained from the PV projects funded by the EC could be directly incorporated into the development in the field of semiconductor electronics.

The ion implantation method/technique was developed in the 1960s, at a the time when the field of semiconductor electronics was beginning to grow.[361] As Professor James W. Mayer, a proponent of applying ion implantation to semiconductors, best describes:

> "Ion implantation is being applied extensively to silicon device technology…Ion implantation is the introduction of atoms into a solid substrate by bombardment with ions in the KeV to MeV energy range…Silicon provides an ideal host for studying the basic parameters and concepts involved in the implantation process."[362]

The method was thus developed for applications in the field of semiconductor electronics. In this context, silicon was 'an ideal candidate' for the study of the method and the dominant material being used by semiconductor electronics and on which the field was built.

In the research projects, we see important actors, such as the Laboratoire de Marcoussis and CNR LAMEL, using this very method to fabricate c-Si cells. Other actors focused on reducing

---

[360] Morris P. R., *A History of the World Semi-conductor Industry*, The Institution of Engineering and Technology (London, United Kingdom: 2008), IET History of Technology Series 12, Series Editor B. Bowens.

[361] John Orton, "Silicon, silicon and yet more silicon", *in* J. Orton, *The Story of Semiconductors*, Oxford University Press (New York: 2004), p. 93-148.

[362] James W. Mayer, "Ion implantation in Semiconductors", *in* 1973 International Electron Devices Meeting, 3-5 December 1973, Washington, DC, IEEE Publications, p. 3.

the manufacturing costs of the cells by intervening in the processing steps inherited from semiconductor electronics (e.g. RTC). Some of the actors wanted to make developments in the purification steps of the Si feedstock. Notable examples are Ansaldo in collaboration with Wacker (and Wacker's subsidiary in collaboration with AEG, Heliotronic), France Photon, Photowatt, Laboratoire de Marcoussis and others.

We should remember that the industrial actors entering PV research were (the) major European companies in the semiconductor electronics sector at the time. Thus, the fact that these companies had explicit and embedded interests in c-Si affected the EC R&D agenda for PV, especially as the EC was constructing the PV market through the pilot programmes. It was precisely these industrial interests in c-Si that drove the EC research agenda for PV. Considering that there were no explicit industrial interests in other materials, one also understands why their research received less funding and attention in the EC R&D funding programmes.

4.2.4 The pilot programme: the first transnational PV networks are forged

Only a small number of pilot projects were supported under the first energy R&D programme. These projects comprised of 'small power systems', with ranging capacity of 1kW to 5kW. One 1kW project was coordinated by the CNRS, whereas the other four projects, each concerning a 5kW PV system, were coordinated by AEG-Telefunken, SERI-Renault Engineering, Laboratoire d' Electronique et de Physique Appliquée (LEP). These small-scale PV systems concerned 'small-scale' applications, such as supplying power to a hotel. Perhaps the most interesting project, however, was a PV system for a 'solar house', coordinated by LEP. Even though LEP did not install the PV system on the rooftop, this is the first mention of linking PV to residential buildings.

In addition to the pilot projects mentioned above, four projects were funded to conduct feasibility studies for intermediate systems. Essentially paving the way for the some of the pilot projects that were realised under the second EC energy R&D programme. These projects concerned PV systems with a capacity that ranged between 0,5MW and 1MW, which the coordinators referred to as medium-sized PV power plants. The studies were coordinated by AEG-Telefunken, ENEL, SERI-Renault and Laboratoire de Marcoussis CGE. Finally, two other projects were funded. One was coordinated by France Photon and focused on solving problems in solar cells due to high voltage applications, whereas the second project was coordinated by Gent University and aimed at providing a system analysis for the interconnection of PV systems with the grid.

4.2.4.1 The first pilot programme (1979-1983): constructing the first European PV market

During the second energy R&D programme (1979-1983), most of the funds were used for the pilot projects. They were described as the 'highlight' of the programme.[363] According to the EC, the pilot projects received about 61-62% of the total R&D funds for PV of the second energy R&D programme.[364] The scale of the pilot projects increased and ranged from 30kW to 300kW. They directly targeted the grand challenge or 'request' of the 1980s, namely rural electrification. In line with industrial policy, the EC instrumentalised the pilots to establish a market for the European actors in the PV industry. With few exceptions, they were mainly private sector actors. The participation and role of universities and research centres was almost negligible. Lastly, the projects acted as the basis for conducting measurements to set standards, stability evaluations/assessments etc.

As can be seen from the following quote, the EC have explicit priority to the installation of c-Si flat-plate PV.

> "**Flat-plate silicon panels should be employed in general. For the sake of comparison a small fraction of the overall capacity may include**: alternative cells, namely CdS cells; concentrator arrays (in the south of Europe); flat mirror boosters."[365] (emphasis added)

---

[363] Palz W., "European Achievements in Photovoltaics", *in* Fifth EC Photovoltaic Energy Conference, Proceedings of the International Conference held at Kavouri, Athens, Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 21-24.

[364] The funding provided by the EC varies. Overall, the EC has provided that the funding for the pilot projects varied from ECU 9,5 mil to ECU 10 mil. Accordingly, the funding for the remaining activities reported varies from ECU 5,9 mil to ECU 6,4 mil. Resulting in the total funding to vary by ECU 1 mil. We should also note that the EC also received a share of this funding. Essentially the salaries and other EC personnel expenses were covered by the same budget, without however a clear account of the exact amount. This results in adding to the difficulties when calculating the total budget and respective project shares.

[365] Call for tenders, (C 50, Volume 23), Official Journal of the European Communities, 28 February 1980, p. 8.

With a clear frontrunner, as illustrated in Figure 4.2 (below), the pilot projects were coordinated by actors from six countries.[366,367,368] Based on the funding they received, these countries are Germany (39,9%), France (28,2%), the United Kingdom (10,7%), Italy (8,7%), Belgium (6,9%) and Ireland (5,5%).

Similar to the geographical distribution of funding for c-Si research, France and Italy continued to receive significant funding. In contrast, the Netherlands attained a stronger position in the research activities. However, Dutch actors continued to play an important role in the pilot projects, even though they are not included in Figure 4.3 (below).[369] Belgian actors accumulated significant research funds, whereas their position in the pilot projects is less significant. This is attributed to the fact that there were no large PV companies in Belgium. Similar is the case for Denmark and Greece, who we only see attaining funding in the research activities. Both Germany and the UK concentrated more funding on the pilot projects than on the c-Si research projects. Both countries had large companies embarking on the PV business, which explains why they play a more prominent role in the pilot projects. From Figure 4.3 we can see that the installation locations/sites varied from the European North to the European South. Climate was an important parameter for the installation of the pilots for the EC. It was the EC's belief that different climates will lead to different measurements. As the pilots were to be used for data collection (by the JRC) to support the measurements for setting PV standards, it was crucial that there was 'diversity' in the pilot projects geographical distribution.[370] Using the information in Table 4.1 (below), we see that all the pilots used either mono-crystalline silicon or multi-crystalline silicon solar cells. These were the only two commercial cells available at the start of the programme.

---

[366] By 1983, the year when the second energy R&D programme ended, the EC comprised of ten member states: the founding members (Belgium, Netherlands, Luxembourg, Germany, France, and Italy) and Ireland, the United Kingdom, Denmark and Greece.

[367] We count the installation in the French Guyana as a French installation. Even though Guyana is in South America, it comprises a French region.

[368] A total of sixteen pilots were supported under the second energy R&D programme. We have not included the pilots that concerned hybrids (i.e. PV and another for of energy like wind) nor have we included PV installations that did not explicitly concern the production of electricity (e.g. water pumping, heating).

[369] See forthcoming analysis, the Netherlands indirectly enters the pilot programmes via subsidiaries.

[370] The Technical Committee (TC82), of the International Electrotechnical Commission (IEC), was established in 1982 in order to establish the standards for the solar photovoltaic energy systems.

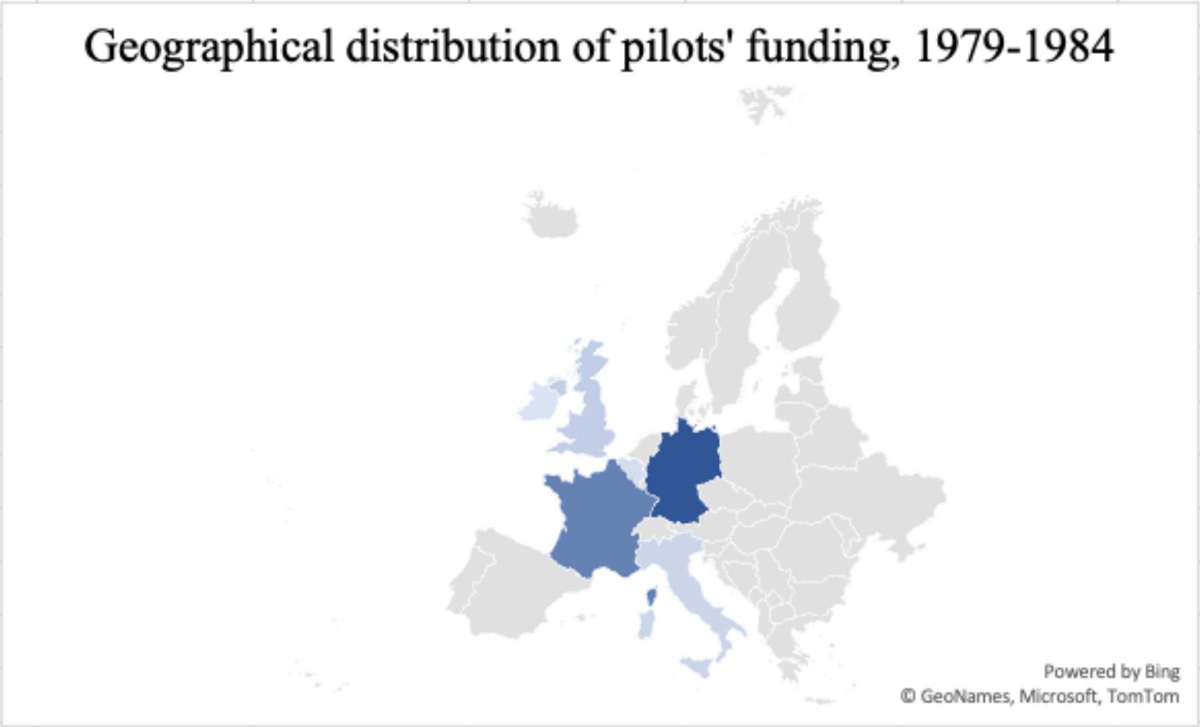


Figure 4.2 Geographical funding distribution of pilot projects, 1979-1984.

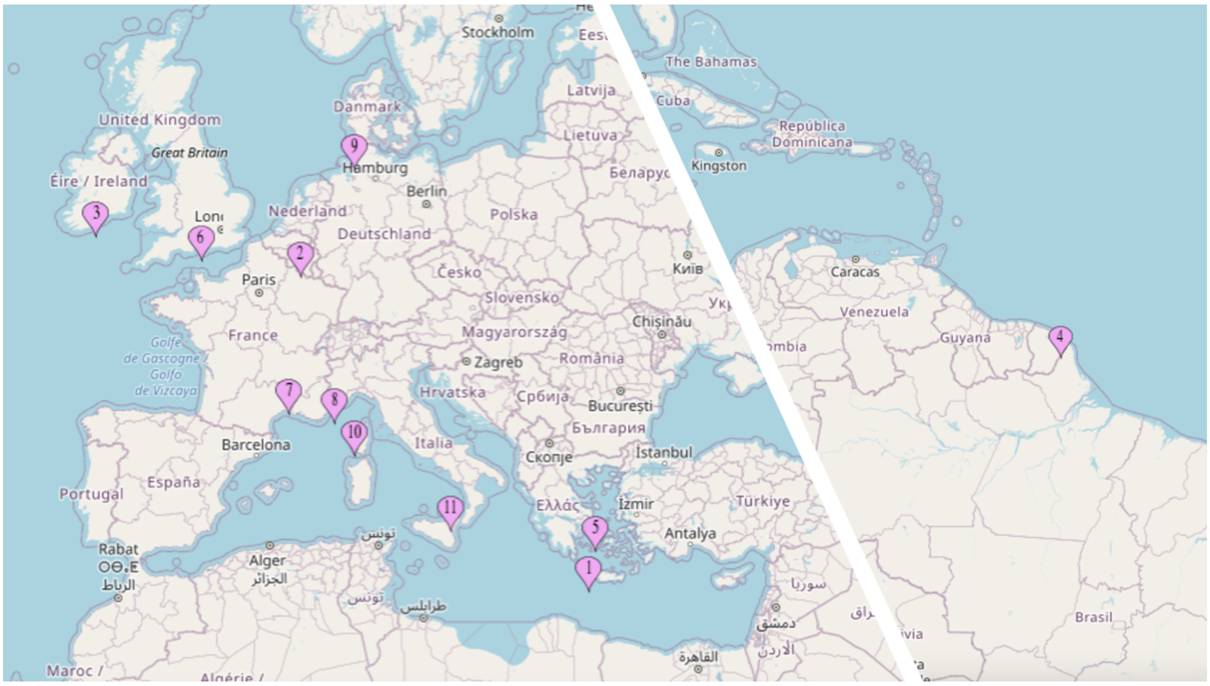


Figure 4.3 Map of the PV pilot project installations.[371,372]

---

[371] Figure created by the author, via the mapcustomizer website. For the interactive version of the map see: https://www.mapcustomizer.com/map/Pilots%20Location,1979-1984

[372] Please note that the map does not show the exact location of the PV pilot installations, rather it depicts their geography.

The majority of projects involved installations with solar cells and modules made of mono-crystalline silicon, whereas there were only two manufacturers producing multi-crystalline silicon solar cells, namely AEG-Telefunken and Ansaldo.[373,374]

Mono and multi c-Si have some differences. Mono c-Si was – and still is – more expensive, but also more efficient than multi c-Si. Even though, for space applications, the use of mono c-Si was more advantageous for the intended applications (e.g. efficiency matters, cost is not an issue), cost became an issue when PV came to earth. Given the intended terrestrial applications for PV, a larger area of active material was required, further driving up costs. It was in this context, and for the needs of terrestrial PV applications that the development of multi c-Si began.

Project	**Country/capacity (kW)**	**Coordinator**	**Coordinator's country**	**Cell**	**Manufacturer**
Ag. Roumeli	GR/50	Seri Renault Ingenierie	FR	Mono c-Si	France Photon
Chevetogne	BE/63	IDE	BE	Mono c-Si	Belgosolar
Fota	IRL/50	University College Cork	IRL	Multi c-Si	AEG Telefunken
Kaw	Fr Guyana/35	Seri Renault Ingenierie	FR	Mono c-Si	France Photon
Kythnos	GR/100	Siemens	DE	Mono c-Si	Siemens
Marchwood	UK/30	Lucas BP Solar Systems	UK	Mono c-Si	BP
Mont Bouquet	FR/50	Photowatt	FR	Mono c-Si	Photowatt
Nice	FR/50	Photowatt	FR	Mono c-Si	Photowatt
Pellworm	DE/300	AEG Telefunken	DE	Multi c-Si	AEG Telefunken
Rondulinu	FR/44	Moteurs Leroy-Somer	FR	Mono c-Si	France Photon
Vulcano	IT/80	Ente Nazionale per l'Energia Elettrica (ENEL)	IT	Multi c-Si/Mono c-Si	Ansaldo/PRAGMA

---

[373] We extensively researched both the industrial actors and the market situation, for the entire period. Based on all the information we have gathered it seems that all EC PV companies participated in the pilot programme. Our research covered selected papers presented in the EC Solar Photovoltaic Energy Conference Proceedings of the period, as well as a series of books; selected list suggested for the reader, including information on the industrial actors, the global annual production, shipments, as well as other industrial and market-related data: Derrick A., Barlow R.W., McNelis B., Gregory J.A. (eds.), *Photovoltaics: A Market Overview*, James & James Science Publishers ltd (London: 1993).; Newham Mark, *Photovoltaics: The Sunrise Industry*, Financial Times Business Information (London: 1986).

[374] As we have explained, Ansaldo was working with Wacker towards the development of silicon feedstock. Their collaboration was based on the development of silicon feedstock for multicrystalline Si cells. Accordingly, AEG was collaborating with Wacker towards the development of silicon feedstock under their jointly established company Heliotronics.

Table 4.1 Breakdown of the pilot projects: coordinators, solar cell material and manufacturer.[375]

The installations were intended to provide an answer to the greatest 'demand' of the time, namely the electrification of rural areas. Most projects targeted isolated and remote areas, with the installation of PV power plants explicitly addressing the issue of rural electrification. Such locations offered PV a market where it could compete with other energy sources.[376] The remaining projects were aimed at supplying energy to individual buildings (Pellworm, Fota) and to FM and TV emitters in isolated areas.

We must emphasize that all European PV companies participated in the EC pilot projects and formed the core of the projects. Moreover, the majority of the coordinators were European PV companies. The only exceptions were the coordinators for the Fota and for the Vulcano pilots; their coordinators were University College Cork and ENEL, respectively. At University College Cork, research on c-Si was conducted by the team of the National Microelectronics Research Centre, founded in 1982.[377] Furthermore, the private sector remained dominant in the networks comprising the pilot projects. The sole exceptions were PPC (Kythnos plant) and EDF (Rondulinu plant), both of public electric utility actors and Aerospatiate (Nice and Mont Bouquet plants). Overall, the networks created for the implementation of the pilot programme were thus mainly actors from the private sector.

The total installation capacity of all PV pilot projects supported by the EC was 1.112kW.[378] This was a considerable number, especially for the European market. Before 1973, the global market for PV was limited to ±10kW in terms of production capacity (worldwide).[379,380]

---

[375] The information and data for Table 4.1 have been compiled from a series of material, including the project proposals, their final reports, papers presented at the European Solar Energy Photovoltaic Conferences etc. For an in-depth analysis of the pilot projects see: Imamura M. S., Helm M. S. and Palz W., *Photovoltaic System Technology: A European Handbook*, Published by H. S. Stephens & Associates on behalf of the European Commission (Bedford, UK: 1992).

[376] M. R. Starr, "The Potential for Photovoltaics in Europe", *in* Fourth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Stresa, Italy, 10-14 May 1982, W. H. Bloss and G. Grassi (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1982), p. 40-50.; Michael R. Starr and Wolfgang Palz, *Photovoltaic Power for Europe: An Assessment Study*, Photovoltaic Power Generation, Vol. II, D. Reidel Publishing Company, (Dordrecht Holland, Boston USA, London England: 1983).

[377] The successor of the National Microelectronics Research Centre it the Tyndall National Centre, Research Centre on Information and Communications Technology (ICT), established in 2004.

[378] Please note that all sixteen pilots have been included in the summary, including the ones that concerned hybrid systems etc.

[379] J. Lindmayer, "Industrialisation of Photovoltaics", *in* Third EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes France, 27-31 October 1980, W. Palz (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London, England: 1981), p. 178-185.

[380] As illustrated in Figure 4.4, we see an impressive change in the global PV production that occurred in 1983. Clearly, this is both an impressive and a significant change, which we analyse in depth. However, since it concerns

Concurrently, the PV applications were restricted for space satellites. Based on the data in Figure 4.4 (below), the annual global PV production in 1979 was about 2,5MW, while the annual production of European PV manufacturers in 1979 ranged from 240kWp to 350kWp (see Figure 4.5 below).[381,382] Thus, when the EC issued the call for proposals for the PV pilot programme, for projects in the range of 30-300kW in early 1980, this was certainly an important initiative for industrial actors, especially considering the production capacity of European PV cell/module producers. By 1981, the total production had not reached the 1MW mark, as each of the six EC companies was "[…] producing and selling approx. 150 kW or somewhat less".[383,384,385]

Figure 4.4 shows that global annual PV production grew significantly by ±1,5 and ±2MW in 1980 and 1981, respectively. In 1982, the growth continued (±1MW), albeit at a slower rate. The annual increases in production capacity, both worldwide and for the European PV manufacturers, help us to better contextualize and evaluate the contribution of the pilot programme of the Commission, which led to the installation of a total 1.112kW of capacity. Essentially, through the pilot programmes, the EC constructed the first European PV market while promoting the international competitiveness of the European PV industry. Until the mid-1980s, the majority of PV cells produced were intended for various, diverse, applications. However, electricity generation was not the mian market for PV, rather it accounted for a negligible part.

---

developments (also) on another material (spoiler, we mean a-Si) we feel that this significant change deserves an extensive analysis on its own. Furthermore, it is directly linked with the shift in EC's research policy during FP1. Thus, for now we focus on the changes that are directly linked to the pilot programmes and which occurred during the 1979-1982 timeframe. We extensively analyse this change in the FP1 section.

[381] It should be noted that Photowatt is not included in the list, as it had not yet started the production of PV cells/modules.

[382] As the reader will observe, there is a variation in the production capacity numbers we provide (both in kW and in MW). The reason for these variations relates, largely, to the unwillingness of many companies in sharing exact data. Moreover, this exact justification is provided by the vast majority of the sources we have used in order to reconstruct this data for all the period covered in our analysis. Each Table and Figured is referenced, so the reader is kindly advised to seek the sources in the corresponding references we make.

[383] G. Schuster, "The future of Photovoltaics in Europe", *in* Third EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes France, 27-31 October 1980, W. Palz (ed.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1981), p. 4-9.

[384] W. Palz, "Overview of the European Community's Activities in Photovoltaics", *in* Fourth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Stresa, Italy, 10-14 May 1982, W. H. Bloss and G. Grassi (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1982), p. 5.

[385] It is likely that the total EC PV production was around 800kW in 1981 (W. Palz, "Overview of the European Community's Activities in Photovoltaics", *in* Fourth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Stresa, Italy, 10-14 May 1982, W. H. Bloss and G. Grassi (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1982), p. 3-8.

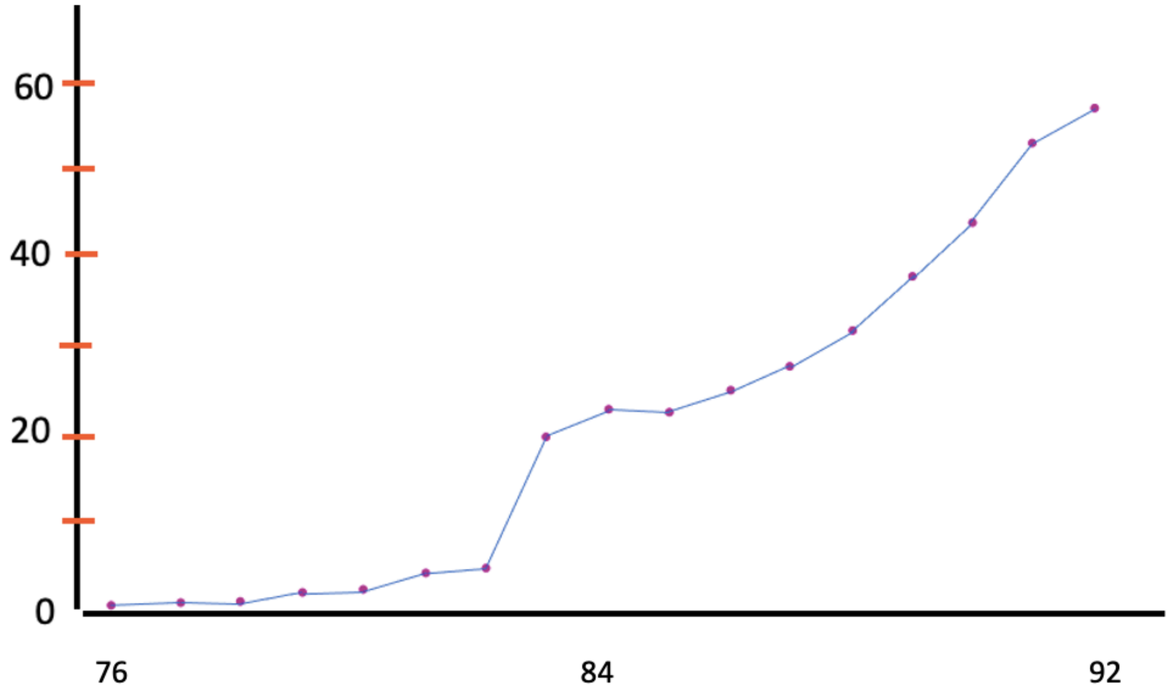
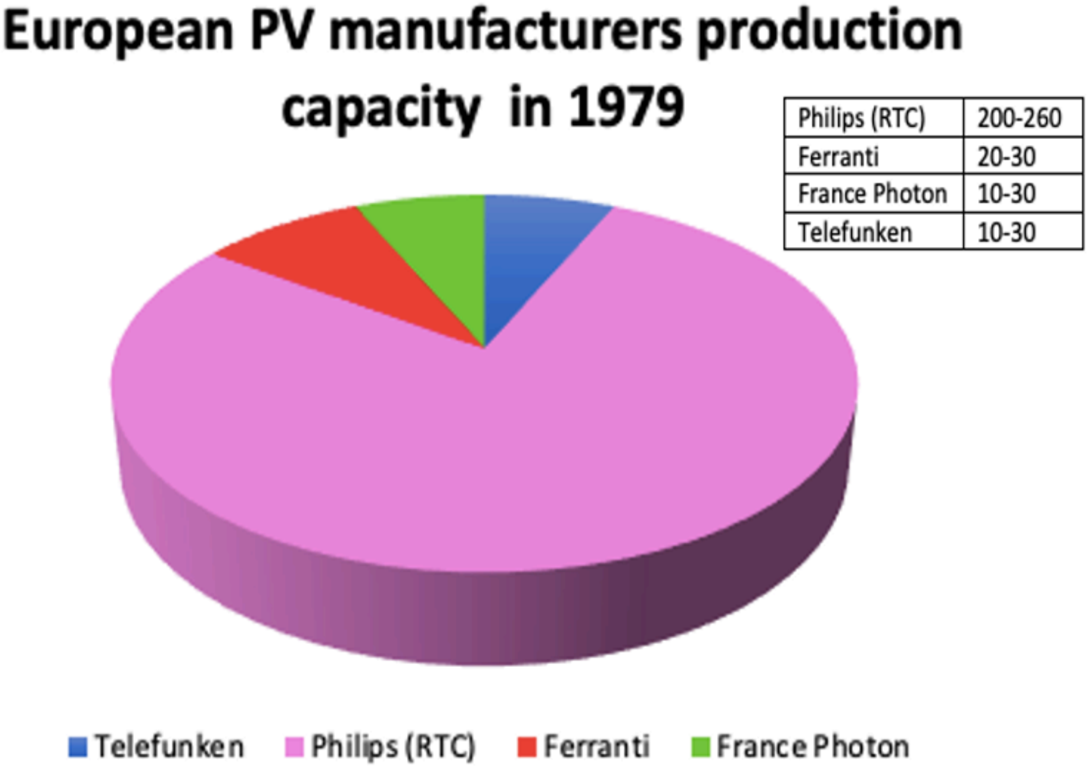


Figure 4.4 Annual global PV production (in MWp), 1976-1992. Adapted from: Derrick A., Barlow R.W., McNelis B., Gregory J.A. (eds.), *Photovoltaics: A Market Overview*, James & James Science Publishers ltd (London: 1993), p. 7.



Philips (RTC)	200-260
Ferranti	20-30
France Photon	10-30
Telefunken	10-30

Figure 4.5 Shares of European PV manufacturers' production capacity (in kW) in 1979, by company. Adapted from: Science Applications Inc, *Characterization and Assessment of*

Potential European and Japanese Competition in Photovoltaics, Solar Energy Research Institute (Colorado: 1979), p. 3-17.

In this period, it was not uncommon for a/the state to provide a secure market for its domestic companies. In contrast, this protectionist industrial policy was the norm.[386] Within this context, the state acted as a 'buyer' on several occasions to help domestic companies compete internationally. An integral part of EC's research policy was to support the European industry, by strengthening its scientific and technological base. Through the pilot projects, the EC supported European PV companies that were making their first steps to compete with their US and Japanese counterparts. It provided a secure market for the PV companies and helped them achieve stable sales over a period of time. The EC constructed the first PV market for the European companies. It secured financing for the companies, promoted their sales and ensured they had a 'secure' place in the context of international competitions. Furthermore, the EC helped save a major European company, namely AEG-Telefunken. This attracted some in business circles, as the following statement shows:

> "…the company (has) only survived commercially because of government support and because the CEC awarded Telefunken the lion's share of its Pilot PV Generator Programme".[387,388]

Indeed, AEG-Telefunken received the lion's share of the EC pilot programme. To be precise, AEG-Telefunken received the largest share of funds dedicated to any contractor, receiving a total of 1.929.000 ECU or about 20% of the total budget of the pilot programme or one fifth of the total budget of the PV programme. Essentially, the EC instrumentalised its pilot programme to help AEG Telefunken overcome its financial problems.

The R&D programmes of the EC have helped solve problems that would aid the commercialisation of PV. In parallel, the EC constructed the first European market for PV for terrestrial applications through the pilot programmes, while aiding the international

---

[386] For a more in-depth analysis of European Community industrial policy, see Victoria Curzon Price, *Industrial Policy in the European Community*, The Macmillan Press (Houndmills, Basigtoke, Hampshire, London: 1981).

[387] Mark Newham, *Photovoltaics: The Sunrise Industry*, Financial Times Business Information ltd. (London: 1986), p. 88.

[388] Despite the efforts towards saving AEG-Telefunken, the company was eventually incorporated to Daimler-Benz in 1985.

competitiveness of the European industry. Lastly, the pilot projects have also helped with the measurements for setting the international PV standards. We now turn to the standards.

4.2.5 The competition runs high: shifting to a-Si and the emergence of the first technoscientific research networks

As indicated by Figure 4.6, FP1 research was redirected towards a-Si and other thin films. A-Si accounted for almost 50% of the funding, whereas the other thin films received about 25% of the R&D funding for PV. C-Si research continued to receive support, but the funding allocated to the dominant technology was significantly lower compared to previous R&D programmes. C-Si research activities accounted for only 5% of the total R&D budget for PV.[389] As we analyse in chapter 6, during FP1 the alternative design option (i.e. CPV), developed by actors from the European South and best suited to the Southern European (and global) climate, was excluded. The pilot projects based mainly on c-Si continued to receive financial support (20%), but at a much lower level compared to the previous programme.

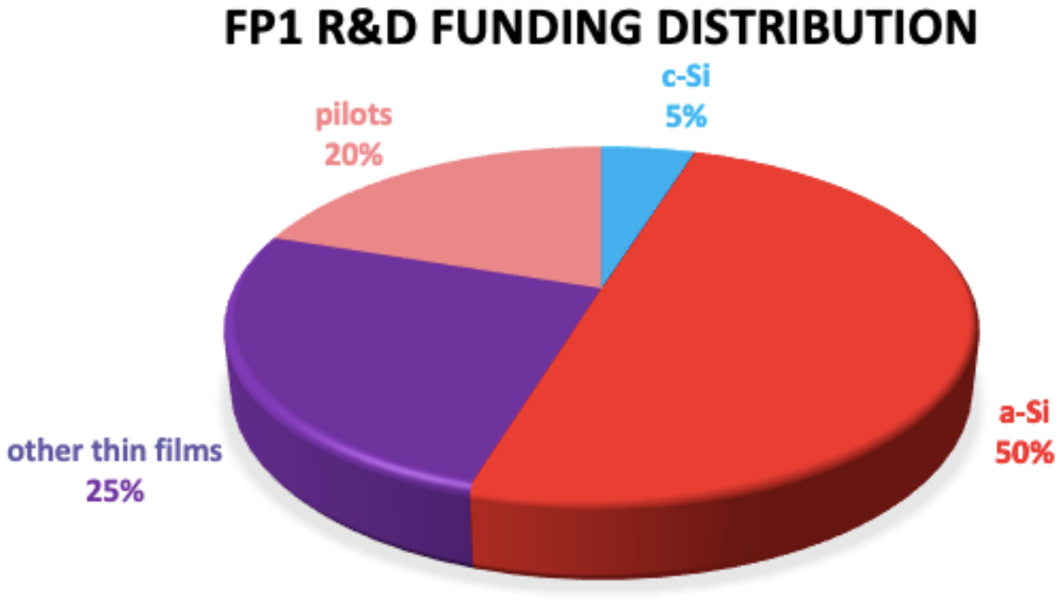


Figure 4.6 R&D funding distribution by technology (1985-1988).

---

[389] This share does not include the pilot activities. If we include the pilot c-Si funding, the share increases to about 25%. The corresponding c-Si research share for the 1975-1984 period was about 25%. If we include the corresponding c-Si pilot funding, this share increases to about 83%.

Last, but equally important, the first transnational EU-wide collaborative technoscientific research networks were established under FP1. In the following sections, we first examine the events that led to funding shift and then turn our attention to the first c-Si technoscientific research network.

4.2.5.1 The temporary shift to a-Si: tracing the events that led to the EC's R&D 'U-turn'

Under FP1, EC R&D made a 'U-turn' in favour of a-Si, in direct response to Japanese competition, and to a lesser extent, in response to the expected silicon (Si) feedstock shortages.[390] The a-Si research activities were organized around two European companies. In this way, research was instrumentalized to respond to the international competitiveness of the European industry by aiding two European companies accelerate the commercialization of this technology, while responding to a raw materials shortage. There is thus continuity in the commitment of the EC to instrumentalize the R&D programmes to constructing a market for the (European) PV companies/industrial actors and help them compete internationally. During the second energy R&D programme, the pilot programmes constructed the first market for PV in Europe, whereas in FP1 the a-Si shift pursued the same goal by organizing the research activities (of a-Si) around two companies.

There were two major events that led to the funding shift in FP1. The first event was the announcement of record high a-Si cell efficiency and the subsequent decision by Sanyo to establish a 2MW production line for a-Si cells. Both announcements were made during the Fourth EC Photovoltaic Solar Energy Conference, in 1982. A-Si was the first and only other technology to challenge the dominance of flat-plate c-Si, in the late 1980s. Competition came primarily from Japan, which was developing fast in the a-Si front. The second event involved issues of Si feedstock availability, which took the form of industry and policy concern(s).[391,392] Both events were influenced by and intertwined with (a) the computer boom of the 1980s, which imposed pressure in the supply of Si feedstock and (b) the prevalent role of the semiconductor electronics industry and international competitions surrounding it, which

---

[390] See analysis in chapter 7.

[391] The first records we found about these concerns were by a DoE funded Jet Propulsion Laboratory report, published in 1979, as well as discussions – and papers – presented in the 1980 EC Photovoltaic Solar Energy Conference; more papers and discussions followed in later EC PV Conferences.

[392] We analyse this event in Chapter 7.

spilled over to field of PV. The link was the selected and dominant material used in both fields, namely c-Si (monocrystalline Si).

4.2.5.1.1 The Japanese competition runs high: a new market for PV!?

The first event took place in the 1982 at the EC PV Conference. This event was the announcement of record high efficiency (8%) of a-Si cells by Dr Yukinori Kuwano of Sanyo and Dr Y. Tawada of Osaka University.[393,394] This announcement was called as "the highlight of the amorphous silicon papers".[395] The record high efficiency announcement was complemented by Sanyo's announcement to manufacture and use a-Si solar cells for demonstration purposes, accompanied by the parallel announcement to advance the (annual) production of 1,5 MW at their production facility.[396] At a time when global annual production of PV cells/modules was around ±6MW (1981), Sanyo's announcement to increase production capacity meant that Japan would soon be **the** leader in PV. By 1984, industry attention at the R&D level was almost exclusively focused on to a-Si; a total of ±150 million USD was invested.[397]

As illustrated in Figure 4.7 (below), in 1988, Japan led global production with a share of 38,1%, followed by the US (33%) and Europe (19,9%).[398] This Japanese expansion is largely due to the rapid commercialization of a-Si cells. This is not to say that the Japanese did not produce or research c-Si solar cells. However, they took a different route. When the first Japanese R&D programme was launched in 1974 in response to the 1973 oil crisis, the funding was primarily directed to solar thermal energy.[399] Under the 'Sunshine' project, funding for PV R&D

---

[393] Sanyo was one of the first Japanese companies to enter the field of PV.

[394] Should the reader be interested in reading the paper, see: Y. Kuwano et al., "Amorphous Silicon Solar Cells Produced by a Consecutive, Separated Reaction Chamber Method", *in* Fourth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Stresa, Italy, 10-14 May 1982, ed. W. H. Bloss and G. Grassi, D. Reidel Publishing Company (Dordrecht, Holland/Boston, USA, London, England: 1982), p. 704-708.

[395] Treble F. C., "Conference Notebook", *in* Fourth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Stresa, Italy, 10-14 May 1982, W. H. Bloss and G. Grassi (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1982), p. ix.

[396] Treble F. C., "Conference Notebook", *in* Fourth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Stresa, Italy, 10-14 May 1982, W. H. Bloss and G. Grassi (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1982), p. ix.

[397] Paul D. Maycock, "The Current PV Scene Worldwide", *in* Sixth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in London, UK, 15-19 April 1985, W. Palz and F.C. Treble (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1985), p. 21-27.

[398] Arnulf Jager-Waldau, *PV Status Report 2003: Research, Solar Cell Production and Market Implementation in Japan, USA and the European Union*, Office for Official Publications of the European Communities (Luxembourg: 2003).

[399] The programme was managed by the Ministry of International Trade and Industry (MITI). In 1980 the New Energy and Industrial Technology Development Organisation (NEDO) was established and became responsible for the R&D programme and budget distribution, under MITI.

increased from 2,000 million yen in 1980 to almost 6,000 million yen in 1981 and peaked in 1985 when about 9,000 million yen were allocated for PV R&D.[400] The involvement of a strong industrial actor (i.e. Sanyo) and the successful commercialisation of a-Si cells gave a justified boost to further – and expand – PV research efforts in Japan. Japan devoted its research funds primarily to a-Si on the grounds that it was "[…] better suited for mass production."[401] In the Japanese context, mass production formed the legitimizing basis for prioritizing a-Si.

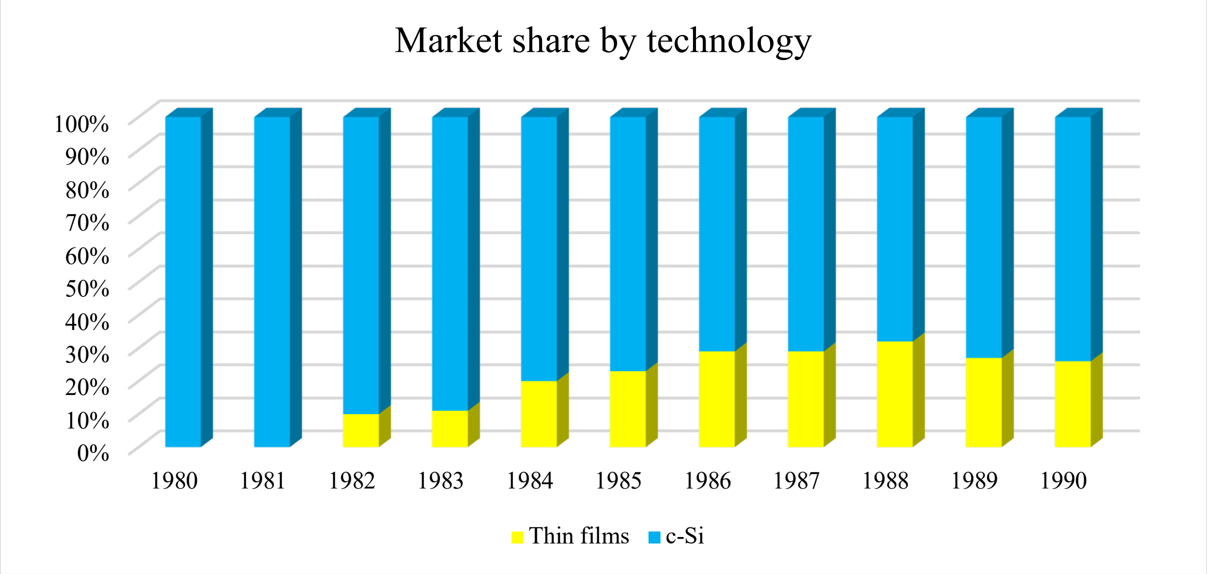


Figure 4.7 Market share by PV technology, 1980-1990. Adapted from Mints Paula, "Overview of Photovoltaic Production, Markets, and Perspectives", *in* Semiconductors and Semimetals, G. Willeke and E.R. Weber (eds.), Elsevier (Oxford, UK: 2012), p. 63.

A-Si was mainly used for small electronic devices (e.g. toys, calculators, watches etc.). By 1988, the field of PV had become 'a multi-million business' because of applications of a-Si in micropower applications or small portable systems etc.[402] A-Si was the only technology that challenged the dominance of c-Si in the history of PV. As can be seen from the annual PV market shares in Figure 4.7 (above), 1988 was the year in which a-Si reached a record share:

---

[400] Tetsuro Kobayashi, Yutaka Hayashi, Naomasa Yui and Kazuki Yoshimura, "Japanese Photovoltaic R&D Program Under the Sunshine Project", *in* Ninth EC Photovoltaic Solar Energy Conference, Proceedings of the international Conference held at Freiburg, Federal Republic of Germany, 25-29 September 1989, W. Palz, G. T. Wrixon and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1989), p. 1206-1208.

[401] Palz Wolfgang, *Power for the World: The Emergence of Electricity from the Sun*, Pan Stanford Publishing Pte. Ltd., 2011.

[402] Ionel Solomon, "Opening Address", *in* Eighth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Florence, Italy, 9-13 May 1988, I. Solomon, B. Equer and P. Helm (eds.), Vol. I, Kluwer Academic Publishers (Dordrecht, Boston, London: 1988), p. 13.

32%![403] It was the year that Japan climbed to the top. These a-Si shares and Japan's production increase are good indicators that competition was 'running-high', justifying the EC's (timely) decision to shift R&D to support the European industry on the a-Si front.

4.2.5.1.2 Organizing the a-Si research: the desirable outcome is for the European industry to reach the commercialization stage

The aim of a-Si research funded by the Commission was:

> "…the reduction of the technological gap between Japanese-US and European advancement in this field by establishing the basis for optimized highly efficient and stable single junction a-Si modules."[404] (emphasis added)

To achieve the above aim, the R&D activities for a-Si funded by the EC were organized around two companies, Messerschmitt-Bölkow-Blohm (MBB) from Germany and Solems from France. MBB was an aerospace manufacturer active in the satellite field.[405] Solems, was – and still is – a solar PV manufacturer specializing in a-Si solar cells.[406] The company was founded in 1981 by Ionel Solomon, a French solid-state physicist from Ecole Polytechnique. In 1986, Solems was listed as one of the smaller European solar cell manufacturers.[407] The involvement and role of these two companies in the EC's a-Si research action (Amorphous Silicon Solar Cells – AMOR) shows that there were industrial actors both willing and committed to supporting the development of a-Si cells and interested in 'transferring' the research conducted at AMOR to the commercialization stage. Concurrently, both the aim and the organization of

---

[403] The thin-film shares, until 1993, correspond only to a-Si. Accordingly, the thin film shares from 1994 onwards also include CIGS and CdTe. However, it should be noted that the CIGS and CdTe shares were small. Even after 1994, the bulk of the thin films' share (over 90%) corresponds to a-Si. By 2000, CdTe and CIGS had not reached even a 3MWp production capacity (Gerhard P. Willeke, "The Fraunhofer ISE Roadmap for Crystalline Silicon Solar Cell Technology", *in* Twenty-Ninth IEEE Photovoltaic Specialists Conference, New Orleans (USA), 19-24 May 2002, p. 53-57).

[404] Wolfgang Palz and Roger Van Overstraeten, "Photovoltaic Power Generation – R&D Programme in Europe", *in* Ninth EC Photovoltaic Solar Energy Conference, Proceedings of the international Conference held at Freiburg, Federal Republic of Germany, 25-29 September 1989, W. Palz, G. T. Wrixon and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1989), p. 1202.

[405] The company was defunct in 1989 and subsequently acquired by Deutsche Aerospace AG (DASA).

[406] Solems, today, is a SME manufacturer of a-Si cells, modules and sensors. For more information on the company and their products see: Solems, solems, *Company*, Available online: https://www.solems.com/en/, (accessed 3 December 2020).

[407] Solems along with other six other manufacturers were accountable for 30% of the PV cells/modules manufactured in Europe in 1986. The remaining 70% was produced by five companies in total, namely: Photowatt, Pragma, Telefunken, S International (a sister company of Photowatt) and Isofotón.

the AMOR activity around two European companies are a testament of the continuous efforts of the EC to use the R&D programmes to help strengthen the international competitiveness of the European industry.

Apart from the two companies mentioned above, the other actors in the a-Si networks had different expertise and/or were specialized in different parts of the PV system. For example, one of the other actors in the network was Saint Gobain, a French glass manufacturer, whereas another actor was Plasma Technology, a UK producer of deposition equipment.[408] The remaining actors, were universities and research centres/organisations, tasked to carry out research for the industrial partners. Some of the actors involved in the AMOR activity were prominent actors active on the c-Si cell research front (e.g. IMEC, ENEA, CNRS etc.). This should not be surprising, as these actors had experience and expertise in working with Si in a slightly different form and purity. Moreover, a-Si cells were meant to also be used for the field of semiconductor electronics. In this sense, the EC's shift to a-Si does not comprise a shift away from the interchangeable link between the two fields. The outcomes of this research could also find direct applications in the field of semiconductor electronics, despite receiving funding for PV applications. The AMOR action focused on the preparation of a-Si solar cells through the glow discharge technique, complemented by the evaluation of other, alternative, a-Si deposition methods. The research funded under the AMOR activity led to the identification of the glow discharge technique "[…] as a reliable and promising preparation method."[409]

Apart from organizing the a-Si research activities around two companies to support the commercialization of the funded research, there is another important point to note. This point concerns the way EC has conceptualized the means to achieve the AMOR aim. With the clear aim of increasing cell efficiency while reducing the corresponding costs, this was to be achieved through the establishment of cooperative transnational networks. The call for proposals from the EC specifically states that: "[…] Significant and cooperative projects will be preferred."[410] This was complemented by statement in the second call for proposals: "The

---

[408] Plasma Technology was not a participant in the AMOR activity, funded under the EC (i.e. there is no record indicating its direct participation in the funding project). However, Palz and Overstraeten inform us that the company supported the activity (see: Wolfgang Palz and Roger Van Overstraeten, "Photovoltaic Power Generation – R&D Programme in Europe", *in* Ninth EC Photovoltaic Solar Energy Conference, Proceedings of the international Conference held at Freiburg, Federal Republic of Germany, 25-29 September 1989, W. Palz, G. T. Wrixon and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1989), p. 1202-1205).

[409] Wolfgang Palz and Roger Van Overstraeten "Photovoltaic Power Generation – R&D Programme in Europe", *in* Ninth EC Photovoltaic Solar Energy Conference, Proceedings of the international Conference held at Freiburg, Federal Republic of Germany, 25-29 September 1989, W. Palz, G. T. Wrixon and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1989), p. 1202.

[410] Commission Communication concerning the development programme — Call for proposals, (C29, Volume 38), Official Journal of the European Communities, 16 March 1985, p. 6.

Commission will give preference to proposals submitted jointly by cooperating bodies located in different Member States."[411] Therefore, not only were the a-Si research activities organized around two European companies, but the EC called for the formation of transnational collaborative networks to achieve the R&D aim. Thus, collaborative networks were considered by the EC as a crucial way to achieve the R&D aim: aiding the European industry's international competitiveness. This means that the EC channeled knowledge produced through the funded projects to the European industry and steered pan-European efforts in a direction to become (industrially) internationally competitive. In this context, the first transnational collaborative networks were also established. The EC actively promoted the establishment of transnational collaborative networks to 'boost' and 'serve' the European industry's international competitiveness.

4.2.6.2 The first technoscientific c-Si network is established

FP1 funded a total of two c-Si projects. One was coordinated by Photowatt and the other by imec.[412] As illustrated in Figure 4.8 (below), the first network was small and consisted of five actors. Photowatt undertook research (alone) to develop a Si feedstock for the PV field (also known as SoG) to respond to the Si feedstock shortages.

We have already analysed imec and CNRS, as well as their role in their respective national contexts. Italsolar was the subsidiary of Eni, which entered the market through various companies (either subsidiaries or joint ventures). Pragma was renamed Italsolar in 1987 when control of the company was transferred to Agip, which was part of Eni's petroleum business. Similarly, we have already analysed the 'man' behind the company in the EC research projects. Prof. Pizzini coordinated these projects either as part of his affiliation with the Eni company or under as part of his affiliation with the University of Milan (Dept. of Physical Chemistry and Electrochemistry). For this project, he used both affiliations.

The Polytechnic University of Madrid (UPM) is a core actor for the CPV networks and research activities and is analysed in depth in chapter 6. To avoid repetition and at the same time support the current analysis, we need to mention that the UPM has been an important domestic actor in the field of PV. The head of the UPM team, Professor Antonio Luque, worked on c-Si as well as other semiconductors. Since the alternative design (i.e. CPV) he was primarily

---

[411] Commission Communication concerning the non-nuclear energy research and development programme – Call for proposals, (C146, Volume 29), Official Journal of the European Communities, 13 June 1986, p. 3.

[412] Each actor in the collaborative network signed separate contracts, in contrast to the projects supported under FP2 onwards where we see all network actors under a single contract.

interested in was excluded during FP1, we interpret his participation in the c-Si flat-plate research as a way to continue his research activities. Despite the differences in the two design options, they use the same semiconductor for the solar cells, so the Spanish team can continue its research activities within the c-Si research activities.

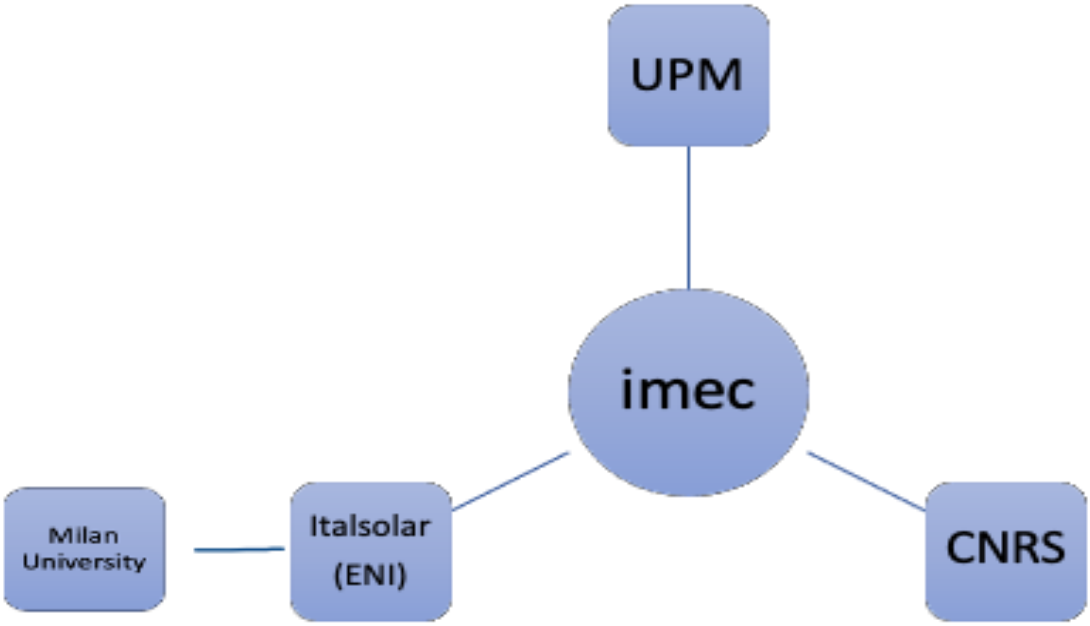


Figure 4.8 The first c-Si technoscientific research network.

Also influenced by the Si feedstock shortages, the actors formed a collaboration that essentially allocated the research activities to the actors involved.[413] In this context, imec was responsible for determining the viability of the c-Si cells made from upgraded metallurgical grade Si substrates, CNRS studied the cell substrates and was tasked with their characterization. UPM was responsible for cell modelling and the feasibility study, while Italsolar was in charge of fabricating the substrates.

4.2.7 The return of c-Si: the 'traditional' frontrunner in R&D funding

As we have already noted, the shift towards a-Si was temporary. For the remainder of the first period, R&D turned back to c-Si. Drawing from Figure 4.9 (below) we can see that c-Si

---

[413] Isofoton appears to have collaborated in the research activities, via UPM. However, the company was not officially listed in the corresponding EC records. It is possible that Isofoton participated in an indirect way, however the company does not seem to have been the recipient of EC R&D funding.

regained its leading funding place, accumulating a share of 43% of the total R&D funds for PV.

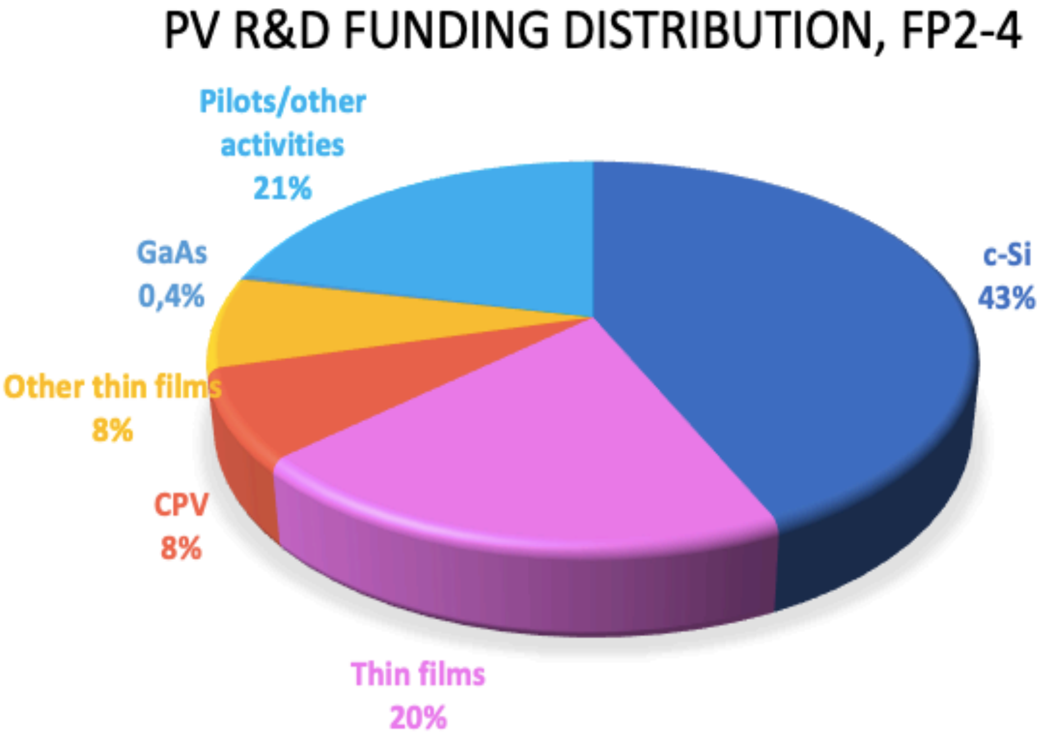


Figure 4.9 PV R&D funding distribution by technology and activity, (1989-1998).[414]

As we analyse in detail in chapter 6, CPV was re-included in the EU R&D activities for the remainder of the first period, but with a low funding share (8%). Thin film research activities received a 20% share of PV R&D funding for the remainder of the first period, but without reaching their FP1 funding glory. In the following sections, we examine why a-Si lost its former glory in funding. Next, we turn to the examination of the FP2-4 c-Si technoscientific research networks.

4.2.7.1 Oh a-Si, where are thou?

Before we analyse the technoscientific research networks of c-Si, we need to shed light on the events that led to the demise of a-Si. What essentially happened to cause interest in a-Si to decline so rapidly? To this end, we first examine the views of the international PV community before the shift. Next, we analyze the EC's rationale and justification(s) for

---

[414] Primarily includes research projects on system components (e.g. inverters, converters, batteries etc.), as well as data collection studies, monitoring and management of PV systems.

supporting c-Si research, while turning away from a-Si. Last, we turn to the first PV standards that were published while the EC was deciding the research priorities of FP2.

4.2.7.1.1 The views of the international PV community

In the early and mid-1980s, the international PV community was very hopeful about the future of a-Si solar cells. A-Si was seen as a possible competitor to c-Si, which dominated the market.[415] There were voices from the international scientific community that considered a-Si to be the 'future of photovoltaics'.[416,417] As Professor Gerhard Willeke noted, a-Si "was very 'on vogue' in the 1970s".[418] Moreover, the scientific community at the time was having "regular intense discussions about whether crystalline silicon was the future or rather thin film".[419] However, the actual potential of a-Si solar cells as a possible competitor to c-Si solar cells was not recognized until the early 1980s, when the a-Si cells were commercialised. Discussions on the potential of a-Si solar cells, involving important actors from the global PV community, can be traced to the EC PV Solar Energy Conferences. In summarising the key findings of the 1982 EC PV Solar Energy Conference, F.C. Treble stated that:

> "[J]udging by this Conference amorphous silicon appears to have displaced cadmium sulphide/copper sulphide as the front runner in this field."[420] (emphasis added)

Treble based the above statement on the lack of papers announcing higher efficiencies for CdS cells, which until the 1980s were the main thin film frontrunners along with CdTe cells. In contrast, papers were presented for a-Si efficiency increases, while were accompanied also by company announcements for the manufacturing of a-Si modules and cells. Prof. Willeke recalls

---

[415] A-Si solar cells entered the market around 1982, until then the only commercial solar cells were c-Si.

[416] Antonio Luque, "Photovoltaics in 1986: Routes to low cost", *in* Seventh EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Sevilla, Spain, 27-31 October 1986, A. Goetzberger, W. Palz and G. Willeke (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1987), p. 9-18.

[417] Indicative to the attention a-Si received is the increased number of papers presented in this area during the EC Photovoltaic Solar Energy Conferences during this period.

[418] Gerhard P. Willeke and Armin Rauber, "On the History of Terrestrial PV Development: With a Focus on Germany", *Semiconductors and Semimetals*, 2012, p. 16.

[419] Gerhard P. Willeke and Armin Rauber, "On the History of Terrestrial PV Development: With a Focus on Germany", *Semiconductors and Semimetals*, 2012, p. 16.

[420] F. C. Treble, "Conference Notebook", *in* Fourth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Stresa, Italy, 10-14 May 1982, W. H. Bloss and G. Grassi (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London, England: 1982), p. ix.

that by 1984, industrialization efforts for CdS had already been halted “due to inherent stabilities in the illuminated solar cells”.[421] Thus, we see how efficiency was used as an important parameter, or perhaps even as the basis for determining whether research on a material was ‘improved’ or not.

A year later, during the 1983 EC Photovoltaic Solar Energy Conference, a panel of experts discussed the future of PV and, in particular the predicted and/or expected long-term competitiveness of c-Si Vs thin films:

> “Dr. Prince (US Department of Energy) replied that it was too early to select or stress any particular approach. Thin-film cells had a long way to go to compete in terms of system cost and we might be surprised by a marked price drop in crystalline silicon once the new processes under current development were introduced. Dr. Barnett (University of Delaware) contended that significant new approaches in thin-film technology could lead to a ‘pay-off’. Mr. Smekens (ENE, Belgium) confessed that reports of advances in a-Si technology during the present Conference had caused him to change his mind on the question of thin-film v crystalline silicon and he now thought that a-Si was a real competitor. On this point, Prof. Hamakawa interjected that a-Si was in a transient stage at present and might compete in about ten years' time. Dr. Rosenfeld (Shell Research Laboratory) doubted the validity of the underlying assumption in the question that there would be a single 'winner'. In small systems, cell efficiency was less important than in large ones and so future applications might well be found for both thin-film and crystalline silicon. Prof. van Overstraeten supported this view. He thought that crystalline silicon had a bright future and that it was too early to judge if and when it would be overtaken by thin-film.”[422] (emphasis added)

Obviously, there were different opinions about thin film and crystalline silicon cells. Indeed, a-Si still had a long way to go if it was to ‘take over’ the place of crystalline silicon. However,

---

[421] Gerhard P. Willeke and Armin Rauber, “On the History of Terrestrial PV Development: With a Focus on Germany”, *Semiconductors and Semimetals*, 2012, p. 7-48.

[422] F. C. Treble, “The Future of Photovoltaics – A Report on the Panel Discussion”, *in* Fifth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Kavouri (Athens), Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 26-27.

many of the actors mentioned above agreed that perhaps there might be more than one 'winner'. This shows us that there was no single, dominant opinion shared by all. All possibilities seemed to be open. AEG-Telefunken, a producer of c-Si cells for satellites, which collaborated with Wacker in the development of multicrystalline Si cells, was also involved in a-Si research.[423] This is not to say that there was a consensus on the potential of a-Si solar cells. But we will come back to that in a later section.[424]

4.2.7.1.2 The EC's rationale and research results

The official statements from the EC on the return to c-Si was made in the context of the preparation of the FP2 call for proposals, during the 1989 PV Solar Energy Conference, when the head of the DGXII RES Unit for PV, Wolfgang Palz, stated:

> "The Commission is now in the process of starting a new R&D programme. It will take into account that Europe has a strong position in crystalline silicon modules and in systems."[425] (emphasis added)

Certainly, this statement reflects well the funding shift we observe in FP2 and which continues for the rest of the first period. As we have argued in earlier sections, the European PV community was built around the dominance of crystalline silicon. A material, in other words, was selected by semiconductor electronics actors who brought the experience and expertise to form the knowledge base of the European PV community. However, the argument of competition and industrial 'lead' does not justify such a rapid shift. While it provides us with a clear rationale that the Commission was consistent (i.e. aiding the industrial competitiveness of its actors), it does not tell us as why the Commission shifted its research agenda away from a-Si. Moreover, it was the Commission that shifted its entire research agenda to help its industrial actors to be competitive on the a-Si front. So, what happened? What changed?

---

[423] Gerhard P. Willeke and Armin Rauber, "On the History of Terrestrial PV Development: With a Focus on Germany", *Semiconductors and Semimetals*, 2012, p. 15.

[424] For the demise of a-Si see section 4.2.7.1.

[425] Wolfgang Palz and Roger Van Overstraeten, "Photovoltaic Power Generation – R&D Programme in Europe", *in* Ninth EC Photovoltaic Solar Energy Conference, Proceedings of the international Conference held at Freiburg, Federal Republic of Germany, 25-29 September 1989, W. Palz, G. T. Wrixon and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1989), p. 1204.

In the FP1 evaluation, the a-Si action was deemed as a success in terms of benefits for the participating companies.[426] This was related to the transnational competitiveness of Europe vis-à-vis the US and Japan, and the possibility that a-Si efforts of FP1 could be used to open-up a new market for the European companies. Another parameter that was praised was the transnational collaborative scope of the networks formed under FP1 to support the a-Si action. Therefore, FP1 praised the a-Si activities and called for a continuation of funding – should an increase not be feasible. The FP2 evaluation, in turn, provided an ex-ante justification shifting away from a-Si. In particular, as the evaluators stated:

> "In the preceding programme (NNE 3) the focus was mainly to start on amorphous silicon in Europe but results did not match expectations, so that it was decided for to renew the effort on crystalline silicon…"[427]

Even though the evaluators are rather cryptic in their 'justification', two things should be noted. First, Europe had a strong industrial interest in c-Si. Since the aim of the R&D programmes was to support European industry, we can only assume that the expected industrial interest in a-Si was not renewed. The second, which is directly related to the first, is the improvement of cell efficiency. The a-Si field in that respect (i.e. efficiency-wise) was deemed 'somewhat disappointing' because the targeted efficiency were not achieved and also because a large percentage increase was not considered possible, at least not compared to other materials.[428] When we spoke to an EC DGXII RES Unit Official about thin films and c-Si and the prioritization of the latter in the EU R&D funding schemes, they told us: "What I can say is that they did not really believe in thin films. Well, perhaps this is the wrong way of phrasing this. Yes, as you say the priority was on c-Si." The priority has (almost) always been on c-Si, as can be seen from the EU R&D funding flows. However, these developments took place at a time when the first PV standards were being prepared and published. It is to these standards that we now turn, as they provided legitimacy for the continued dominance of c-Si and indirectly marginalizing other technologies. This legitimization 'boosted' the measurement of

---

[426] Bondi Hermann, Amman Fernando, Jaumotte André, Marnet Chrysanth, Palomares Juan-José, Uffen Robert, Waldteufel Philippe, *Evaluation of the R & D programme in the field of Non-Nuclear Energy (1985-1988)*, Office for Official Publications of the European Communities (Luxembourg: 1988).

[427] Booth R. H., Bernardini O., Meyer-Henius U., Nuesser H., Williams R. H., Pereira de Moura D., "*Evaluation of the JOULE Programme (1989-1992)*", Office for Official Publications of the European Communities (Luxembourg: 1994), p. 60.

[428] Booth R. H., Bernardini O., Meyer-Henius U., Nuesser H., Williams R. H., Pereira de Moura D., "*Evaluation of the JOULE Programme (1989-1992)*", Office for Official Publications of the European Communities (Luxembourg: 1994).

the efficiency of c-Si flat plate PV and formed the base against which all other PV technologies had to be measured.

4.2.7.1.3 Settling the standards dispute: the winner takes it all!

> "…to hold a solar cell into the sunlight outside the atmosphere is not simple at all (neither is the measurement)."[429]

Indeed, measurements have proved to be at the very heart of heated debates and contestations. Whether it is about the use of different instruments, different principles, or different interests etc., measurement is never a simple topic. William Shockley and Hans J. Queisser were the first to measure the theoretical maximum limits of the c-Si cell efficiency in 1961.[430] William Shockley was one of the inventors of the first working transistor built on c-Si (monocrystalline). Shockley was called the father of Silicon Valley, which, as the name suggests, was built on the basis of a single material: (c-)Si. However, this theoretical measurement was based on monocrystalline silicon. As such, the first calibrations for applications were also based on the monocrystalline Si cell. When PV came to Earth, new calibrations had to be made because the parameters for the space calibrations were different. But how far did the PV fall from the tree when landing?

Robert Moore's description, made at the 1980 EC Solar Photovoltaic Energy Conference, is quite important.

> "The present technology for "terrestrial" Czochralski-Si solar cells is an adaptation of the processing developed and standardised for space/satellite power supply applications. This technology is in turn dominated by the processing techniques created by the general semiconductor industry."[431]

---

[429] Bogus K., Larue J. C., Crabb R. L., "SOLAR CELL CALIBRATION: RECENT EXPERIENCES AT ESTEC AND PROPOSAL OP A COMBINED SPACE AND TERRESTRIAL CALIBRATION PROCEDURE", *in* Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Luxembourg, 27-30 September 1977, D. Reidel Publishing Company (Dordrecht Holland, Boston USA: 1978), p. 755.

[430] W. Shockley and H. J. Queisser, "Detailed Balance Limit of Efficiency of *p-n* Junction Solar Cells", *Journal of Applied Physics*, 1961, p. 510-519.

[431] Robert M. Moore, "Czochralski-Silicon Solar Cell Modules: Present Cost and Future Prospects", *in* Third E.C. Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes, France, 27-31 October 1980, Wolfgang Palz (eds.), D. Reidel Publishing Company (Holland, Boston, London: 1980), p. 215.

Did the measurements for space PV influence the calibrations for terrestrial PV? Did the selection of c-Si for space applications influence the selection of c-Si as the dominant terrestrial material?

In May 1982, the International Electrotechnical Commission (IEC) formed a Technical Committee, known as TC82, to develop standards for terrestrial flat plate PV modules. During its inaugural meeting, TC82 established its first working groups (WGs). WG1 was responsible for terminology, WG2 focused on modules, whereas WG3 was responsible for systems.[432] The countries represented at the first TC82 meeting were the USA, Canada, Australia, UK, Germany, France, Spain, Italy and Japan.[433] The main focus was on the standards of WG2, which focused on the module (levels) standards. Two areas in particular were identified as priorities for WG2 module standardization: (1) performance measurement and (2) design qualification.[434]

By 1989, three standards on performance measurement had been published, whereas three others had been accepted and were pending publication. The three standards already published in 1989 were the following: IEC (60)904-3 1989: Measurement Principles, IEC (60)904-1 1987: Measurement of I-V characteristics, IEC 891 1986: Temperature and Irradiation Corrections. These three standards describe and define the conditions under which the measurements must be carried out: AM1.5, 1000Wm^{-2}, 25^{o}C etc.[435] The standards approved for publication were: computation of spectral mismatch error, spectral responses measurement, and solar simulator requirements.[436] In addition, there was another standard, "Requirements for reference Solar Cells", but unlike the others, no consensus was reached. In fact, it was not until 2009 that a standard for the "reference cell or device" was finally published.

The above standards were for flat plate PV for terrestrial applications. This means that the 'preferred' design of flat plate – and not concentrating PV (CPV) – was prioritised in the

---

[432] The IEC TC82 PV-related standards fall under the 60904 series. Since 1982 more WGs were established, each dealing with a different subject.

[433] Ossenbrink H., Mullejans H., Kenny R., Dunlop E., "Standards in the Photovoltaic Technology" *in* Photovoltaic Technology, W. G. J. H. M. van Sark (ed.), Vol. I, *in* Comprehensive Renewable Energy (ed. A. Sayigh), Elsevier (Oxford: 2012), p. 787-803.

[434] F. C. Treble, "IEC Standards for Photovoltaic Modules", *in* Ninth E.C. Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Freiburg, Fed. Rep. of Germany, 25-29 September 1989, Wolfgang Palz, G. T. Wrizon, and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1989), p. 627-630.

[435] F.C. Treble, "The CEC Photovoltaic Pilot Projects", *in* Sixth E.C. Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in London UK, 15-19 April 1985, Wolfgang Palz and F.C. Treble (eds.), D. Reidel Publishing Company (Holland, Boston, London: 1985), p. 474-480.

[436] F. C. Treble, "IEC Standards for Photovoltaic Modules", *in* Ninth E.C. Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Freiburg, Fed. Rep. of Germany, 25-29 September 1989, Wolfgang Palz, G. T. Wrizon, and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1989), p. 627-630.

standards. Furthermore, all measurements were based on the mono (or single) crystalline Si cell and took it as the 'reference point'. This meant that mono c-Si was legitimized as the preferred solar cell/module material in this way. In addition, to monocrystalline Si, multicrystalline Si was also legitimized in this way.[437] Through the standards, the established interests of the semiconductor electronics actors were legitimized.

However, in addition to the legitimization of the 'winning' material, there was also an indirect marginalisation. In particular, as later commented by JRC representatives in relation to IEC 60904 and 60891 (standards) series:

> "**All standards are applicable to PV devices in crystalline silicon technology**. However, there are **limits on their application to thin film technologies and more importantly to multi-junction technologies**. … there remain two areas which are not covered, namely multi-junction (nonconcentrating) PV devices and concentrating devices. Standards for the latter are under development …, whereas for multi-junction flat-plate PV devices, there is a lack of any IEC standard while the industry is producing such devices in noticeable volumes."[438] (emphasis added)

The c-Si cell was used as the baseline for the measurements. The calibrations would therefore be based on the properties and specific characteristics of this material. All other materials would be compared and contrasted with c-Si. The JRC representatives – some of whom participated in the original measurements carried out by the JRC in the late 1970s – explain or justify the selection of c-Si by the period in which these standards were developed. In particular, as the authors note, c-Si "was the dominating technology at that time".[439]

> "The work of WG2 on measurement procedures around the series IEC 60904 was almost completed; however, **the standardisation of calibration methods for reference cells** (used as reference standards to calibrate PV modules and

---

[437] Both mono and multi c-Si are wafer-based technologies – following similar processes known to the semiconductor electronics actors.

[438] Ossenbrink H., Mullejans H., Kenny R., Dunlop E., "Standards in the Photovoltaic Technology" *in* Photovoltaic Technology, W.G.J.H.M. van Sark (eds.), Vol. I, *in* Comprehensive Renewable Energy (ed. A. Sayigh), Elsevier (Oxford: 2012), p. 792.

[439] Ossenbrink H., Mullejans H., Kenny R., Dunlop E., "Standards in the Photovoltaic Technology", *in* Photovoltaic Technology, W.G.J.H.M. van Sark (eds.), Vol. I, *in* Comprehensive Renewable Energy (ed. A. Sayigh), Elsevier (Oxford: 2012), p. 792.

> solar simulators) **turned out to be difficult, as the few laboratories had different methods**, which produced some discrepancies in a range of round-robin tests. **It was only in 2009 that a document addressing the traceability of reference cells to SI standards could be published**."[440] (emphasis added)

The IEC TC82 standards legitimised both the choice of c-Si as the dominant PV solar cell technology and the design option (i.e. meaning flat-plate modules and not CPV). At the same time, the fact that the standards were based on calibrations for the c-Si cells indirectly marginalized other materials for the solar cells and the alternative design option. All other materials that could compete with c-Si would be 'measured' against the calibration standards created based on the dominant cell material. This indirectly empowers the role and dominance of the c-Si actors in the market and further reinforces their dominant position in the markets.

To summarize, the publication of the first PV standards and their content have led to two complementary and interrelated outcomes. First, the standards made c-Si the dominant technology based on which all measurements in PV were made. Second, all other technologies had to be constantly compared and contrasted to c-Si and the properties of c-Si on which the PV standards are based. This leads to an indirect marginalisation of all other technologies and design options as well as the actors supporting these technologies and designs.

With the emergence of c-Si as the dominant technology, the EC reoriented its research on c-Si. In this way, the EC could (continue giving) support a technology in which 'Europe had a strong position' – to paraphrase Palz's words. Concurrently, this could also be seen as a solution to the Japanese competition through standards, which further explains EC's shift. Essentially, one could say that the legitimization of c-Si through the standards gave a boost to the technology in which Northern Europeans had invested heavily. This strengthened their position in the international market and allowed them to claim a better 'place' in international competitions – also by marginalizing the technology that the Japanese had promoted and had an advantage.

---

[440] Ossenbrink H., Mullejans H., Kenny R., Dunlop E., "Standards in the Photovoltaic Technology", *in* Photovoltaic Technology, W.G.J.H.M. van Sark (eds.), Vol. I, *in* Comprehensive Renewable Energy (ed. A. Sayigh), Elsevier (Oxford: 2012), p. 789.

4.2.7.2 The geography of c-Si funding: the dominance of the European North continues

A total of twenty-eight (28) c-Si projects were funded for the remainder of the first period. Figure 4.10 (below) shows that R&D funding for c-Si was distributed among actors from eight countries. Based on the funding received by each actor, these countries are: Belgium, France, Germany, Italy, the United Kingdom, the Netherlands, Spain and Norway. Actors from Belgium, France and Germany accounted for approximately 77% of the total c-Si funding, whereas the remaining one-third of the funding was distributed among the other five countries.

The geographical distribution of R&D funds for c-Si from 1989 to 1998 does not show any striking differences from the rest of the first period. Denmark, Ireland and Greece, which were only marginally represented in the previous programmes, have stopped coordinating projects. In contrast, Norway appears on the PV R&D map for the first time. Towards the end of the first period, the European Economic Area agreement had entered into force, allowing Norway to participate in EU R&D programmes. As we analyse in a forthcoming section, Norway had several actors with vested interests in c-Si, and a booming Si feedstock and mining industry.[441] Spain continued to receive a small share of c-Si funding, similar to the previous programmes. Moreover, Spanish actors were primarily interested in CPV R&D. Given the re-inclusion of CPV in the EU R&D funding programmes, we note that the Spanish actors were 'transferred' there and formed the core of the CPV network and research agenda.[442]

Actors from Belgium, France, Germany, and Italy remained to be at the forefront of EU c-Si research activities. Belgium's rise in EU R&D funding is largely due to the creation of EUREC Agency, which we analyse in a forthcoming section. The Dutch initiated a national R&D programme in the late 1970s that included solar energy. However, solar thermal energy was given priority over photovoltaics.[443,444] In the 1990s, and especially in the context of climate change and the reduction of CO_2 emission, PV gradually started to play

---

[441] Regarding the latter, see chapter 7.

[442] See chapter 6.

[443] P. F. Sens, "The Dutch National Solar Energy and the International Energy Agency's Solar Heating and Cooling Programme", *in* First EC Conference on Solar Heating, Proceedings of the International Conference held at Amsterdam, April 30-May 4, 1984, C. Den Ouden (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 7-10.

[444] The programme primarily focused on heating and cooling from solar energy, not in the production of electricity.

a more important role in the Netherlands. This is reflected in the increased R&D funding that Dutch actors received in the 1990s.

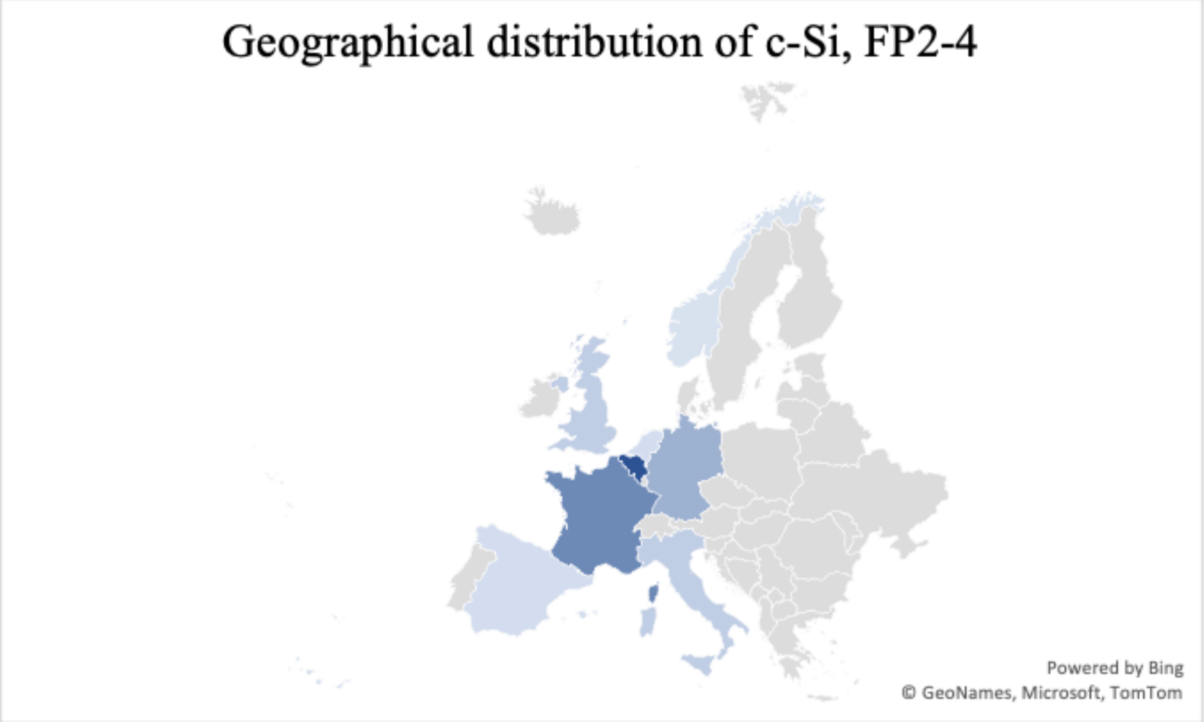


Figure 4.10 Geographical distribution of c-Si funding, 1989-1998.

It is important to remind the reader that the 1990s saw a general – OECD-wide – decline in public R&D spending on energy.[445] Despite the temporary 'boost' in energy (including RES), efforts on RES R&D declined steadily and steeply throughout the 1990s after the Chernobyl disaster. Even in countries like Germany, which traditionally spent a lot of money, R&D budgets were cut drastically.[446]

National research programmes (e.g. in Germany and France) continued to prioritize c-Si research.[447] In Italy, there has been a complete lack of R&D funding for PV since the mid-

---

[445] Breyer Ch., Kersten F., Gerlach A., Goldschmidt Jan, Stryi-Hipp Gerhard, Montoro D.F., Riede Moritz, "Research and Development Investments in PV: a limiting factor for a fast PV diffusion?", *in* 25th European Photovoltaic Solar Energy Conference /5th World Conference on PV Energy Conversion, Proceedings of the International Conference held in Valencia, Spain, 6-10 September 2010, G. F. De Santi, H. Ossenbrink and P. Helm (eds.), WIP Renewable Energies: 2010, p. 5385-5408.

[446] Schott T. and Neerf H. J., "The German Photovoltaic R&D Programme: Status and Prospects", *in* Fourteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Barcelona, Spain, 30 June – 4 July 1997, H. A. Ossenbrink, P. Helm and H. Ehmann (eds.), Vol. I, Published on behalf of WIP by H. S. Stephens & Associates (Oxfordshire, UK: 1997), p. 437-440.

[447] Wollin K., "Photovoltaics in Germany: Research. Development and Application", *in* Twelfth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Amsterdam, The Netherlands, 11-15 April 1994, Robert Hill, W. Palz and P. Helm (eds.), Vol. II, H. S. Stephens & Associates (UK: 1994), p. 1469-1473..; Schott T. and Neerf H. J., "The German Photovoltaic R&D Programme: Status and

1990s, which can help us understand why major Italian actors surged to the EU R&D programmes.[448] The situation of R&D funding in the UK was similarly dire.[449] However, UK actors had diversified their research interests as evidenced by the simultaneous decline in UK for c-Si and the simultaneous increase in CPV research funding.[450]

In the late 1980s and late 1990s, the first national demonstration programmes for PV were launched (e.g. in Germany and Austria).[451,452] These programmes were national initiatives to promote the further installation of PV systems. In parallel to these programmes, the first policy initiatives were adopted that promoted a more 'friendly' environment for the implementation of PV installations. Although these programmes cannot be compared in size with other similar programmes launched following the 1997 White Paper for RES, they represent the precursors of the efforts made to pave the way for these influential programmes and initiatives of the late-1990s.

The geographical scope of c-Si research activities supported by FP2-4 grew to include actors from Poland, Hungary, Lithuania, Greece, Denmark, Portugal, Austria and Australia. The actors from these countries were project participants and did not coordinate c-Si research projects. Apart from their 'limited capacity' participation, the majority of the actors from these countries were continuously involved in c-Si research activities and networks. Therefore, c-Si research funding, activities and networks remained concentrated in a handful of countries, mainly from the European North.

Prospects", *in* Fourteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Barcelona, Spain, 30 June – 4 July 1997, H. A. Ossenbrink, P. Helm and H. Ehmann (eds.), Vol. I, Published on behalf of WIP by H. S. Stephens & Associates (Oxfordshire, UK: 1997), p. 437-440.; A. Claverie A., Bal J. L., Chartier P., "Photovoltaics in France: Research, Development and Promotion", *in* Thirteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Nice, France, 23-27 October 1995, W. Freiesleben, W. Palz, H. A. Overstraeten, P. Helm (eds.), Vol. I, H. S. Stephens & Associates (UK: 1995), p. 891-893.

[448] A detailed analysis of the Italian R&D funding programmes and overall situation can be found in Chapter 6.

[449] A detailed analysis of the UK R&D funding programmes and overall situation can be found in Chapter 6.

[450] See analysis in Chapter 6.

[451] This point is further analysed in forthcoming sections.

[452] Even though we do not analyse the Austrian demonstration activities for PV, it is important to note that the electric utilities, which were in charge of the projects, supported and/or promoted the installation of different of PV system scale(s) and system integration options. Ranging from stand alone to grid connected and small-scale PV installations to power plants. For more information see: Nentwich Alfred, Schneeberger Michael, Szeless Andreas, Wilk Heinrich, "Photovoltaic activities of Austrian Electric Utilities – Projects and Experiences", *in* Ninth EC Photovoltaic Solar Energy Conference, Proceedings of the international Conference held at Freiburg, Federal Republic of Germany, 25-29 September 1989, W. Palz, G. T. Wrixon and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1989), p. 1119-1121.; Nentwich Alfred, Schneeberger Michael, Szeless Andreas, Wilk Heinrich, "30kW Photovoltaic Plant in the Alps of Austria", *in* Tenth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Lisbon, Portugal, 8-12 April 1991, A. Luque, G. Sala, W. Palz, G. Dos Santos, and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1991), p. 766-770.

4.2.7.3 The technoscientific c-Si research networks: the concentration in the European North continues

As illustrated in Figure 4.11 (below), several and interlinked networks emerged between FP2 and FP4. These networks included a total of twenty-five actors from Germany, France, Belgium, Italy, the Netherlands, Spain, the UK, Norway, Switzerland and Denmark.[453] Together, the actors in these interlinked networks form the EU's knowledge base for PV.

We developed a methodology for producing the following illustrations, for both periods and in all case studies. Overall, one criterion for including the actors in the network illustrations was their continuous presence in the EU-funded research projects.[454] Based on this criterion, for the FP2-4 c-Si networks, actors from Poland, Hungary, Lithuania, Greece, Denmark, Portugal, Austria and Australia, who participated in the projects but were not continuously involved were excluded from the illustration. In the illustration (Fig. 4.11), the actors are arranged in a circle or a rectangle. The actors who (also) coordinated c-Si projects have been placed in a circle, while the actors who only 'entered' the networks as participants have been placed in a rectangle. We understand the project coordinators as actors with recognized expertise who can also promote and enable the establishment of collaborations. Usually, project coordinators have overall supervision of the project. They can concentrate all the knowledge generated within the project and 'decide' about its direction. In contrast, the project partners, even though they also have expertise in the particular task they are undertaking, now have a holistic overview of the knowledge generated and therefore play a less decisive role in its directionality.

The network illustration actors indicate places or spaces where knowledge is created and/or constructed and places where knowledge is situated. Correspondingly, patterns of collaboration and the links between actors (lines connecting the actors) indicate the circulation and diffusion of knowledge.[455] The number of ties/links is understood as an important parameter. Not only because it indicates the ability of actors to forge collaborations, but also because it reinforces the role and centrality of actors in networks.

---

[453] The analysis of the Spanish and British actors and domestic research landscapes is analysed in Chapter 6. Thus, for the needs of the current analysis we only provide brief examples to avoid repetition. Similarly, some of the Italian actors are thoroughly analysed in Chapter 5, as well as the Italian domestic R&D landscape and activities. Here we only analyse the actors that had were involved in c-Si research, which are not analysed in Chapter 6.

[454] This means that the actors had to participate in more than one c-Si research project – similar for coordination – either within a single FP or throughout different FPs. Actors with a single participation have been excluded from the illustration.

[455] The arrows do not indicate the directionality of knowledge. Rather they have been employed for making the links clearer.

More ties, especially in combination with the coordinator/partner criterion, indicate the actors' extensive expertise in c-Si research. Thus, they indicate where knowledge is situated and where knowledge originates and/or is diffused or concludes. This is further complemented by the forthcoming analysis. Finally, we used different colours when drawing the lines to aid the better distinguish of links between the actors. The different colours do not denote any asymmetry in the relationships between the links or between the actors. They were only employed for better visualization and convenience, to make the illustration 'clearer' and to reduce the number of lines that would possibly lead to overlapping and less visible lines.

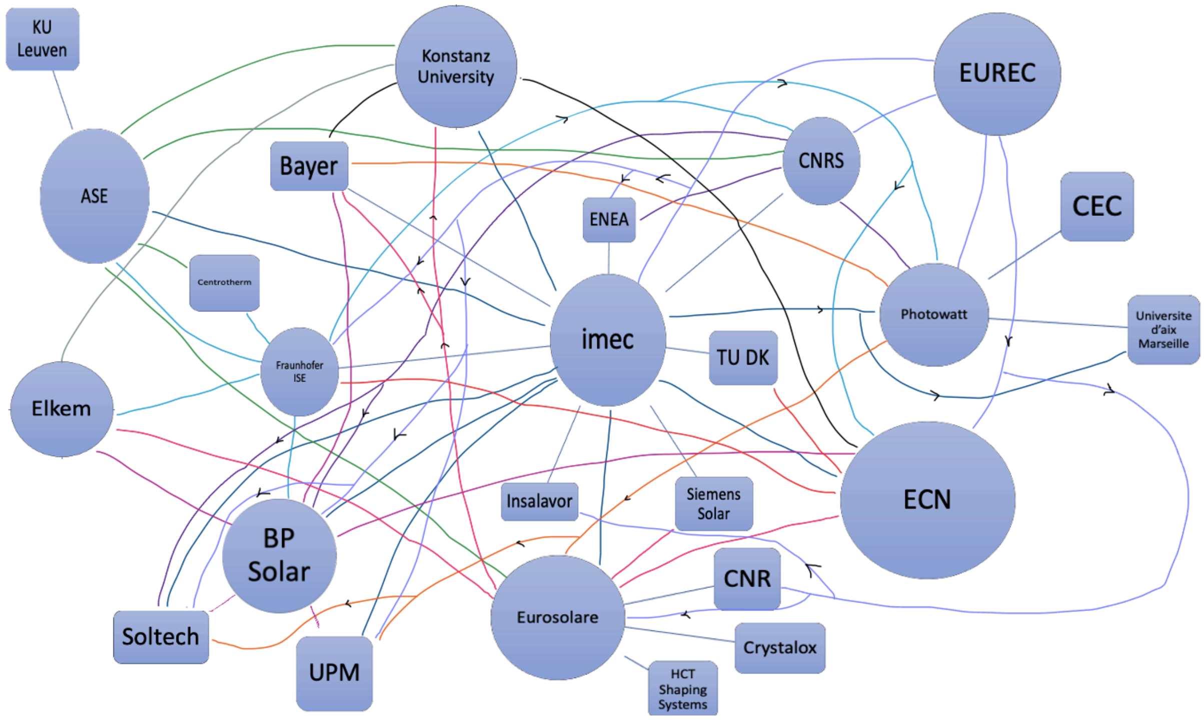


Figure 4.11 The c-Si technoscientific research networks, 1989-1998.[456]

During the first period, the majority of c-Si projects were coordinated by companies (43,9%), followed by (large) research centres (27,7%) and universities (19,7%). Accordingly, the participation of companies in the projects was the highest (44,6%), followed by research centres (28,3%) and universities (19,7%).[457,458]

---

[456] All actors within a circle continuously coordinated projects, in contrast to the actors within a square that had a continuous presence in the programmes and in the networks but only as project participants.

[457] The remaining shares for both cases, coordinators and participation ratios, correspond to other actors (i.e. a public electric utility (EDF)).

[458] These shares correspond to the entire first period (1975-1998).

From Figure 4.11 we see that only a handful of companies played a central role in the networks (i.e. Photowatt, Eurosolare, ASE, BP Solar, and Elkem). This suggests that knowledge was either created and/or (re)directed to a small number of companies that were primarily c-Si cell/module manufacturers.[459] This resonates well with the primary research focus of the first period: the solar cell.

It is important to note that although the first projects to develop a silicon feedstock for the PV industry appear in 1997 and 1998 (the end of the first period), they are different from the corresponding projects of the second period. The contextualization and justification for the development of a SoG by the historical actors themselves is different from the second period. In these (few) projects, the development of SoG is defined as an issue of dependency from the electronics industry. Essentially, the actors sought to develop feedstock that was independent of the electronics industry. The projects were not linked to the White Paper for RES, and thus to energy policy, nor to the impeding feedstock crisis (second period). Their justification and rationale was based on economic reasons (cheaper SoG) and to a lesser extent on helping European industry to remain competitive and independent.

The share of research centers is greater, as almost all of them coordinated projects and established collaboration ties and/or links with a large number of actors.[460] Lastly, among the universities, the situation is somewhat more balance, with the University of Konstanz and UPM playing a more central role and the University of Newcastle, KU Leuven and Universite d'aix Marseille being involved in the networks only through collaborations.

It is almost impossible to elaborate every single collaboration. It is equally not desirable. The (majority of the) actors from Spain and the UK are not analysed here, as they formed the core of the CPV technoscientific research networks and are examined in chapter 6. The analysis of the Spanish and British research landscape is also found in chapter 6. Similarly, the analysis of the Italian R&D programme, research landscape and actors is found in chapter 6. In the following analysis, we only briefly discuss the actors from these countries in relation to their contribution to the c-Si networks when/where necessary.

Despite the large number of actors depicted in Figure 4.11, we can see that a large number of actors participated with a limited capacity. These actors are the following: HCT Shaping Systems, KU Leuven, Newcastle Uni, UPM, Crystalox, CEC, Centrotherm, TU DK, Insalavor, CNR, Universite d'aix Marseille, ENEA, Soltech, Siemens Solar and Bayer. Some of these

---

[459] All except Elkem, during the period under examination.

[460] Exception is the CNR.

actors, comprised project partners and thus dependent on other ('core') actors to enter the networks. Some of these actors had a (highly) specialized expertise. For example, HCT Shaping Systems, which was established in 1984, specialized in the development of machines for sawing wafers. The company is credited with being the "first introduced the wire saw, which proved to be important for mass production of crystalline silicon solar wafers and, therefore, for the early PV industry."[461,462] Similarly, Centrotherm develops and supplies the electronics and PV industries with machinery and equipment, specializing in furnaces.[463] Soltech and Bayer collaborated with a larger number of actors than any of the other actors listed above. Bayer started participating in the c-Si projects at the end of the first period (FP4), which covered research on more than one PV system component (e.g. from feedstock to module). Soltech, a spin-off from imec, was founded in 1989 to "commercialize PV systems based on IMEC's silk-screen process".[464] As the company had very limited manufacturing capabilities, its production in the 1990s was based on 'by-hand' assembly.[465] This shows the tie between imec and Soltech in the networks. Soltech participated – almost exclusively – in projects that were either coordinated by imec or in which imec was involved. Essentially a means for imec to transfer the knowledge generated by the projects to its spin-off. The contribution of these actors can be accounted by the discrete expertise they 'brought' with them to 'serve' a highly specialized part of the research activities, while (enabling them) to further enhance their expertise according to the scope and theme of the projects. The universities primarily participated in the projects to conduct studies, measurements and simulations.

In contrast to the actors mentioned above, the remaining ten actors played a central role both in generating knowledge about c-Si, in transforming its technical characteristics and in directing and actively shaping the research agenda for c-Si. Even though we will elaborate further in the analysis that follows, we should note that (i) these companies were major PV cell/module manufacturers at both a European and global level and (ii) the scientific actors (research centres and universities) had emerged from their respective national research

---

[461] Philip R. Wolfe, "Profiles of Early PV Companies and Organizations", *in* The Solar Generation: Childhood and Adolescence of Terrestrial Photovoltaics, John Wiley & Sons Inc. (Hoboken, New Jersey: 2018), p. 236.

[462] Sassault Systemes, 2002, 3ds, *HCT Shaping Systems S.A., Innover tout en ameliorant la productivite*, Available online: https://www.3ds.com/fileadmin/customer-stories/import/pdf/HCT-SHAPING-SYSTEM-Flyer.pdf, (accessed 2 December 2020).

[463] Centrotherm, Centrotherm, *Company – Our mission*, Available online: https://www.centrotherm.de/en/company, (accessed 1 December 2020).

[464] Philip R. Wolfe, "Profiles of Early PV Companies and Organizations", *in* The Solar Generation: Childhood and Adolescence of Terrestrial Photovoltaics, John Wiley & Sons Inc. (Hoboken, New Jersey: 2018), p. 252.]

[465] Solems, solems, *Company - About us*, Available online: https://www.solems.com/en/, (accessed 3 December 2020).

landscapes as the dominant PV research hubs and were internationally recognized as c-Si experts.

Based on all the above, the main geographical loci of the c-Si technoscientific networks are Belgium, Germany and, to a lesser extent, Norway, the Netherlands, France and Italy. In the following analysis, we first examine the national research landscape of each country and place the main actors in this landscape by providing information on their background and national collaborative patterns that relate to EU networks – where applicable. Furthermore, we provide examples of the direction of knowledge and the particular expertise of the actors, while the analysis of the actors allows us to show the continuity and further dominance of semiconductor electronics in the field of PV.

The actors continuously involved in the c-Si projects (FP2-4) were imec, CNRS, Photowatt, Eurosolare and Fraunhofer ISE. Thus, the main Belgian, French, and German scientific actors were continuously involved in the c-Si research activities, complemented by (the) main Italian and French industrial PV actors. From FP3 onwards, EUREC and ENC were involved, whereas in FP4 Elkem, ASE, BP Solar and the University of Konstanz started to enter the c-Si networks. Hence, the networks were gradually joined by the larger Dutch scientific actor, another important German actor and large European industrial actors from Germany, Norway and the UK.[466]

Belgium

Even though we know that Belgium had a national R&D energy programme that included research on PV, we do not have detailed information on its contents (e.g. priorities, technologyies etc.). The Belgian R&D programme for PV was not as extensive financially as the German, French and Italian programmes. Rather it was at about the same level as the Dutch and the British.[467]

The European Renewable Energy Centres Agency (EUREC) was founded in 1991 by Professor Roger van Overstraeten to revive interest in RES, by bringing together all the major European research centres and universities under a single umbrella.[468] It is important to note that we include EUREC in the Belgian actors and in the calculation of funding shares because EUREC

---

[466] Primarily the Germans, and to a lesser extent given their network position, the French had a prominent position in the networks had both the scientific and industrial capacities to (i) develop the knowledge generated by the research activities supported by the EU and (ii) to redirect it and/or incorporate it for the commercialization of the technology.

[467] Christopher Flavin, “Photovoltaics: International Competition for the Sun”, *Environment: Science and Policy for Sustainable Development*, 1983, p. 7-44.

[468] EUREC Agency was part of the European Renewable Energy Council, see analysis in chapter 2.

is based in Belgium. However, as EUREC is an umbrella for several large European actors, we focus our attention on the actors that comprise the EUREC-led c-Si projects. Before the creation of EUREC, the Belgian actors had a 69,8% share in the funding of c-Si research (FP2). Due to EUREC this share increased to 93,6% in FP3, whereas the corresponding share decreased to 27,3% in FP4.

The most prominent Belgian actor and a crucial actor for the networks is the imec. The imec was continuously involved in c-Si research from FP2 to FP4, embarking on projects that covered research on more than one PV system component and coordinating projects focused on the solar cell (increasing solar cell efficiency while reducing the corresponding costs). This actor was involved in more than half of the c-Si projects and was linked to/collaborated with sixteen actors. Moreover, imec collaborated with all the other main actors; the only exception being Elkem.

We have already analysed both imec and Prof. Roger van Overstraeten and his role and expertise in a previous section. Prominent individuals such as Jef Poortmans, whom we analyse in the second period section, started to lead imec's c-Si research activities in the 1990s. Imec emerged as a major actor in EU-funded c-Si research in the mid-1980s, a 'place' that was further strengthened in the 1990s.

Germany

It was not until FP4 that German actors began to coordinate c-Si projects, which accounted for 17,7% of the funding. Of all the German actors we see in the network illustration, Fraunhofer ISE was the only actor that continuously participated in the c-Si projects from FP2 to FP4. The majority of the other German actors we see in the networks are large PV cell/module manufacturers, accompanied by the University of Konstanz, which was the only university that played an important role in EU research for c-Si. This clearly shows that the German actors had a strong position in generating knowledge and had industrial interests and capabilities. Given the above, and the synergies formed (both domestically and in the EU-funded networks), the German actors also had an interest in transferring this knowledge to industry.

German national R&D programmes have traditionally prioritized c-Si since the launch of the first R&D programme in the 1970s.[469] Despite declining domestic funding, c-Si continued to

---

[469] Koepke R., "Photovoltaic Research and Development Projects in the Federal Republic of Germany", *in* Second Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Berlin (West), 23-26 April 1979, R. Van Overstraeten and W. Palz (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London, England: 1979), p. 1120-1127.; Eisenbeiß G. and Batsch J., "The Photovoltaic Program of the Federal Republic of Germany", *in* Seventh EC Photovoltaic Solar Energy Conference, Proceedings of the

be a priority in German research programmes in the 1990s.[470] Solar PV in Germany met opposition in the early 1980s, but this time in the establishment of what now is one of the largest and most influential institutes in the field of PV worldwide: the Fraunhofer's Institute for Solar Energy Power (ISE). The person behind the establishment of ISE is Professor Adolf Goetzberger, a German physicist who was at the epicenter of the flourishing field of semiconductor electronics and spent several years alongside a key figure in the field, William Shockley.[471] Goetzberger was a strong proponent of solar photovoltaics, which he believed would and could become a competitor to fossil fuels. However, his opinion was not shared by everyone. When Fraunhofer announced its plans to found ISE, a representative of the research administration commented:

> "A German solar institute is even more unnecessary as the American Solar Energy Research Institute. It can only be used to collect university-educated solar energy researchers that cannot find a job in industry."[472]

The above statement helps us understand, at least in part, why PV met with so much opposition in Germany. Apart from the powerful nuclear lobbies that helped determine energy policy priorities, there was another side to the opposition.[473] They did not believe that PV could be a viable alternative to fossil fuels, let alone a "real" option for electricity generation. Moreover, we must not forget that during this period the field of PV was still small. The production

---

International Conference, held at Sevilla, Spain, 27-31 October 1986, A. Goetzberger, W. Palz and G. Willeke (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster, Tokyo: 1987), p. 1162-1169.; Eisenbeiß Gerd, "The PV Program of the Federal Republic of Germany", *in* Eighth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Florence, Italy, 9-13 May 1988, I. Solomon, B. Equer, and P. Helm (eds.), Vol. II, Kluwer Academic Publishers (Dordrecht, Boston, London: 1988), p. 1609-1614.

[470] Schott T. and Neerf H. J., "The German Photovoltaic R&D Programme: Status and Prospects", *in* Fourteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Barcelona, Spain, 30 June – 4 July 1997, H. A. Ossenbrink, P. Helm and H. Ehmann (eds.), Vol. I, Published on behalf of WIP by H. S. Stephens & Associates (Oxfordshire, UK: 1997), p. 437-440.

[471] For more information of Professor Adolf Goetzberger see: Fraunhofer ISE, 30 November 2018, Press Release: Professor Adolf Goetzberger Turns 90: Pioneer of the Energy Transformation and Founder of Fraunhofer ISE, ise-fraunhofer, Available online: https://www.ise.fraunhofer.de/en/press-media/press-releases/2018/professor-adolf-goetzberger-turns-90-pioneer-of-the-energy-transformation-and-founder-of-fraunhofer-ise.html, (accessed 5 October 2019).

[472] Quote as cited in Willeke Gerhard P. and Rauber Armin, "On the History of Terrestrial PV Development: With a Focus on Germany", *Semiconductors and Semimetals*, 2012, p. 15.

[473] Michael Schüring, "Advertising the nuclear venture: the rhetorical and visual public relation strategies of the German nuclear industry in the 1970s and 1980s", *History and Technology*, 2013, p. 369-398.; Christian Joppke, "Social Movements during Cycles of Issue Attention: The Decline of the Anti-Nuclear Energy Movements in West Germany and the USA", *The British Journal of Sociology*, 1991, p. 43-60.; Andrew S. McFarland, "Energy Lobbies", *Ann. Rev. Energy*, 1984, p. 501-527.

capacity of PV cells/modules had not exceeded the total of 5-6 MW globally in 1981. Europe accounted for only a very small part of global production; the USA was the main producer. Furthermore, in a country like Germany, where linking research, industry and production was crucial 'to be taken seriously', it was important that PV research found support in industry. Because of his commitment to solar PV, and despite all the opposition he faced, Goetzberger succeeded in establishing ISE in 1981. As an important figure in the field of PV, Professor Willeke, noted[474]:

> "It was only due to the perseverance and stubbornness of the founding director, Prof. Adolf Goetzberger, that the founding of the today's second largest Fraunhofer institute was carried out against all odds."[475]

Soon after ISE was founded, several other research institutions were established in the late 1980s (e.g. ISET in Kassel, SEHR in ZSW etc.). However, there were at least two events that affected the changing attitude towards PV research in Germany in the mid to late 1980s. First, large industrial actors such as AEG-Telefunken and Wacker Chemitronic became involved in solar PV. These actors received substantial financial support from both the German and the EC R&D programmes for PV. The confirmed interest and commitment of industry thus contributed to changing the view of PV in Germany and provided the link between research and industry desired by the research administration. Second, the Chernobyl accident in 1986 helped to gradually steer research towards RES and away from nuclear energy.[476] Nuclear energy met resistance from activist movements and civil society.[477] Concurrently and directly related to the first point, RES was understood as a means of responding to climate change and hence as a more environmentally friendly energy source.[478] This helped to legitimize the further support for RES and strengthened the position of RES supporters domestically.

---

[474] For more information on Professor Willeke, see the corresponding analysis in chapters 4-5.

[475] Willeke Gerhard P. and Rauber Armin, "On the History of Terrestrial PV Development: With a Focus on Germany", *Semiconductors and Semimetals*, 2012, p. 15.

[476] Karl-Werner Brand, "Dialectics of institutionalisation: The transformation of the environmental movement in Germany", *Environmental Politics*, 1999, p. 35-58.; Russel J. Dalton and Robert Rohrschneider, "The Environmental Movement and the Modes of Political Action", *Comparative Political Studies*, 2003, p. 743-771.

[477] Christian Joppke, "Nuclear Power Struggles after Chernobyl: The Case of West Germany", *West European Politics*, 1990, p. 178-191.

[478] Eisenbeiß Gerd, "The PV Program of the Federal Republic of Germany", *in* Eighth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Florence, Italy, 9-13 May 1988, I. Solomon, B. Equer, and P. Helm (eds.), Vol. II, Kluwer Academic Publishers (Dordrecht, Boston, London: 1988), p. 1609-1614.

With a long tradition in the field of c-Si PV dating back to the 1970s, the current Photovoltaics Division at the University of Konstanz (Department of Physics) is recognized internationally as a knowledge-hub for PV. The Konstanz team started participating in the EU-funded c-Si activities at the end of the first period (in FP4) and was the only university to take a central position in the c-Si networks. The University of Konstanz collaborated with (five) other research centres and companies that were core actors in the c-Si networks. Similarly, Fraunhofer ISE collaborated with a large number (six) of core actors from different regions. Within the German research landscape, Fraunhofer ISE and the University of Konstanz collaborated with each other, while building synergies with industry. The two actors, although not shown in the illustration, collaborated on c-Si projects. One such case was a project led by the leading German PV company at the time, Angewandte Solarenergie GmbH (ASE) (see ASE links in Fig. 4.11).

ASE, which we see in the c-Si networks is in fact an actor we have seen before in c-Si research. ASE consists of a company that emerged from several mergers and acquisitions. When AEG went bankrupt in the late 1980s, despite the efforts of both by the EC and the German government, its solar PV division was bought by Daimler Benz for its Deutsche Aerospace AG (DASA). DASA was an aerospace manufacturer established in 1989 by the company we now know as Mercedez-Benz (Daimler Benz AG). DASA was established on the basis of the acquisition of two large German companies, AEG and MBB, both of which we have seen in the EC R&D PV programmes. In parallel, MBB collaborated with Total Energie. In the context of this collaboration, they jointly established Phototronix (c-Si cells manufacturer). Nukem started manufacturing c-Si cells in 1979 through its subsidiary RWE. In 1994, RWE established ASE, which was essentially created from the know-how of the PV activities of DASA, Nukem and Phototronix. Essentially, ASE incorporated the know-how and expertise of several major companies with a background in semiconductor electronics. As a late entrant in the networks (FP4), ASE collaborated with Fraunhofer ISE and the University of Konstanz.[479] Hence, both important domestic scientific actors of Germany. ASE and Fraunhofer ISE worked together continuously in half of the projects we see ASE.[480] Additionally, ASE collaborated mainly with research centres (imec, CNRS), but also collaborated with other companies (Eurosolare and Centrotherm) and a university (KU Leuven). ASE primarily embarked on projects involving

---

[479] We attribute the late (re)entrance of ASE in the c-Si research activities to the reformulations the company was undergoing.

[480] Under FP4, the projects coordinated by one of the two included the collaboration with the other. Essentially, the Fraunhofer-led project included ASE in its network and vice versa.

the examination and evaluation of the potential thermal cost reduction in the manufacturing of c-Si cells. In one such project, ASE was responsible for the economic evaluation of the proposed route, whereas Fraunhofer ISE conducted measurements to determine the conversion efficiency of the cells that would be produced using the route under study.

Lastly, Siemens Solar must also be mentioned, although it was only a project participant. Even though Siemens had manufacturing know-how and capacity for solar cells (for space applications), its interest in terrestrial PV remained limited in the 1970s. Instead, Siemens began its terrestrial PV activities in the 1980s. Siemens Solar was established in 1986 and specialized in the production of monocrystalline Si cells. In 1991, Siemens acquired the PV business of Arco Solar, which allowed Siemens to further expand both its market and its production capacity.[481] This acquisition made Siemens a leading PV company worldwide.[482]

The Netherlands

After the 1973 oil crisis, Dutch energy research activities were extended to other energy sources. When the first programme started in 1978, PV was not considered a possible energy option due to the country's climatic conditions and because "…of the small scale of applications."[483] In the Dutch framework, therefore, both the country's geographical climatic conditions and the small-scale applications of PV were not considered an attractive option. The small-scale of PV was used as a justification for limiting domestic research and development.

Thanks to the extensive efforts of researchers, who were the only promoters of PV until the 1980s, the sentiment towards PV began to change in the early 1990s.[484] PV were described as "the ultimate renewable energy option for the (long-term) future."[485] Two additional parameters contributed to the change in attitude towards PV: (i) environmental concerns and (ii) the placement of PV in Shell's vision. Changing public perception and the role of Greenpeace played an important role. In addition to the interest of universities and research

---

[481] Philip R. Wolfe, "Profiles of Early PV Companies and Organizations", *in* The Solar Generation: Childhood and Adolescence of Terrestrial Photovoltaics, John Wiley & Sons Inc. (Hoboken, New Jersey: 2018), p. 199-270.

[482] Data and information about the PV companies can be accessed via the JRC PV Status Reports that are published annually.

[483] Geert Verbong, Frank W. Geels, Rob Raven, "Multi-niche analysis of dynamics and policies in Dutch renewable energy innovation journeys (1970-2006): hype-cycles, closed networks and technology-focused learning", *Technology Analysis & Strategic Management*, 2008, p. 566.

[484] Within the Dutch PV R&D programmes, c-Si cells were (continuously) prioritized.

[485] Geert Verbong, Frank Geels, "The ongoing energy transition: Lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960–2004)", Energy Policy, 2007, p. 1034.

centres in PV, private sector support for PV was also important.[486] Shell had been involved in PV efforts since the early days of PV development. The company entered the PV business by acquiring shares of other companies (e.g. Shell acquired a 35% share in Photowatt in 1991) and through joint ventures (e.g. Shell and Motorola established Solavolt in the 1980s). Despite the long history of Shell's PV activities, perhaps one of the most important contributions to PV was a publication. Shell was the first oil company to include PV in its future projection scenarios – and thus in its energy vision – and attributed a significant contribution to PV.[487] Following these projections, Shell further expanded its PV business in 2002 after acquiring Siemens Solar (PV division).[488]

The Energy Research Centre of the Netherlands (ECN), as the largest Dutch energy research centre, has played an important role in the country's R&D in the field of RES, including PV.[489] It is a crucial hub in shaping the scientific basis for the development of PV. The Netherlands Agency for Energy and the Environment (Novem) has been responsible for managing and coordinating the Dutch solar PV programmes. In the 1990s, and especially after 1996, renewable energy was re-casted in the Dutch framework. As they were understood as a means to address the urgent challenge of climate change and the need for CO_2 emission reductions, RES began to garner more support. The projects that the programme supported until the mid-1990s were exclusively "(flat-plate) semi-crystalline silicon cells".[490] For the rest of the 1990s, R&D funding for PV continued to be directed towards cell research, especially c-Si.[491] This clearly shows that the Dutch were explicitly interested in c-Si. Thus, the Dutch 'used' the EU R&D programmes as a means to further strengthen their main domestic research interest (i.e.

---

[486] We have already discussed Phillips extensively in the present Chapter and how this major Dutch company embarked on PV research early on since the 1970s. Moreover, we have already analysed how Phillips entered the EC PV R&D projects through various (French) subsidiaries.

[487] Shell, *The Evolution of the World's Energy Systems*, Shell International (London: 1996).

[488] For more information on Shell, as well as all other major European and international PV industrial actors see: Philip R. Wolfe, *The Solar Generation: Childhood and adolescence of terrestrial photovoltaics*, John Wiley & Sons Inc. (Hoboken, New Jersey), 2018.

[489] ECN was founded in 1955 as the Reactor Centre Netherlands and was renamed to ECN in 1976 following the oil crises. ECN's R&D activities focused on PV, wind energy and biomass, as well as energy efficiency etc. In 2018, ECN joined forces with TNO (Netherlands Organisation for Applied Scientific Research). In the beginning of 2020, the ECN part of TNO was renamed to Energy Transition.

[490] A. F. J. van de Water, E. H. Lysen, L. Bosselaar, "Solar Energy in the Netherlands: recent progress", *Renewable Energy*, 1994, p. 1375.

[491] M. Muradin-Szweykowska, E. W. ter Horst, "The Netherlands Photovoltaic National Programme", *in* Tenth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Lisbon, Portugal, 8-12 April 1991, A. Luque, G. Sala, W. Palz, G. Dos Santos, and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1991), p.1390-1393.; A. F. J. van de Water, E. H. Lysen, L. Bosselaar, "Solar Energy in the Netherlands: recent progress", *Renewable Energy*, 1994, p. 1371-1378.; E. E. M. Luiten and K. Blok, "Energy R&D in the Netherlands", Prepared for the US Department of Energy under contract DE-AC06-76RLO 1830, April 1999, Battelle Memorial Institute.

c-Si) and as a means of complement other PV technologies that were not supported in the domestic R&D programmes.

ECN, which led the Dutch c-Si project(s), started coordinating c-Si projects towards the end of the first period (FP4) and received a total of 4% of the corresponding funding share. Despite the small share, ECN was a core actor in the networks, collaborating with several other core actors. These included the traditional c-Si core (imec), the German scientific actors (Fraunhofer ISE and University of Konstanz) and industrial actors (Eurosolare and BP Solar).

Norway

As we mentioned earlier, Norway's participation in EU-funded programmes was a result of the entry into force of the EEA agreement. The first Norwegian-led project(s) in FP4, accounted for 2,3% of the corresponding funding. Despite the low funding share, the EU R&D programmes enabled a major Norwegian Si feedstock and cells manufacturer (i.e. Elkem) to enter PV activities and networks.[492,493] Elkem had an interest in the development of Si feedstock for PV (SoG), dating back to the 1970s through various collaborations with other 'giants' such as Dow Corning and the JET Propulsion Laboratory (DoE) etc.[494] The company was able to enrich its knowledge and know-how on SoG feedstock development through the EU R&D programmes. These endeavours were met with success in the second period, and the knowledge acquired through the EU-funded projects and networks has been acknowledge by the individuals who were working on the development of SoG feedstock at at Elkem at the time.[495]

France

The R&D programmes for PV in France were coordinated and implemented by the French Agency for Energy Management (AFME). Since the 1970s, the French R&D programme

---

[492] Elkem produces other Si-based products or products that are derivatives of Si. As such, the company supplies a variety of different fields/sectors and industries with raw materials (e.g. construction, chemical, packaging and more).

[493] We discuss the Norwegian research landscape in depth in the second period analysis, since it was during the second period that more Norwegian actors emerged as 'core actors' in the c-Si networks. This is at large attributed to the Si crisis in PV, which comprised a critical event of the second period.

[494] Elkem's Si feedstock efforts and collaborations are analysed in detail in the book: Solar Silicon Processes: Technologies, Challenges and Opportunities, Bruno Ceccaroli, Eivind Ovrelid, Sergio Pizzini (eds.), Taylor & Francis Group (Boca, Raton, London, New York: 2017).

[495] Bruno Ceccaroli and Ragnar Tronstad, "Elkem Solar and the Norwegian PV Industry", *in* Solar Silicon Processes: Technologies, Challenges and Opportunities, Bruno Ceccaroli, Eivind Ovrelid, Sergio Pizzini (eds.), Taylor & Francis Group (Boca, Raton, London, New York: 2017), p. 141-198.

had continuously prioritized research on c-Si solar cells.[496,497] Funding for the PV programme came from the CNRS, AFME and the EC (funding programmes). The CNRS played an important role in both funding and scientific developments in PV. Given the role of AFME, the organization essentially fostered a favourable environment for synergies between public and private sector. We have already analysed both the CNRS and Photowatt in previous sections. Photowatt underwent changes in the late 1980s and in the 1990s. In the late 1980s, the majority share of the company was bought by Chronar France, whereas Shell acquired a minority share in Photowatt in 1991.

French actors concentrated 29,4% of FP2 funding for PV and 27,9% of FP4 funding. Steady project coordinators and participants, the CNRS and Photowatt collaborated with each other (also in the national R&D programmes) and with other major European actors. Both formed collaborations with the main actors of the c-Si network actors (imec and Fraunhofer), whereas both actors collaborated with companies from other countries (e.g. CNRS with ASE, Photowatt with Eurosolare).

The Italians

We analyse the Italian PV programmes and activities in chapter 6. As Italy still played a strong(er) role in c-Si research activities and networks in the first period, we briefly review some key aspects of the domestic situation and then continue with the analysis of the actors. The Italian R&D programme for PV did not continue from the mid-1990s to 2000. This decline in domestic R&D funding had an impact on the Italian PV research community.

We have already analysed the CNR and its role in the Italian research landscape. The Italian National Agency for New Technologies, Energy and Sustainable Economic Development (Agenzia Nazionale per le nuove technologie, l'energia e lo sviluppo economico sostenibile)

---

[496] Indicatively see: M. Rodot, "The French Program on Photovoltaic Conversion", *in* Second EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Berlin (West), 23-26 April 1979, R. Van Overstraeten and W. Palz (ed.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1979), p. 1135-1140.; P. Chartier, M. Bremont, B. Chabot, "The French Photovoltaic Programme", *in* Seventh EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Sevilla, Spain, 27-31 October 1986, A. Goetzberger, W. Palz and G. Willeke (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster, Tokyo: 1987), p. 1155-1161.

[497] Philippe Chartier, Andre Claverie, Bernard Chabot, "From R&D to the Market: The French Photovoltaic Programme", *in* Ninth EC Photovoltaic Solar Energy Conference, Proceedings of the international Conference held at Freiburg, Federal Republic of Germany, 25-29 September 1989, W. Palz, G. T. Wrixon and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1989), p. 1183-1186.; A. Claverie, "Photovoltaic Solar Cells: State of the Art, National Strategies and Perspectives", *Solid State Phenomena*, 1994, p. 441-452.; A. Claverie, J. L. Bal, P. Chartier, "Photovoltaics in France: Research, Development and Promotion", *in* Thirteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Nice, France, 23-27 October 1995, W. Freiesleben, W. Palz, H. A. Overstraeten, P. Helm (eds.), Vol. I, H. S. Stephens & Associates (UK: 1995), p. 891-893.

(ENEA), played an important role alongside the CNR in organizing the Italian research activities. ENEA, which was closely linked to the CNR, was established in the early 1950s as part of CNR and focused on nuclear energy. Like other large organizations of this kind, the institution diversified its activities after the Chernobyl disaster to include other forms of energy.[498] In view of the new culture that had emerged in Italy as a result of the environmental movements, the ENEA's institute (CRE) dropped out of its nuclear energy research activities in 1991. To mark this departure, ENEA was renamed.[499] ENEA's research activities are organized through its research institutes. The Casaccia Ente Per le Nuove Technologie, l'energia, l'ambiente (CRE) research institute focused on c-Si PV and comprises ENEA's largest laboratory consortium.[500] Like CNR, ENEA set the R&D agenda and the distribution R&D funds in the first period. In this context, ENEA collaborated closely with the CNR, universities and the local industrial actors.

ENI (a large Italian oil company) entered the PV business through Agip. Agip founded Pragma (see PV pilot projects under the second energy R&D programme) in the early 1980s. In 1987, Agip was renamed Italsolar. Italsolar absorbed Ansaldo's solar division in 1992 and renamed it Eurosolare. Hence, Eurosolare comprises the expertise of two large Italian PV manufacturers Ansaldo and Pragma.

Even though these collaborations are not visible in the network illustration, they are part of the c-Si networks, albeit to a lesser extent or intensity than in other cases (e.g. Fraunhofer and ASE). ENEA and Italsolar participated in a Photowatt-led project under FP2, whereas all three actors are involved in a EUREC-led project under FP3. One possible explanation for the lower intensity of collaboration is that, unlike other cases, only Eurosolare was a core actor in the c-Si networks, whereas both ENEA and CNR failed to gain a stronger position in the networks. Additionally, as one company became core actor, it is likely that the actor sought to use the networks to 'attract' as much knowledge from transnational collaborations with other core actors (e.g. imec and ECN etc.), which in turn could be used domestically to enrich the company's manufacturing capabilities. Essentially, Eurosolare had to employ a different

---

[498] Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile, *About us*, enea, Available online: https://www.enea.it/en/enea/about-us, (accessed 16 October 2019).

[499] ENEA's former name was Comitato Nazionale der l'energie Nucleare.

[500] Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile – Centro Ricerche Casaccia, *Il Centro*, casaccia.enea, Available online: https://www.enea.it/it/centro-ricerche-casaccia, (accessed 16 October 2019).; Italian National Agency for New Technologies, Energy and Sustainable Economic Development – Cassaccia Research Centre, *The Centre*, old.enea, Available online: http://old.enea.it/com/ingl/center/Casaccia/centre.html, (accessed 16 October 2019).

strategy in terms of the purpose and ‘use’ of the EU-funded programmes, as the major Italian scientific actors were among the main actors in the c-Si networks.

Spain and the UK

The analysis of the main Spanish and British actors and the national research landscape of the countries is given in chapter 6. The close collaborative ties between UPM and BP Solar are evident in Figure 4.11 (above). These close ties are based on the active research interest of these actors in the development of CPV, which used c-Si in the first period. UPM and BP Solar form a core duo in the technoscientific research networks for CPV, and we see that this close tie also pertains the c-Si networks. Although UPM is part of the c-Si networks, it did not gain a core role/place in the c-Si networks. With the involvement of BP Solar in c-Si funded projects, UPM collaborated almost exclusively with the company; entering projects led by BP Solar.[501]

BP entered the PV business in 1981 through Lucas Energy Systems. In the mid-1980s, BP acquired Lucas and BP Solar was born. BP Solar entered the PV business, focusing on c-Si, through the acquisition of Lucas but soon expanded its research activities to include almost all PV technologies and designs.[502] The company was involved in both cell and module manufacturing, supplying the required cells and modules for the projects while becoming the recipient of the project ‘outcome’. The late entry of BP Solar into c-Si activities shows that the company prioritised R&D for CPV. Similar to CPV, BP Solar did not enter c-Si research until FP3.[503]

4.2.8 The directionality of research policy to energy policy: demarcating the pilot, research, and demonstration components

Even through the EC initiated an energy policy for RES in 1997 (with the 1997 White Paper for RES) based on the technological possibilities offered by research policy, there is at least an additional way in which we trace the directionality of (EU) research policy back to the precursors of energy policy or the ‘energy-policy equivalent’ during the first period. Even if there was no energy policy for RES during this period, what existed was the demonstration

---

[501] BP Solar first appeared in the c-Si research projects during FP3.

[502] BP Solar was interested in nearly all PV technologies, ranging from CPV, to flat-plate c-Si and thin films. A detailed analysis its CPV activities and collaborations can be found in chapter 6.

[503] As we have already analysed, the precursors of BP Solar were involved in the c-Si activities in earlier EU R&D programmes (early to mid 1980s).

programmes of the DGXVII. At this level, a continuity from the R&D programmes to the demonstration programmes can be identified in the technologies and in the actors forming their networks.

In the following sections we first distinguish between the two R&D components, namely pilot and research. Although both are components of the EU R&D programmes, they differ in the way they strived to achieve the research aim. A key difference between the two is their proximity to the market. This difference is also crucial for defining the difference between pilot and demonstration and for defining what 'demonstration' means. With the aid of oral history, we revive the voice of a former EC official on this distinction. Finally, we show how research policy influenced and directed 'energy policy' during the first period by tracing the continuities and differences between the respective programmes through an empirical analysis of the technologies and the actors that formed the demonstration networks.

4.2.8.1 Distinguishing between the research and pilot components of EU R&D programmes: delineating the means of achieving the R&D aim

Although both the pilot and research components were part of the EC R&D programmes during the first period, and although both aimed to aid the European industry, the ways in which the two components south to achieving this aim (i.e. international competitiveness) differed. In particular, the pilot component involved actual installations of PV systems. These installations helped to set standards through measurements and studies, and in this way the pilot projects informed research. The pilot component thus directly concerned the market and the construction of the European PV market, while paving the way for standardization, which in turn informed research. In contrast, the research component concerned the development of techniques and methods to increase cell efficiency while reducing costs. This component thus directly concerned the means to strengthen the scientific and technological base of European industry and in this way that contributed to the international competitiveness of the European industry. Despite these differences, the two programme components share commonalities and continuities in the technological choices and in the actors that comprise the networks.

Although the pilot component was part of the EC R&D programmes throughout the first period, it has been significantly weakened since 1985.[504] Therefore, the market-related efforts on the

---

[504] See analysis of the next two sections.

pilot component undertaken by DGXII have been weakened. We attribute this to the concurrent and increasing efforts of the EC (DG XVII) through the demonstration programmes, which we analyse in a later section. Through the demonstration programmes, most of the efforts directly related to the market have been transferred to DGXVII. This also means a fragmentation in the market efforts by the EC. This fragmentation was also the reason why the demonstration programmes became part of the FPs at end of the first period, while in the early years of the second period (1999) the EC called for and tried to merge the pilot with the demonstration programmes.

When we discussed these changes with an EC official from DGXII (RES Unit), they linked them to the issue of overlap between the R&D and Demonstration programmes. Towards this end, the need to merge the two programmes was justified as follows:

> "This is where this leads to [in overcoming the issue of overlap]. Of course, there was competition between the two [DGs], but this is reasonable; competition in a good sense. Back in 1993-1994 … let's say that DGXII did some serious funding. The first large WTs were funded (WEGA). That was DGXII's funding, but in essence, you could say that these [WEGA project] are demonstration, do you see? So, the issue I talked to you about previously, started to enter the discussions: **"where does one end and the other begin?", namely why is this research and not demonstration?** The response coming from research was "if we do not fund it, no one will". These kinds of issues existed, they were real issues and they concerned policy priorities etc. because, **RES were DGXVII's neglected child**. So, this is how they tried to resolve [the issue of overlap] between JOULE and Thermie, at the time."[505] (emphasis added)

Overlap seems to have been a constant or 'unresolved' issue. One wat to solve this issue was to merge the two programmes. However, this merger had no impact on the implementation of the two programmes. The two DGs continued to organize their activities and manage their budgets separately. Put simply, the incorporation of the demonstration programme into the FPs did not solve the issue of overlap.

DGXII played a catalytic role in strengthening efforts to RES. Being an almost negligible sector, they could not compete with the big energy lobbies in DGXVII. This was, at least

---

[505] Interview with former EC DGXII RES Unit Scientific Officer (via Skype), 14 May 2020, Athens, Greece.

partially, remedied by DGXII. This essentially laid the foundation for the sector of RES sector to grow and receive the support it needed in its early days.

4.2.8.2 Defining what 'demonstration' means: the relationship between research and demonstration and the 'place' of the market

The difference between the pilot and demonstration programmes of the EC is 'traditionally' loosely defined. Whether in legislation that established the programmes or in the aim and objectives they pursue, the boundaries (demarcation) are unclear.

Until the late 1980s, demonstration programmes were defined as the 'next stage' after research or as a continuation of the research efforts and activities of the EC, whereas towards the end of the first period, 'market-proximity' was also included in the demarcation between the two.[506] Upon asking an EC Officer from the DGXII RES Unit about the differences between the pilot and the demonstration programmes, they replied:[507]

> "… being two different DGs, each one defined its own policy… the basic thing that they didn't want was to have an overlap in the activities between the two. Something that was not always obvious, because you know let's say the question was – always – what does pilot mean and what does demonstration mean? The pilots were in DGXII and the demonstration was in DGXVII. Thus, where does one end and the other begin? And there layed the issue of the overlap. So, for this there was some coordination of the kind 'what do we do and what do the others do', exactly because they wanted to avoid the concept of the overlap. That was the key factor."[508]

As our interviewee says, each of the two DGs had its own policy, and each DG defined its own policy. On a broader level, the lack of – actual – cooperation between the DGs in informing each other's policies is a well-known 'secret'. This is traced in the books written for the history of the Commission and this was also a remark made by another interviewee who was in

---

[506] See analysis in below section and Appendix A.

[507] Our interviewee was an EC Scientific Officer in the DGXII RES Unit until the late 1990s.

[508] Interview with former EC DGXII RES Unit Scientific Officer (via Skype), 14 May 2020, Athens, Greece.

Brussels in the 2000s.[509] Therefore, we could say that historically there is a continuity in that the DGs operate separately.

The two DGs had their own budgets, which they used for their different programmes. However, as the two programmes had common activities (i.e. in our case RES and PV in particular), they had to respond to a potential issue: the (possible) overlap of the actions supported by their programmes. This issue was indeed crucial, as an overlap could have led to budget cuts or perhaps even to the restructuring and/or renegotiation of the programmes. Hence, in order to avoid a possible overlap, the two DGs coordinated at this level. We trace this avoidance of overlap in the somewhat discrete aims and objectives of the two programmes. When we asked our interviewee if there were any continuities between the two programmes, they responded:

> "Look, **the continuity exists essentially from those carrying out the programmes**. That is, **if someone felt that their programme could/was ready to go to the next stage, they would go to DGXVII**. Thus, **the ones carrying out the programmes were the ones 'causing' this**. **Besides, many of them were in both [programmes]** and this is logical, depending on what kind the[ir] programme was. **Hence, there was continuity – in actuality**. Now, on the administrative [level] there was not. What I want to say is that there was [an administrative continuity] on a general level, what they say "this is pilot, it goes there. This [project's] pilot stage is over so now if you want to do something go to DGXVII". This is what for example DGXII would say in case they thought that the research part [of the project] had completed its cycle."[510] (the words in brackets are the authors, they are used to better explain what the interviewee meant) (emphasis added)

Therefore, during the first period a bottom-up approach prevailed in terms of who participated in the programmes. Furthermore, it was the actors who formed the EU networks who 'defined' where their projects should 'go' (by submitting the proposals for the relevant programme).

---

[509] Regarding the European Commission books, see: The European Commission 1958-72: History and Memories of an Institution, Michel Dumoulin (eds.), Publications Office of the European Union (Luxembourg: 2014).; The European Commission 1973-86: History and Memories of an Institution, Éric Bussière, Vincent Dujardin, Michel Dumoulin, Piers Ludlow, Jan Willem Brouwer and Pierre Tilly (eds.), Publications Office of the European Union (Luxembourg: 2014).; The European Commission 1986-2000: History and Memories of an Institution, Vincent Dujardin, Éric Bussière, Piers Ludlow, Federico Romero, Dieter Schlenker and Antonio Varsori (eds.), Publications Office of the European Union (Luxembourg: 2019). The interviewee we mention was a representative of the UK in Brussels in the 2000s.

[510] Interview with former EC DGXII RES Unit Scientific Officer (via Skype), 14 May 2020, Athens, Greece.

Moreover, this contributed to the continuity from research to demonstration, which was even the unintended the result of this bottom-up approach.

4.2.8.3 **From** Pilot **to** Demonstration: tracing the continuities and delineating their differences

Since the early 1980s we observe a decline in the number of pilot projects (and PV installations) under the R&D programmes and a parallel increase in the number of demonstration projects (and PV installations). From FP1 to FP4 only four pilot projects supported the installation of PV systems. All other projects in the 'pilot' category were concerned with the development of other system components (e.g. inverters, batteries etc.), studies, measurements and general pre-installation activities.[511]

In contrast, by the end of the first period, almost two hundred demonstration projects had supported the installation of more than 10MW.[512] Therefore, the actual installation of PV systems has been gradually transferred from R&D to the demonstration programmes since the early 1980s. In the FP1 evaluation, the DGXVII demonstration programmes were distinguished according to the following criteria:

> "The **need for demonstration programmes is due to the fact that most of the research had failed to be commercialized**. At present time, not all desirable contacts are established between this directorate and DG XII."[513] (emphasis added)

The lack of commercialization of the research projects was used by DGXVII as a criterion for distinguishing between the two programmes, as well as a justification criterion for continuing

---

[511] It is critical to note that during the second period the pilot component of the R&D programmes ceased to exist. Pilots stopped appearing as a distinct category to be funded. Rather, as we show in Chapter 5, (some of) the research projects incorporated the pilot component (e.g. pilot manufacturing lines). Thus, upon the incorporation of the demonstration programmes in the FPs and the 'merge' of the R&D and D components, the pilots became part of the research projects.

[512] Yordi B., Gillet W., Gerhold V., "Four years experience of the multi-MWp THERMIE programme", *in* 2nd World Conference on Photovoltaic Solar Energy Conversion/15th European PV Solar Energy Conference/27th US IEEE Photovoltaics Specialists Conference/10th Asia/Pacific PV Science and Engineering Conference, Proceedings of the International Conference held at Vienna, Austria, 6-10 July 1998, J. Schmid, H. A. Ossenbrink, P. Helm, H. Ehmann and E. D. Dunlop (eds.), Vol. II, WIP Renewable Energies: 1998, p. 2457-2462.

[513] Bondi Hermann, Amman Fernando, Jaumotte André, Marnet Chrysanth, Palomares Juan-José, Uffen Robert, Waldteufel Philippe, *Evaluation of the R & D programme in the field of Non-Nuclear Energy (1985-1988)*, Vol. I, Office for Official Publications of the European Communities (Luxembourg: 1988), p. 96.

the demonstration programmes. Whether or not this criticism is justified, it is important to note that 'market-proximity' was the main criterion for distinguishing between the two programmes. As we move from the 1980s to the 1990s, we observe a gradual shift in the dominant and/or prevalent applications for PV (within the demonstration programmes). Until the late 1980s, the majority of PV installations focused on supporting rural electrification of isolated areas (either stand-alone small-scale systems or large PV power stations), which were a demand during this period of time.[514,515] In the 1990s, the majority of projects involved building-integrated and grid-connected PV systems. This can be attributed to the gradual prevalence of climate change and the need to reduce CO_2 emissions in the European environmental policy and the links established between renewable energy to addressing these challenges. Concurrently, national demonstration programmes were launched in the 1990s that promoted the installation of PV systems on rooftops and highlighted the use of this use for PV.

4.2.8.3.1 The actors and technologies of the demonstration programme: continuity with the R&D programmes

The directionality of research policy to energy policy is attributed to the continuity of the actors that comprise the respective programme networks. As the former EC Officer noted, the continuities between the two programmes lie in the actors themselves.[516] Essentially, the actors of the R&D programmes also participated in the demonstration programmes of the EC. In this way, we can trace the directionality of (EU) research policy to (EU) energy policy.

Indeed, when we examine both the coordinators and the partners of the demonstration programmes, we see many familiar actors from the technoscientific research networks (for c-Si). Either as coordinators or as partners, actors from the c-Si technoscientific research networks were strongly present in the demonstration programmes and networks. Over 30% of the projects in the demonstration programme were coordinated by actors from the

---

[514] That is not to say that PV were not used for other applications. There was a variety of PV applications ranging from water pumping to lighting and agriculture. Rather, as we explain the prevalent applications concerned the electrification of isolated and/or rural areas. Both the number of funded projects and the actual installed PV capacity for these applications garnered the most attention and funding.

[515] Paul Cook, "Rural Electrification and Rural Development", *in* Rural Electrification Through Decentralized Off-grid Systems in Developing Countries, S. Bhattacharyya (ed.), Springer (London: 2013), p. 13-38.; E. Lorenzo, "Photovoltaic Rural Electrification", *Progress in Photovoltaics: Research and Applications*, 1997, p. 3-27.; A. Claverie, P. Courtiade, P. Vezin, "Photovoltaic Rural Electrification in France", *in* Proceedings of 1994 IEEE First World Conference on Photovoltaic Energy Conversion, Vol. II, p. 2283-2286.; V. Ranganathan, "Rural electrification revisited", *Energy Policy*, 1993, p. 142-151.; Gerald Foley, "Rural electrification in the developing world", *Energy Policy*, 1992, p. 145-152.

[516] See corresponding quote in previous section.

technoscientific research networks and over 54% of the demonstration networks consisted of actors from the technoscientific research networks.[517]

Apart from the continuities mentioned above, the demonstration programme actors also show some discontinuities with the R&D networks. These discontinuities can be attributed to the increased involvement of the electric utilities and other local actors (e.g. Compania Sevillana, Hidrola, Club Alpine Français etc.). The involvement of electric utilities and other relevant stakeholders has been an integral part of the demonstration programmes.[518]

The directionality of EU research policy to energy policy can also be traced at the technological level. Given the fact that all major European industrial actors were involved in both programmes, the technological continuity is no surprise. The dominant technology promoted in the demonstration programmes was c-Si, whereas other technological options (e.g. CPV) were also explored to a lesser extent.

4.3 Concluding remarks

In the first period, the European Commission instrumentalized research policy to support industrial policy. With a central R&D aim of strengthening the scientific and technological basis of the European industry while helping the industry to compete internationally, research focused mainly on the solar cell. Although an energy crisis was the main trigger for the launch of the first energy R&D programme, research policy (in tandem with industrial policy) directed the research priorities and set the character of research in the first period. Moreover, it was the research networks that established the research priorities and set and defined the research agenda. Furthermore, as we have shown, it was research that directed the precursors of the then EU 'energy policy' / energy policy 'equivalent' (by the demonstration programmes) during this period.

Even though both the pilot and research components were part of the EC R&D programmes during the first period, and although both aimed to support the European industry, the way in which the two components achieved this aim (i.e. international competitiveness) was different. In particular, the pilot component involved the actual installations of PV systems. These installations helped to set standards through measurements and studies, and in this way the

---

[517] We have examined the demonstration projects and their networks from 1978 to 1998. For the period of 1983 to 1989 we only managed to collect the information regarding the coordinators of the demonstration projects. For Thermie I (1990-1994) we are missing the full information of the projects funded under the last call for proposals. Despite these gaps, the findings reinforce the actors from the technoscientific research networks forged the demonstration networks, as any additional information can only increase their shares.

[518] See legislative material for the demonstration programmes in Appendix A.

pilots projects informed research. Thus, the pilot component directly concerned the market and the construction of the European PV market, while paving the way for standardization, which in turn informed research. In contrast, the research component concerned the development of techniques and methods to increase cell efficiency while reducing costs. Thus, this component directly concerned the means to strengthen the scientific and technological basis of the European industry and in this way contributed to the international competitiveness of the European industry. Even though the pilot component was part of the EC R&D programmes throughout the first period, it was significantly weakened from 1985 onwards. The market-related efforts made by DGXII through the pilot component were thus weakened. We attribute this to the concurrent and increasing efforts of the EC (DG XVII) through the demonstration programmes. Through the demonstration programmes, most of the directly market-related efforts were transferred to DGXVII. This also means a fragmentation of the market efforts by the EC. This fragmentation was also the reason why the demonstration programmes became part of the FPs at the end of the first period, while the EC called for the merging of the programmes in early years of the second period (in 1999). This resulted in pilots to cease to exist as a 'separate' category during the second period. Instead, pilots became a component of some of the research projects funded during the second period (e.g. pilot manufacturing lines). This can also be understood as a 'resolution' to the overlap issue pointed out by the former EC Officer. Thus, during the second period, the demarcation between 'demonstration' and 'pilot' was resolved and the latter ceased to exist.

To aid the international competitiveness of the European industry, the EC showed flexibility in reorienting its research policy. For example, R&D funding in FP1 was reoriented towards a-Si to counter Japanese competition. The publication of the standards for c-Si cells came at an opportune time (mid and late 1980s), which helps us to better understand why research funding for the rest of the first period was again mainly directed towards c-Si. The EC justified the shift to c-Si with the argument of strengthening European industry. We must remember that the actors who formed the research networks of this period came from the semiconductor electronics sector. As such, they had extensive expertise, know-how and vested interests in c-Si, on which the field of semiconductor electronics was built. Moreover, this helps us to better understand why PV research activities were geographically concentrated in the countries of the European North. Despite the 'wide' geographical distribution of PV research activities during this period, funds were accumulated by a handful of countries (and actors) that had vested interests in c-Si. This led to other countries (e.g. Denmark, Greece) forming the periphery of PV activities.

The PV research networks of the time explored the potential applications of different PV technologies and designs, leading to technological pluralism. It was these networks that determined the material possibilities of their technological choices and set the research priorities (bottom-up research policy). Given the way the ‘problem’ was defined, the networks had a very clear mission (i.e. to respond to the energy crisis), at the same time they played a crucial role in developing new technologies that promoted industry competitiveness (electronics background). On this basis, research focused on the development of a single system component: the solar cell. In this context, the politics of the networks which directed research towards small-scale PV systems gave a clear technological frontrunner at the end of the first period: the c-Si flat plate PV.

Even though an EU energy policy (for RES) started to take form towards the end of the first period, we showed the directionality of research policy in the energy policy precursors on two levels (i) in the actors and networks of the demonstration programmes and (ii) in the selection of the technological option that was to be the basis of the EU energy policy for PV: c-Si flat plate modules.

References

Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile, *About us*, enea, Available online: https://www.enea.it/en/enea/about-us, (accessed 16 October 2019).

Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile, *History and Law references*, enea, Available online: https://www.enea.it/en/enea/history-and-law-references, (accessed 16 October 2019).

Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile – Centro Ricerche Casaccia, *Il Centro*, casaccia.enea, Available online: https://www.enea.it/it/centro-ricerche-casaccia, (accessed 16 October 2019).

Bogus K., Larue J. C., Crabb R. L., "SOLAR CELL CALIBRATION: RECENT EXPERIENCES AT ESTEC AND PROPOSAL OP A COMBINED SPACE AND TERRESTRIAL CALIBRATION PROCEDURE", *in* Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Luxembourg, 27-30 September 1977, D. Reidel Publishing Company (Dordrecht Holland, Boston USA: 1978), p. 754-769.

Bondi Hermann, Amman Fernando, Jaumotte André, Marnet Chrysanth, Palomares Juan-José, Uffen Robert, Waldteufel Philippe, *Evaluation of the R & D programme in the field of Non-Nuclear Energy (1985-1988)*, Office for Official Publications of the European Communities, (Luxembourg: 1988).

Booth R. H., Bernardini O., Meyer-Henius U., Nuesser H., Williams R. H., Pereira de Moura D., *Evaluation of the JOULE Programme (1989-1992)*, Office for Official Publications of the European Communities (Luxembourg: 1994).

Boyle Miriam J. and Robinson M. E., "French Nuclear Energy Policy", *Geography*, 1981, p. 300-303.

Brand Karl-Werner, "Dialectics of institutionalisation: The transformation of the environmental movement in Germany", *Environmental Politics*, 1999, p. 35-58.

Breyer Ch., Kersten F., Gerlach A., Goldschmidt Jan, Stryi-Hipp Gerhard, Montoro D.F., Riede Moritz, "Research and Development Investments in PV: a limiting factor for a fast PV diffusion?", *in* 25th European Photovoltaic Solar Energy Conference /5th World Conference on PV Energy Conversion, Proceedings of the International Conference held in Valencia, Spain, 6-10 September 2010, G. F. De Santi, H. Ossenbrink and P. Helm (eds.), WIP Renewable Energies: 2010, p. 5385-5408.

Call for tenders, (C 50, Volume 23), Official Journal of the European Communities, 28 February 1980.

Ceccaroli Bruno, Ovrelid Eivind, Pizzini Sergio (eds.), *Solar Silicon Processes: Technologies, Challenges and Opportunities*, Taylor & Francis Group (Boca, Raton, London, New York: 2017).

Centrotherm, Centrotherm, *Company – Our mission*, Available online: https://www.centrotherm.de/en/company, (accessed 1 December 2020).

Chartier P., Bremont M., Chabot B., "The French Photovoltaic Programme", *in* Seventh EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Sevilla, Spain, 27-31 October 1986, A. Goetzberger, W. Palz and G. Willeke (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster, Tokyo: 1987), p. 1155-1161.

Chartier Philippe, Claverie Andre, Chabot Bernard, "From R&D to the Market: The French Photovoltaic Programme", *in* Ninth EC Photovoltaic Solar Energy Conference, Proceedings of the international Conference held at Freiburg, Federal Republic of Germany, 25-29 September 1989, W. Palz, G. T. Wrixon and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1989), p. 1183-1186.

Claverie A., "Photovoltaic Solar Cells: State of the Art, National Strategies and Perspectives", *Solid State Phenomena*, 1994, p. 441-452.

Claverie A., Courtiade P., Vezin P., "Photovoltaic Rural Electrification in France", *in* Proceedings of 1994 IEEE First World Conference on Photovoltaic Energy Conversion, Vol. II, p. 2283-2286.

Claverie A., Bal J. L., Chartier P., "Photovoltaics in France: Research, Development and Promotion", *in* Thirteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Nice, France, 23-27 October 1995, W. Freiesleben, W. Palz, H. A. Overstraeten, P. Helm (eds.), Vol. I, H. S. Stephens & Associates (UK: 1995), p. 891-893.

Commission Communication concerning the development programme — Call for proposals, (C29, Volume 38), Official Journal of the European Communities, 16 March 1985.

Commission Communication concerning the non-nuclear energy research and development programme – Call for proposals, (C146, Volume 29), Official Journal of the European Communities, 13 June 1986.

Commission of the European Communities, *Energy in Europe: Energy policies and trends in the European Community*, Office for Official Publications of the European Communities (Luxembourg: 1989).

Cook Paul, “Rural Electrification and Rural Development”, *in* Rural Electrification Through Decentralized Off-grid Systems in Developing Countries, S. Bhattacharyya (ed.), Springer (London: 2013), p. 13-38.

Council Resolution of 17 December 1974 concerning Community energy policy objectives for 1985 (C. 153), Official Journal of the European Communities, 9.7.1975.

Council Resolution of 16 September 1986 concerning new energy policy objectives for 1995 and convergence of the policies of the Member States (86/C 240/01) (C. 241), Official Journal of the European Communities, 25.09.1986.

Dalton Russel J. and Rohrschneider Robert, “The Environmental Movement and the Modes of Political Action”, *Comparative Political Studies*, 2003, p. 743-771.

Derrick A., Barlow R.W., McNelis B., Gregory J.A. (eds.), *Photovoltaics: A Market Overview*, James & James Science Publishers ltd (London: 1993).

Dollery A. A., “Photovoltaic Activities in the United Kingdom”, *in* Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Luxembourg, 27-30 September 1977, D. Reidel Publishing Company (Dordrecht Holland, Boston USA: 1978), p. 522-531.

Eisenbeiß G. and Batsch J., “The Photovoltaic Program of the Federal Republic of Germany”, *in* Seventh EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Sevilla, Spain, 27-31 October 1986, A. Goetzberger, W. Palz and G. Willeke (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster, Tokyo: 1987), p. 1162-1169.

Eisenbeiß Gerd, “The PV Program of the Federal Republic of Germany”, *in* Eighth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Florence, Italy, 9-13 May 1988, I. Solomon, B. Equer, and P. Helm (eds.), Vol. II, Kluwer Academic Publishers (Dordrecht, Boston, London: 1988), p. 1609-1614.

Flavin Christopher, “Photovoltaics: International Competition for the Sun”, *Environment: Science and Policy for Sustainable Development*, 1983, p. 7-44.

Foley Gerald, “Rural electrification in the developing world”, *Energy Policy*, 1992, p. 145-152.

Fraunhofer ISE, 30 November 2018, *Fraunhofer ISE*, Press Release: Professor Adolf Goetzberger Turns 90: Pioneer of the Energy Transformation and Founder of Fraunhofer ISE, Available online: https://www.ise.fraunhofer.de/en/press-media/press-releases/2018/professor-adolf-goetzberger-turns-90-pioneer-of-the-energy-transformation-and-founder-of-fraunhofer-ise.html, (accessed 5 October 2019).

Imamura M. S., Helm M. S. and Palz W., *Photovoltaic System Technology: A European Handbook*, Published by H. S. Stephens & Associates on behalf of the European Commission (Bedford, UK: 1992).

Institute for Microelectronics and Microsystems – National Research Council of Italy, *IMM-CNR*, LAMEL History, Available online: https://www.bo.imm.cnr.it/unit/history, (accessed 15 December 2020).

Institute of Atomic and Molecular Physics, *amolf*, History, Available online: https://amolf.nl/about/history-of-amolf, (accessed 20 October 2019).

Institute of Atomic and Molecular Physics, *amolf,* Professor Jaap Kistemaker (1917-2010), Available online: https://amolf.nl/about/history-professor-jaap-kistemaker, (accessed 20 October 2019).

Institute of Atomic and Molecular Physics, *amolf*, Short portrait of Jaap Kistemaker, Available online: https://amolf.nl/wp-content/uploads/2016/03/Short-portrait-of-Jaap-Kistemaker_Impact-60-years-AMOLF.pdf, (accessed 20 October 2019).

Italian National Agency for New Technologies, Energy and Sustainable Economic Development – Cassaccia Research Centre, *old.enea*, The Centre, Available online: http://old.enea.it/com/ingl/center/Casaccia/centre.html, (accessed 16 October 2019).

Jäger-Waldau Arnulf, *PV Status Report 2003: PV Status Report 2003: Research, Solar Cell Production and Market Implementation in Japan, USA and the European Union*, Office for Official Publications Office of the European Communities (Luxembourg: 2003).

Jäger-Waldau Arnulf, *PV Status Report 2019*, Publications Office of the European Union (Luxembourg: 2019).

Joppke Christian, "Nuclear Power Struggles after Chernobyl: The Case of West Germany", *West European Politics*, 1990, p. 178-191.

Joppke Christian, "Social Movements during Cycles of Issue Attention: The Decline of the Anti-Nuclear Energy Movements in West Germany and the USA", *The British Journal of Sociology*, 1991, p. 43-60.

Kobayashi Tetsuro, Hayashi Yutaka, Yui Naomasa, Yoshimura Kazuki, "Japanese Photovoltaic R&D Program Under the Sunshine Project", *in* Ninth EC Photovoltaic Solar Energy Conference, Proceedings of the international Conference held at Freiburg, Federal Republic of Germany, 25-29 September 1989, W. Palz, G. T. Wrixon and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1989), p. 1206-1208.

Koepke R., "Photovoltaic Research and Development Projects in the Federal Republic of Germany", *in* Second Photovoltaic Solar Energy Conference, Proceedings of the International

Conference held at Berlin (West), 23-26 April 1979, R. Van Overstraeten and W. Palz (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London, England: 1979), p. 1120-1127.

Kuwano Y., Ohnishi M., Nakano S., Fukatsu T., Nishiwaki H., Tsuda S., "Amorphous Silicon Solar Cells Produced by a Consecutive, Separated Reaction Chamber Method", *in* Fourth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Stresa, Italy, 10-14 May 1982, W. H. Bloss and G. Grassi (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London, England: 1982), p. 704-708.

Laird Frank and Stefes Christoph, "The diverging paths of German and United States policies for renewable energy: Sources of difference", *Energy Policy*, 2009, p. 2619-2629.

Lindmayer J., "Industrialisation of Photovoltaics", *in* Third EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes France, 27-31 October 1980, W. Palz (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London, England: 1981), p. 178-185.

Lorenzo E., "Photovoltaic Rural Electrification", *Progress in Photovoltaics: Research and Applications*, 1997, p. 3-27.

Luiten E. E. M. and Blok K., "Energy R&D in the Netherlands", Prepared for the US Department of Energy under contract DE-AC06-76RLO 1830, April 1999, Battelle Memorial Institute.

Luque Antonio, "Photovoltaics in 1986: Routes to low cost", *in* Seventh EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Sevilla, Spain, 27-31 October 1986, A. Goetzberger, W. Palz and G. Willeke (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1987), p. 9-18.

Maycock Paul D., "The Current PV Scene Worldwide", *in* Sixth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in London, UK, 15-19 April 1985, W. Palz and F.C. Treble (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1985), p. 21-27.

Mayer James W., "Ion implantation in Semiconductors", *in* 1973 International Electron Devices Meeting, 3-5 December 1973, Washington, DC, IEEE Publications, p. 3-5.

McFarland Andrew S., "Energy Lobbies", *Annual Review of Energy*, 1984, p. 501-527.

Mints Paula, "Overview of Photovoltaic Production, Markets, and Perspectives", *in* Semiconductors and Semimetals, G. Willeke and E.R. Weber (eds.), Elsevier (Oxford, UK: 2012), p. 49-84.

Moore Robert M., “Czochralski-Silicon Solar Cell Modules: Present Cost and Future Prospects”, *in* Third E.C. Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes, France, 27-31 October 1980, Wolfgang Palz (eds.), D. Reidel Publishing Company (Holland, Boston, London: 1980), p. 215-219.

Morris P. R., *A History of the World Semi-conductor Industry*, The Institution of Engineering and Technology (London, United Kingdom: 2008), IET History of Technology Series 12, Series Editor B. Bowens.

Muradin-Szweykowska M. and Horst E. W. ter, “The Netherlands Photovoltaic National Programme”, *in* Tenth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Lisbon, Portugal, 8-12 April 1991, A. Luque, G. Sala, W. Palz, G. Dos Santos, and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1991), p.1390-1393.

Nentwich Alfred, Schneeberger Michael, Szeless Andreas, Wilk Heinrich, “Photovoltaic activities of Austrian Electric Utilities – Projects and Experiences”, *in* Ninth EC Photovoltaic Solar Energy Conference, Proceedings of the international Conference held at Freiburg, Federal Republic of Germany, 25-29 September 1989, W. Palz, G. T. Wrixon and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1989), p. 1119-1121.

Nentwich Alfred, Schneeberger Michael, Szeless Andreas, Wilk Heinrich, “30kW Photovoltaic Plant in the Alps of Austria”, *in* Tenth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Lisbon, Portugal, 8-12 April 1991, A. Luque, G. Sala, W. Palz, G. Dos Santos, and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1991), p. 766-770.

Newham Mark, *Photovoltaics: The Sunrise Industry*, Financial Times Business Information (London: 1986).

Nugent Neil, “Policies”, *in The Government and Policies of the European Union*, Neil Nugent and William E. Paterson (eds.), Palgrave Macmillan (Basingstoke: 2006), p. 351-391.

Orton John, “Silicon, silicon and yet more silicon”, *in The Story of Semiconductors*, J. Orton (eds.), Oxford University Press (New York: 2004), p. 93-148.

Ossenbrink H., Mullejans H., Kenny R., Dunlop E., “Standards in the Photovoltaic Technology”, *in* Photovoltaic Technology, W. G. J. H. M. van Sark (ed.), Vol. I, *in* Comprehensive Renewable Energy (ed. A. Sayigh), Elsevier (Oxford: 2012), p. 787-803.

Pizzini S., Califano F., Soncini G., “Italian Activities in Photovoltaics”, *in* Second EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at

Berlin (West), 23-26 April 1979, R. Van Overstraeten and W. Palz (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1979), p. 1128-1134.

Pizzini Sergio, sergiopizzini, *Cirriculum Vitae*, Available online: http://www.sergiopizzini.eu/curriculum.html, (accessed 10 December 2020).

Palz W., "Overview of the European Community's Activities in Photovoltaics", *in* Fourth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Stresa, Italy, 10-14 May 1982, W. H. Bloss and G. Grassi (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1982), p. 3-8.

Palz W., "European Achievements in Photovoltaics", *in* Fifth EC Photovoltaic Energy Conference, Proceedings of the International Conference held at Kavouri, Athens, Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 21-24.

Palz Wolfgang, *Power for the World: The Emergence of Electricity from the Sun*, Pan Stanford Publishing Pte. Ltd., 2011.

Palz Wolfgang and Overstraeten Roger Van, "Photovoltaic Power Generation – R&D Programme in Europe", *in* Ninth EC Photovoltaic Solar Energy Conference, Proceedings of the international Conference held at Freiburg, Federal Republic of Germany, 25-29 September 1989, W. Palz, G. T. Wrixon and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1989), p. 1202-1205.

Perlin John, *From Space to Earth: The Story of Solar Electricity*, AATEC Publications (Michigan: 1999).

Price Victoria Curzon, *Industrial Policy in the European Community*, The Macmillan Press (Houndmills, Basigtoke, Hampshire, London: 1981).

Ranganathan V., "Rural electrification revisited", *Energy Policy*, 1993, p. 142-151.

Rodot M., "The French Program on Photovoltaic Conversion", *in* Second EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Berlin (West), 23-26 April 1979, R. Van Overstraeten and W. Palz (ed.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1979), p. 1135-1140.

Rüdiger Mogens, "From import dependence to self-sufficiency in Denmark, 1945−2000", *Energy Policy*, 2019, p. 82-89.

Sassault Systemes, 2002, 3ds, *HCT Shaping Systems S.A., Innover tout en ameliorant la productivite*, Available online: https://www.3ds.com/fileadmin/customer-stories/import/pdf/HCT-SHAPING-SYSTEM-Flyer.pdf, (accessed 2 December 2020).

Schott T. and Neerf H. J., “The German Photovoltaic R&D Programme: Status and Prospects”, *in* Fourteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Barcelona, Spain, 30 June – 4 July 1997, H. A. Ossenbrink, P. Helm and H. Ehmann (eds.), Vol. I, H. S. Stephens & Associates (Oxfordshire, UK: 1997), p. 437-440.

Schüring Michael, “Advertising the nuclear venture: the rhetorical and visual public relation strategies of the German nuclear industry in the 1970s and 1980s”, *History and Technology*, 2013, p. 369-398.

Schuster G., “The future of Photovoltaics in Europe”, *in* Third EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes France, 27-31 October 1980, W. Palz (ed.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1981), p. 4-9.

Science Applications Inc, *Characterization and Assessment of Potential European and Japanese Competition in Photovoltaics*, Solar Energy Research Institute (Colorado: 1979).

Seitz Frederik and Einspruch Normal G., “Bardeen and Shockley: New Careers”, *in* Electronic Genie: The tangled history of Silicon, Frederick Seitz and Norman G. Einspruch (eds.), University Illinois Press: 1998, p. 186-196.

Sens P. F., “The Dutch National Solar Energy and the International Energy Agency’s Solar Heating and Cooling Programme”, *in* First EC Conference on Solar Heating, Proceedings of the International Conference held at Amsterdam, April 30-May 4, 1984, C. Den Ouden (ed.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 7-10.

Shell, *The Evolution of the World’s Energy Systems*, Shell International (London: 1996).

Shockley W. and Queisser H. J., “Detailed Balance Limit of Efficiency of *p-n* Junction Solar Cells”, *Journal of Applied Physics*, 1961, p. 510-519.

Solems, solems, *Company - About us*, Available online: https://www.solems.com/en/, (accessed 3 December 2020).

Solomon Ionel, “Opening Address”, *in* Eighth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Florence, Italy, 9-13 May 1988, I. Solomon, B. Equer and P. Helm (eds.), Vol. I, Kluwer Academic Publishers (Dordrecht, Boston, London: 1988), p. 11-13.

Starr M. R., “The Potential for Photovoltaics in Europe”, *in* Fourth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Stresa, Italy, 10-14 May 1982, W. H. Bloss and G. Grassi (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1982), p. 40-50.

Starr Michael R. and Palz Wolfgang, *Photovoltaic Power for Europe: An Assessment Study*, Photovoltaic Power Generation, Vol. II, D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1983).

Tonini Alberto, "The EEC Commission and European Energy Policy: A Historical Appraisal", *in* Rosella Bardazzi, Maria Grazia Pazienza, Alberto Tonini (eds.), *European Energy and Climate Security: Public Policies, Energy Sources, and Eastern Partners*, Springer (New York, London: 2016), p. 13-35.

Treble F. C., "Conference Notebook", *in* Fourth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Stresa, Italy, 10-14 May 1982, W. H. Bloss and G. Grassi (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1982), p. vii-ix.

Treble F. C., "The Future of Photovoltaics – A Report on the Panel Discussion", *in* Fifth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Kavouri (Athens), Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 26-27.

Treble F. C., "The CEC Photovoltaic Pilot Projects", *in* Sixth E.C. Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in London UK, 15-19 April 1985, Wolfgang Palz and F.C. Treble (eds.), D. Reidel Publishing Company (Holland, Boston, London: 1985), p. 474-480.

Treble F. C., "IEC Standards for Photovoltaic Modules", *in* Ninth E.C. Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Freiburg, Fed. Rep. of Germany, 25-29 September 1989, Wolfgang Palz, G. T. Wrizon, and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1989), p. 627-630.

Verbong Geert and Geels Frank, "The ongoing energy transition: Lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960–2004)", *Energy Policy*, 2007, p. 1025-1037.

Verbong Geert and Geels Frank W., Raven Rob, "Multi-niche analysis of dynamics and policies in Dutch renewable energy innovation journeys (1970-2006): hype-cycles, closed networks and technology-focused learning", *Technology Analysis & Strategic Management*, 2008, p. 555-573.

Water A. F. J. van de, Lysen E. H., Bosselaar L., "Solar Energy in the Netherlands: recent progress", *Renewable Energy*, 1994, p. 1371-1378.

Willeke Gerhard P., “The Fraunhofer ISE Roadmap for Crystalline Silicon Solar Cell Technology”, *in* Twenty-Ninth IEEE Photovoltaic Specialists Conference, New Orleans (USA), 19-24 May 2002, p. 53-57.

Willeke Gerhard P. and Rauber Armin, “On the History of Terrestrial PV Development: With a Focus on Germany”, *Semiconductors and Semimetals*, 2012, p. 7-48.

Wolfe Philip R., *The Solar Generation: Childhood and adolescence of terrestrial photovoltaics*, John Wiley & Sons (Hoboken, New Jersey), 2018.

Wollin K., “Photovoltaics in Germany: Research. Development and Application”, *in* Twelfth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Amsterdam, The Netherlands, 11-15 April 1994, Robert Hill, W. Palz and P. Helm (eds.), Vol. II, H. S. Stephens & Associates (UK: 1994), p. 1469-1473.

Wolsink Maarten, “Dutch wind power policy: Stagnating implementation of renewables”, *Energy Policy*, 1996, p. 1079-1088.

Yordi B., Gillet W., Gerhold V., “Four years experience of the multi-MWp THERMIE programme”, *in* 2nd World Conference on Photovoltaic Solar Energy Conversion/15th European PV Solar Energy Conference/27th US IEEE Photovoltaics Specialists Conference/10th Asia/Pacific PV Science and Engineering Conference, Proceedings of the International Conference held at Vienna, Austria, 6-10 July 1998, J. Schmid, H. A. Ossenbrink, P. Helm, H. Ehmann and E. D. Dunlop (eds.), Vol. II, WIP Renewable Energies: 1998, p. 2457-2462.

Chapter 5. The politics of the c-Si research networks direct energy policy: towards energy market liberalization

5.1 Introduction

In this chapter, we analyse the EU-funded R&D activities and technoscientific research networks for flat plate c-Si PV during the second period (1999-2020).[519] A common EU energy policy begun slowly started to take shape in 1992 with the establishment of the European Single Market (SEM).[520,521] The actions relevant to energy policy concerned the establishment of 'common rules for the internal market in electricity'. A major trigger for a common energy policy was climate change.[522,523] The objective of reducing CO_2 emissions played an important role in (re)defining European energy policy and its objectives. For example, the Kyoto Protocol and 1997 White Paper called for a reduction in greenhouse gas (GHG) emissions and set specific reduction targets expressed as a percentage relative to 1990 baseline (for the EC, 8% reduction of the six GHGs within the first commitment period 2008-2012).[524] This overall target was divided into country-specific targets via a European Union (EU) burden-sharing agreement. The country-specific targets varied significantly from country to country and depended on the prosperity of each country as well as its previous energy efficiency and emission reduction measures. These GHG emission reductions were accompanied by EC policies and measures to be taken to reach the targets. The dominant technology (i.e. flat plate c-Si PV) that emerged as the 'victorious' technology from the first period formed the basis for writing up the 1997 EC White Paper for RES. Small-scale c-Si flat-plate PV enabled a unique system integration option that was an integral part of the 1997 White Paper's goals for PV.

---

[519] The second period covers the following EU R&D programmes: fifth Framework Programme (FP5) (1999-2002), sixth Framework Programme (FP6) (2002-2006), seventh Framework Programme (FP7) (2007-2013). Even though not included in the analysis of the present chapter, Horizon 2020 (2014-2020) is also part of the second period. In Chapter 7 we have included a brief analysis of the Horizon 2020 funded PV projects. However, at the time we were collecting data for this dissertation, not all the Horizon 2020 PV projects were completed. As such, we draw insights for the direction of the programme but since not all projects were completed, we could not incorporate them in our analysis (and network visualizations).

[520] Alberto Tonini, "The EEC Commission and European Energy Policy: A Historical Appraisal", *in* Rosella Bardazzi, Maria Grazia Pazienza, Alberto Tonini (eds.), *European Energy and Climate Security: Public Policies, Energy Sources, and Eastern Partners* (New York, London: Springer, 2016), p. 13-35.

[521] SEM was to create a unified European market by deregulating. It provided the EU with more powers and, along with the Single European Act, 'allowed' regulating energy policy.

[522] Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity, Official Journal of the European Communities (30.1.1997).

[523] Jegen Maya, "Energy policy in the European Union: The power and limits of discourse", *Les cahiers européens de Sciences Po*, n°2, 2014, p. 1-22.

[524] European Commission, *Energy for the Future: Renewable Sources of Energy White Paper for a Community Strategy and Action Plan*, COM (97)599 final, 1997.

Essentially, small-scale c-Si flat plate PV enabled a move away from centralized electricity generation and towards distributed electricity generation, distribution and consumption of electricity in which civil society can play a more active role.

The 1997 EC White Paper placed RES on the energy policy map and essentially gave the green light to the sector of PV to become industrial (in terms of production). The introduction of an energy policy for RES in turn led to a reorientation of the research policy for PV, initiating the second period. In this period, research priorities and activities were reoriented to respond to a raw material crisis (silicon crisis in PV), which was the direct result of the EU energy policy goals, and to resolve the presupposed upscaled production issues. Furthermore, research that could narrow down the gap between research and the market was promoted. All these changes are reflected in the technoscientific research networks for c-Si, which were restructured to conduct 'upscaled research'. Resulting in the emergence of large research centres as the core actors in the networks and the indirect marginalization of small research groups and universities.

In the following sections, we first analyse the geographical distribution of EU R&D funding for c-Si during the second period and by technology. This allows us to trace continuities and discontinuities in the distribution of funding during the first period and thus make a comparison between the two periods. We then link the distribution of R&D funding to energy policy goals and show how energy policy has directed research priorities and funding during the second period. Furthermore, we employ the analytical concept of 'upscaled research' to better define and characterize the changes in the character of research policy during this period.[525] The analysis continues with an examination and visualization(s) of the technoscientific research networks for c-Si. We zoom-in on the actors that emerged as the core of the EU-funded R&D programmes and those who were (perhaps indirectly) marginalized by the research's changing character and content, which we compare to the first period. Next, we examine the networks' responses to the silicon crisis in PV, which was the direct result of energy policy goals/targets for PV. Towards this end, we argue that energy policy did not only impact the structure of the c-Si networks but also re-directed research activities, the structure of the networks and the geography of a-Si research funding. Before concluding with the main arguments and findings of our analysis, we zoom-out to the changes that took place at the market level (both in the production of c-Si cell/module production and in installation) during this period.

---

[525] This analytical concept was prompted by an interview with a Fraunhofer-ISE Head of Department. We developed this concept to situate and better explain the changes in the character of research policy we describe in this chapter.

5.1.1 The geographical distribution of c-Si funding

As illustrated in Figure 5.1 (below), a total of eight countries coordinated the c-Si projects of the second period. These countries were the following according to the funding they received: the Netherlands, Germany, France, Belgium, Norway, Italy, Spain, and Sweden. Actors from the first four countries (i.e. NL, DE, FR, BE) accounted for 84,23% of the total c-Si funds.[526] Hence, the bulk of EU funding for c-Si was concentrated in a handful of countries in the European North, similar to the first period. Despite the geographical distribution of c-Si funding in the second period, expanding from the European North to the European South, there are some continuities and discontinuities between the programmes of the second period, as shown in Figure 5.2 (below). In particular, actors from Spain, Italy, and Sweden gradually stopped both coordinating and participating in c-Si research projects.[527] Additionally, in contrast to the first period, no projects were coordinated by actors from the UK.

Spain has been involved in c-Si activities since FP1, after joining the EEC in 1986, but has traditionally received only a small fraction of c-Si research funding. As we will see in detail in chapter 6, Spanish R&D priorities were set bottom-up and subsequently incorporated into the national energy policy. The R&D priorities aimed at using domestic know-how and expertise on CPV and made concrete links to this selection with the silicon crisis. Towards this end, the decades-long scientific tradition in CPV, which had become a critical European locus of expertise in CPV, was placed centre stage. The limited Spanish participation in c-Si projects from FP6 onwards steadily declined, signalling the beginning of a new R&D era in Spain.

The situation was similar in Sweden. However, PV research in Sweden never focused on Si.[528] This can help us understand why Sweden never attained a large share of R&D funding for c-Si. Rather, the focus has always been on the development of CIGS thin films.[529] The main producers of (c-Si) module in Sweden were subsidiaries of Norwegian and German companies (i.e. ScanModule of Norway's REC and Gallivare Photovoltaics of Germany's Solar World).

---

[526] The country-specific shares are the following: 30,45% - Netherlands, 24,85% - Germany, 15,11% - France, 13,82% - Belgium. The other countries received the following funding shares: 5,17% - Norway, 4,75% - Italy, 4,41% - Spain, 1,41% - Sweden.

[527] Even though the geographical funding distribution only shows the coordinators, upon examining the corresponding projects we see that the actors from these countries did not only stop coordinating c-Si research projects but also gradually stop – altogether – participating in the c-Si research activities supported by the EU.

[528] Pamblad Linus, Jacobsson Staffan, Sanden Bjorn, and Hall Maria, "Dynamics of the Swedish PV Innovation System – The impact of a recent market formation programme", *in* Twenty first European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Dresden Germany, 4-8 September 2006, J. Poortmans, H. Ossenbrink, W. Palz, P. Helm (eds.), WIP Renewable Energies: 2006, p. 3136-3151.

[529] The Swedes had a strong CIGS team at Uppsala University. Prof. Lars Stolt and some of his colleagues established Solibro AB in 2003 to commercialize the teams' research.

In addition, there was no domestic production of (Si) feedstock, wafer, ingots or cells in Sweden. Considering (i) the opportune moment provided by the silicon crisis for the development of alternative technologies (ii) the development of a national R&D programme in favour of BIPV and (iii) the establishment of Solibro AB – a spin-off company from Uppsala University – to develop CIGS technology, Swedish research interests focused on the development of CIGS and were thus reoriented (completely) away from c-Si. The participation of Swedish actors in the c-Si networks, which decreased throughout the second period, does not include key actors from the Swedish PV R&D landscape. Rather, the actors that participated in the c-Si networks were companies with expertise in different techniques (e.g. Scanarc specializes in plasma technologies).

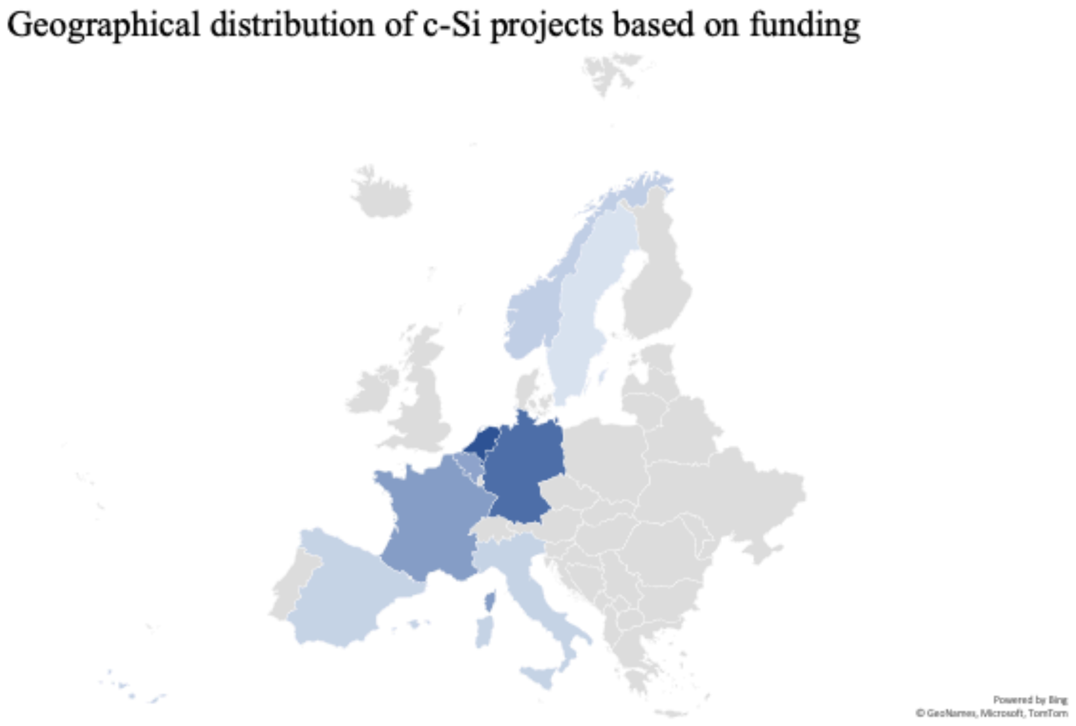


Figure 5.1 Geographical distribution of c-Si R&D funding, 1999-2013.

As we saw in the analysis of the first period, Italy's interest in c-Si continuously declined. Even though Italy was a major actor during the first two energy R&D programmes (1975-1983), its share declined steadily during the remainder of the second period, resulting in only a 7,36% of the funding being received for c-Si in the last three programmes (i.e. FP2-4). Italian participation in the second period c-Si networks also decreases from one FP to the next. Similar to Spain and Sweden, Italy stopped coordinating c-Si projects after FP5. As we analyse in detail in chapter 6 (CPV), the unfavourable domestic atmosphere towards PV, with continuously decreasing or absent R&D funding, followed by the silicon crisis, caused Italian actors to redirect their PV R&D activities. This is reflected in the limited participation of Italian actors in post-FP5 research projects and in the steadily growing share of Italian actors in CPV networks.

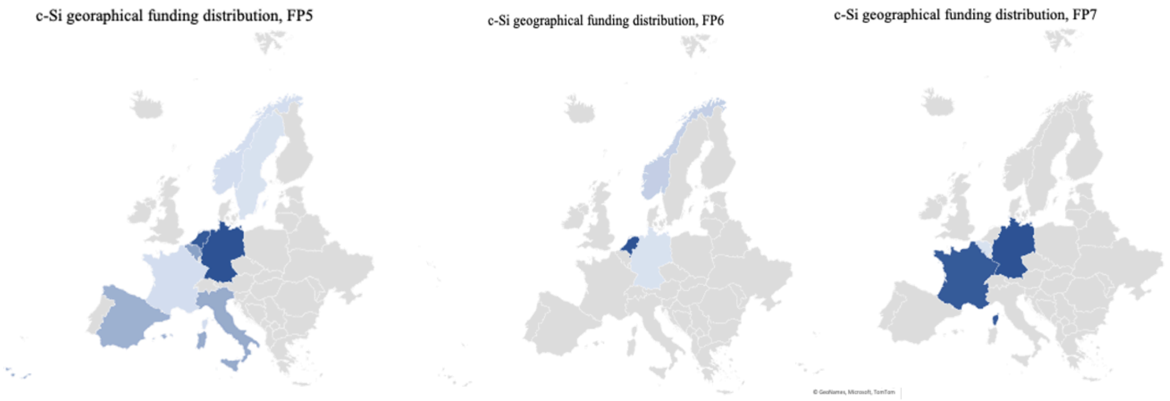


Figure 5.2 Geographical distribution of c-Si R&D funding, by programme.

In the second period, we observe the absence of UK actors in the coordination of c-Si research projects, while the participation of UK actors in c-Si networks steadily decreased. This can be attributed to the introduction of a national R&D agenda for PV, which prioritised thin films, and the exit of the largest private sector actor (i.e. BP Solar) from the PV business.

In contrast, German actors continued to play a central role in c-Si activities and technoscientific research networks throughout the second period. Belgian actors also continued to be part of the c-Si technoscientific research networks, whereas actors from the Netherlands and Norway attained a stronger position in the c-Si research activities and the corresponding technoscientific research networks of the second period. Finally, French actors started to accumulate larger funding shares towards the end of the second period (FP7). Although they played a more important role in the first period, the 'inactivity' of French actors can be attributed to the unfavourable domestic environment towards PV deployment.

German actors were the only ones to continuously coordinate c-Si R&D projects throughout the second period. This is due to the strong commitment of the German (federal) government in providing continuous investment for c-Si R&D, the involvement of private and public sector actors, and the various initiatives that flourished in Germany during the second period and created a favourable climate for the deployment of PV, especially c-Si.

Norwegian actors followed a different path. Norway initially participated in c-Si projects under Joule III (FP4) but received only small part of funding. Norway's jump to fifth place in the R&D funding programmes can be attributed to the collective efforts of Norwegian actors (both scientific and industrial) to embark on and expand their expertise in different steps of the silicon 'production chain'.[530] We delve into a detailed analysis of the Norwegian actors comprising the c-Si networks in the forthcoming technoscientific research networks' analysis. Similar is the case for the Netherlands, that attained a stronger position in c-Si research and climbed to the top of EU R&D activities for c-Si. This can at least partly attributed to the increasing Dutch – national – R&D efforts for c-Si; establishment of a Dutch R&D for RES with a focus on PV.[531]

In sum, the EU R&D funding for the dominant technology (c-Si) was unevenly distributed between a handful of countries in the European North. In particular, the Netherlands, Germany, France, and Belgium accumulated two-thirds of the c-Si research funds of the second period. In contrast, countries in the European South (i.e. Italy and Spain) have gradually stopped participating in c-Si research activities and thus funding. At the same time, we observe that the number of actors from these countries participating in c-Si networks is decreasing, largely due to their national research strategy being reoriented towards CPV.

Apart from the Southern European countries that discontinued c-Si research under EU R&D funding programmes, this has also been the case for the UK and Sweden. The UK stopped c-Si activities after the largest UK company (BP Solar) stopped its solar PV business. Sweden had no industrial interest in c-Si and the participation of Swedish actors in c-Si remained limited. Norway, in contrast to Sweden, has achieved a stronger position in EU funding of c-Si. This difference can be explained by the research and industrial capabilities of each country, which have developed around different semiconductors.

The geographical distribution of c-Si research activities in the second period included actors from fourteen other countries. Actors from Hungary, Lithuania, Greece, Denmark, Austria, and Australia continued to participate in c-Si activities.[532] Additionally, actors from Ireland, Cyprus, Bulgaria, Slovenia, Ukraine, Russia, the Czech Republic and Israel were included in the EU-funded c-Si research activities. Although c-Si research activities expanded further geographically in the second period even more during the second period, we see that a 'strong'

---

[530] We employ the term 'production chain' to denote the steps covering the extraction all the way to recycling (see Chapter 7).

[531] We analyse the Dutch actors and national R&D, in depth, in a forthcoming section.

[532] Actors from these countries also participated in the c-Si research activities of the first period.

geographical centre/core in c-Si has emerged in Northern Europe. The formation of this strong centre/core entails – albeit indirectly – the geographical marginalization of actors mainly from the European East. Some of the actors from the European South (Italy and Spain) have redirected their research agendas on CPV and form the core of CPV research activities and networks.

In the following analysis, we first analyse the relationship between EU research and energy policies in the second period, focusing on how this relationship affected the character of research and on how this changing relationship redirected the research priorities and themes for c-Si. Next, we examine the technoscientific research networks for c-Si. In this way, we establish links between the geographical distribution of funding in the second period and the overall changing research strategy and priorities and show how this was reflected and how played out in the structure and formation of the networks.

5.1.1.1 Distribution of EU R&D funding by technology

As indicated in Figure 5.3 (below), during the second period R&D funding has shifted away from c-Si that concentrated the bulk of the funding during the first period.[533] We see that in the second period, the majority of R&D funding went to thin film technologies, which accouned for about 38% of total PV funding. Despite the shares shown in Figure 5.3, it is important to note two things. First, this shift occurred gradually. R&D funding gradually prioritised thin film technologies (from 19,27% in FP5 to 35,76% in FP6 to 44,88% in FP7), while CPV also received significant funds (from 12,76% in FP5 to 14,89% in FP6 to 16,48% in FP7). At the same time R&D funding for c-Si gradually declined (from 46,47% in FP5 to 26,37% in FP6 and only 13,25% in FP7).[534] Second, and perhaps more importantly, it should be noted that despite the decline in research funding for c-Si, the actors forming the relevant networks received significant funding under both c-Si and thin film projects while pursuing the same agenda and/or seeking developments that would benefit the same agenda (i.e. the c-Si thin film agenda).[535]

---

[533] During the first period, the EU R&D funding continuously prioritized c-Si. From 1989 to 1998, c-Si accounted for 43% of the total PV R&D funding. The sole exception to the c-Si 'trend' was FP1, where another technology (a-Si thin films) took the funding lead in an effort to respond to the Japanese competition. For more information see: Efi Nakopoulou and Stathis Arapostathis, "Reconfiguring Technologies by Funding Transitions: priorities, policies, and the renewable energy sources in the European Community funding schemes", *Journal of Energy History/Revue d'Histoire de l'Énergie* [Online], n°4, published 27 July 2020.

[534] All R&D funding shares have been calculated by the author.

[535] This is evident by the constantly increasing R&D funding for a-Si, which gradually accumulated the bulk of the thin films funding (accounting for 45,83% of the thin films funding under FP7 – excluding projects with more than one technology, including a-Si). During the second period, the c-Si thin films agenda impacted the a-Si

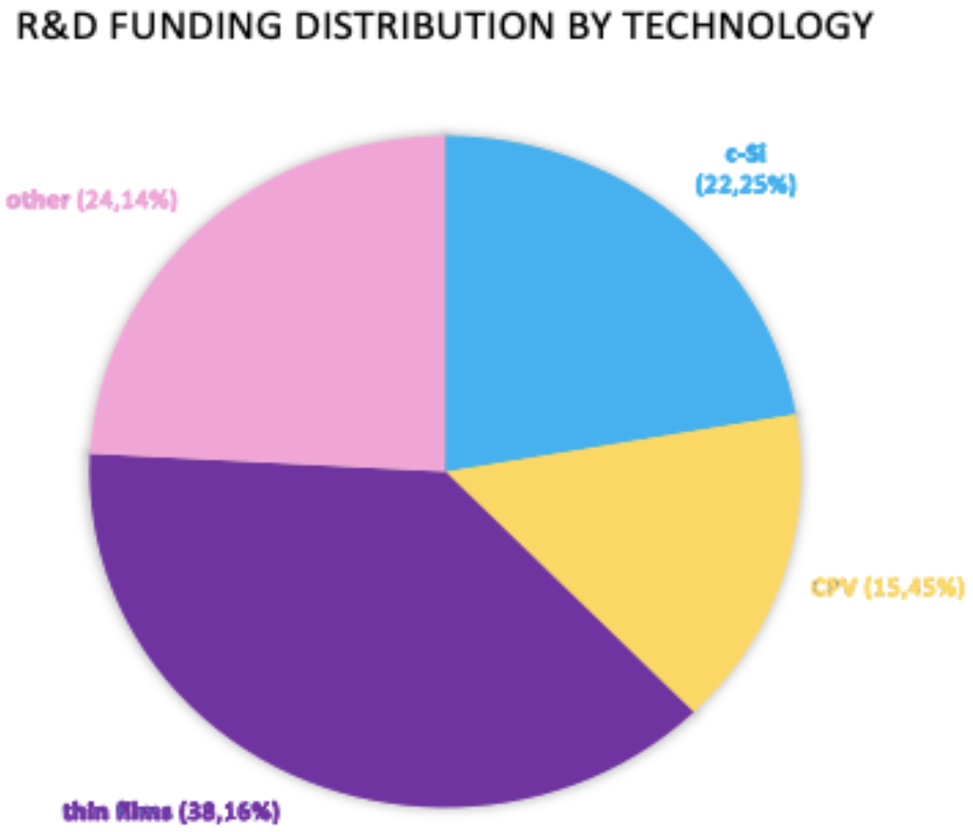


Figure 5.3 EU R&D funding distribution by PV technology, 1999-2013.

With a central R&D aim of transferring research to the market faster (i.e. narrow the gap between two), the PV technology options offered sought to provide solutions to the silicon crisis in PV while supporting industrial production.

5.1.2 The directionality of EU's energy policy and the call for 'upscaled production': c-Si research 'enters' the factory and strives to deliver industrial pilot production lines

---

research activities, geography and networks' structure (see analysis of a-Si networks in a forthcoming section). Under Horizon 2020 the c-Si thin films agenda dominated the c-Si research activities and c-Si climbed back to the R&D funding ladder. The reason for the 'inconsistency' (i.e. FP5-7 the c-Si thin film agenda research activities were distributed both under c-Si and thin film projects and under Horizon 2020 these activities were concentrated under the c-Si funded projects) is attributed to the actors. In particular, for the R&D funding allocation by technology (e.g. c-Si, thin films) we follow the historical actors and their selections. Essentially, the allocation is based on how the actors contextualized their projects (i.e. as c-Si or thin film), despite pursuing the same agenda and/or developments that would benefit the same agenda as in the c-Si thin film case.

The 1997 White Paper for RES essentially meant the inclusion of RES on the energy policy map and gave the PV sector the green light towards becoming industrial (in terms of production). The research efforts of the first period resulted in a clear technological frontrunner with the corresponding 'winners' (i.e. actors). C-Si formed the basis for the formulation of PV installation targets in the 1997 EC White Paper. Moreover, the unique system integration option enabled by c-Si was also detrimental to energy policy. The installation targets (or take-off campaign) of the White Paper concerned roof-top PV installations.[536] This opened a new 'horizon' for EU energy policy. In turn, the White Paper and the corresponding energy policy targets redirected research towards resolving the presupposed upscaled production issues and the impending crisis resulting from this upscaled production: the silicon crisis in PV. Therefore, research was redirected towards responding to challenges and/or problems directly arising from energy policy and energy policy targets. Research for c-Si was not exempt from this. Under the strong influence of the 1997 White Paper for RES and the corresponding energy policy targets, research was redirected towards solving the issues and/or problems that resulted from the energy policy targets.

In the second period, the research projects were reoriented by the energy policy goals. For PV, this meant solving issues related to the upscaled industrial production of the main (c-Si) technology, which expanded throughout the entire PV value chain (from feedstock to panel). Towards this end, a major problem was targeted: the supply of adequate silicon feedstock for the expansive needs of the PV industry. Until the 1990s, when there was no provision or vision for the industrialization of PV, off-spec Si feedstock, which were the 'reject/waste' or 'leftovers' from the electronics industry (Si) from the semiconductor industry, were used to produce PV. However, given the targets set by the EU and the simultaneous developments in Germany, which included RES in its energy policy and fostered the establishment of a PV market, the supply of feedstock was deemed as **the** critical bottleneck of the PV deployment and a barrier to the expansion of PV production. The c-Si research projects of the second period included the forthcoming silicon feedstock challenge in their objectives and aimed to provide possible solutions. Towards this end, research was reoriented to (i) produce industrial pilot production lines, (ii) contribute to mass production of PV, (iii) provide tools for accurate and

---

[536] Papoutsis Christos, [Introductory conference speech], *in* Second World Conference on Photovoltaic Solar Energy Conversion, Fifteenth European PV Solar Energy Conference, Twenty Seventh US IEEE Photovoltaics Specialists Conference, Tenth Asia/Pacific PV Science and Engineering Conference, Proceedings of the International Conference held at Vienna, Austria, 6-10 July 1998, J. Schmid, H. A. Ossenbrink, P. Helm, H. Ehmann and E. D. Dunlop (eds.), Vol. II, WIP Renewable Energies: 1998, [CD-ROM], p. xl-xliii.; European Commission – Directorate General for Energy, *THERMIE-ALTENER: Renewable Energy Report*, Office for Official Publications of the European Communities (Luxembourg: 1998).

fast production quality control and (iv) solve production issues. Given the PV technology (i.e. c-Si) on the basis of which the White Paper goals were formulated, the PV sector had to respond to an important issue: the silicon feedstock supply. This issue was identified as the most important bottleneck for the development of the PV sector and for achieving the White Paper goals for PV. Therefore, due attention was given to this issue in the research projects of the second period, which impacted both the research activities for c-Si and the prioritisation of PV funding.[537]

The possible pathways explored to solve the silicon feedstock problem included the following interlinked options: (i) routes to develop a solar grade feedstock exclusively for the PV industry, (ii) recycling, (iii) reducing silicon consumption, (iv) reducing wafer thickness and (v) developing c-Si thin films to reduce material cost. In addition, we observe that the projects 'entered' the factory. The proximity of research to the market, dictated by the reorientation of the FPs and the fulfillment of the energy policy goals, pertain the research projects of the second period. In this context, priority was given to research that could shorten the gap between research and market (i.e. develop near-market products directly from the research projects or solutions to production problems). This was mainly expressed by linking research to the market and industrial production. All c-Si projects made direct references to cost reduction (either in terms of low-cost feedstock or end-device cost(s) etc.), which became an inseparable part of the project objectives. These cost reduction targets, which became an integral part of the R&D projects and activities, were directly related to the forthcoming silicon crisis in PV. In the context of addressing this pressing issue, research activities for c-Si changed. With the projects targeting different parts of the PV value chain – or in certain cases covering all steps/parts of the PV value chain – they sought to find concrete solutions to the problems of the European industry.

One might ask: "How are the cost objectives different from those of the first period?". When discussing with a Fraunhofer Head of Department about the changes in the second period, they commented the following:

> "…you have an established industrial production process for Si cells that does not change every now and again because you know, you need all the machinery, it's a lot of investment and then you want to keep it running and every time you

---

[537] We have analysed these points in depth in previous sections. The Si crisis in PV, as a direct result of the industrialisation of the PV sector enabled by the energy policy objectives, was an 'internal' to the PV sector issue that directly affected the research activities and priorities of the second period.

> change something you might fail, so they are rather conservative. But the two bigger projects are that you would develop new processes that try to improve two things: reduction of cost and increase of efficiency of the solar cell."[538]

Based on the above, we can see a continuity between the two periods of PV research: the cost-efficiency relationship. The centrality of the cost-efficiency relationship in the PV research projects of both periods can be explained by the intention of the FPs. The EC set up the FPs as a means to bridge the gap between scientific research and industry, which was in line with the core aim of the FPs to strengthen the scientific and technological basis of the European industry. Moreover, it was envisaged (and achieved) that the R&D projects would enable the formation of transnational cooperation networks between industry and science, which could provide fertile ground for advancing the international competitiveness of the European industry. Based on the above, we can better understand why the cost-efficiency relationship comprised an incremental part of the EU PV R&D activities. The needs of the industry were transferred to the R&D programmes and projects and had become an inseparable part of the project objectives in the second period. The difference between the two periods, however, lies in the means of achieving these objectives and the way they impacted both research priorities and activities and the structure of the networks. Another but directly related difference between the two periods is that the scope of the second period's projects was expanded, which also had a direct impact on the structure of the networks. Essentially, this is the aforementioned research that covers the entire PV value chain, rather than research that focuses on individual PV parts (e.g. cell research).

The reorientation of research is (also) reflected in the priorities set by the SRAs, which provide further concrete cost targets to be achieved by the FPs and place them in specific timeframes. The focus of the R&D programmes on narrowing down the gap between research and market pertains the entire second period. This is evident in the PV research projects and their respective aims and objectives (e.g. achieving specific cost targets) and their deliverables (e.g. producing near market products, delivering pilot or precommercial manufacturing lines). This shift is also reflected in the structure of the networks that have supported this market-oriented research and includes the marginalisation and/or exclusion of small research groups (mainly from universities). Even though we analyse the dominant network actors in depth in a forthcoming section, it is important to shed light on the marginalization that has resulted from the

---

[538] Interview with Fraunhofer ISE Head of Department (via Skype), 13 December 2019, London, UK.

reorientation of research. Towards this end, we ask the following questions: How did the market-led character of research in the second period impact the structure of the networks? Where did the knowledge for c-Si originate and which actors had the capacity to conduct this 'upscaled research'? Did the changing character of research directly or indirectly lead to restrictions in terms of participation in the technoscientific research networks for c-Si?

Upon discussing the changes in EU R&D programmes with a former DGXII Scientific Officer from the RES Unit, they commented:

> "**My estimation**, if you will, **is that RES had a lot of help then**. In the sense that before **there were small companies, collaborating with universities and trying to do different things. So, they were on a small scale**. What I mean is that **large scale** would have killed them. I believe it **did kill them to a large extent, afterwards**. **Large scale killed the smaller groups, which were capable in producing some novel work, more innovative work etc**. **Then [the attention] fell to the companies**, and this is reasonable as large companies started to grow."[539] (emphasis added)

Research during the first period was more inclusive for all RES. When research in the second period focused on solving production issues, attention shifted toe companies, which resulted to a(n) (indirect) marginalization of smaller (research) groups. Larger consortia conducting research close to the market, while entering the factory or even having the facilities of the research centres to resemble a miniature factory, represent a striking difference from the first period. Essentially, the 'scale' of research also changed and became industrial.

From the first to the second period, the number of projects coordinated by universities shrank by more than half (from 19,7% to 8,3%), while university participation in c-Si networks similarly declined (from 19,7% to 16,2%). The number of projects coordinated by companies has also decreased (from 43,9 to 25%), but their corresponding participation rate has increased (from 44,6% to 49,4%). At the same time, the number of projects coordinated by (large) research centres almost doubled (from 27,7% to 63,9), while the participation rate of research centres declined slightly (from 28,3% to 27,1%).[540]

---

[539] Interview with former EC DGXII RES Unit Scientific Officer (via Skype), 14 May 2020, Athens, Greece.

[540] The remaining shares for both cases, coordinators and participation ratios, correspond to other actors (e.g. electric utilities).

The above numbers give us an overall view of where the knowledge for c-Si originated and/or was produced and where this knowledge was transferred to. Both the role and the participation of universities was minimized in the second period, whereas the role of large research centres was strengthened. The above changes correspond to the respective 'location' of knowledge production, which was increasingly initiated by the research centres, while the universities were simultaneously and continuously marginalised. Moreover, the reorientation of research towards the achievement of market goals and the narrowing of the gap between research and the market led to an even greater participation of the companies.

As we progress deeper into to the second period, we see a gradual shift in the role and position of university groups in the networks. At the same time, we observe that the participation of large research centres (e.g. Fraunhofer ISE, IMEC, ECN etc.) is increasing, while the number of projects coordinated by them is also increasing. It is worth noting that under in the sixth and seventh FPs all but one of the projects were coordinated by large research centres. Companies have always had a strong involvement in the EU-funded R&D projects for c-Si, while at the same time making up the largest part of the network, especially during the second period.

As research had to respond to the needs of an industry that was upscaling its production and find solutions to production issues, smaller research groups were marginalized. University participation became marginal, in contrast to the first period when a larger number of projects were led by universities. At the same time, this shift favoured, albeit indirectly, the large research centres that emerged as the crucial links in the technoscientific research networks for c-Si in the second period. Even though the changing character of research in terms of a shift in research priorities aimed at narrowing the gap between research and the market by delivering near-market products or even pilot production lines is crucial, the shift in the character of research had another impact.

The above are supplemented by the insights of a Fraunhofer ISE Head of Department. When discussing with the second interviewee about the German PV research landscape and 'where' Si research is located in Germany, they made similar remarks that complement the first interviewees' points very nicely. Although the discussion focused on the German framework, the insights they provided help us to make some general observations about the participation and marginalisation of certain actors in the EU c-Si networks. As the interviewee from Fraunhofer-ISE noted:

> "For **Si PV research is really not so much university-driven**. **The reason is very simple: you need a lot of machinery**. You need really large machines and

> groups and for small to mid-sized university groups, which are mostly focused on academic output and PhDs it is not really viable. So, this is the reason why in Germany the Si solar cell research is mostly located at Fraunhofer ISE, the Helmholtz Centre in Berlin. There is another institute called ISFH and there is one more in Konstanz. These are the main players. Of course, there are small University groups that contribute to very specific topics. But having really a semi-industrial manufacturing line, for this you will only see in these institutions. […] **Every time you step towards production it becomes of course very big because speed output is let's say one of the decisive factors in order to be able to compete – to bring the price down – and therefore small machines do not work**. **In Si you need large ovens, big machines – they are expensive**. You need people who are experts in running them because if it breaks down then the whole process cannot work. This is very different in organic and perovskite PV, because you there you only need a couple of hundred of Euros and you can start. And you don't need much area. You need a glovebox […]. So, it is not very capital intensive and therefore many small university groups can work on that topic. They can never upscale – never make large modules with some industrial-relevant manufacturing, but for the science they can build small solar cells and investigate them and write papers. So, this is very different between Si and especially OPV and perovskite. Thin films are somewhere in between. CIGS requires more machinery, but OPV and perovskite cells are easy to make on small areas."[541]

As our interviewee pointed out, scale increases as we move towards production. To carry out this research it involves large machinery and equipment that is capital intensive and requires large areas (physically) and personnel with specialized expertise. During the second period, this was also expressed in the marginalisation of smaller research groups (mainly universities) that did not have the large machinery and equipment and the actual physical space/area required to conduct the research promoted. Essentially, universities were limited to certain very specialized topics as the projects aimed to deliver actual production lines. Apart from the indirect consequences this has for who has the capacity to conduct this 'upscaled research',

---

[541] Interview with Fraunhofer ISE Head of Department (via Skype), 13 December 2019, London, UK.

and thus for participation in the c-Si networks, it also has implications for the material surroundings of the laboratory.

The laboratory landscape (i.e. the material surroundings) has been was reshaped and transformed by the reorientation of research. The laboratory landscape has been transformed by the reorientation of research. This is the reason for this is the large and capital-intensive machines required to carry out the research that was promoted. These large machines require large spaces, as well as skilled personnel to handle them. The laboratory landscape is also changing due to the type of research promoted by the R&D programmes – capital-intensive machinery, tools etc. The laboratory is gradually becoming a small factory, which is also more energy-intensive to carry out this kind of research. In contrast, OPV and perovskite research do not necessitate such machinery and large areas (they just need a glovebox). But as we get closer to production the scale and material surrounding change.

In this way, not only was the role of the smaller research groups and universities limited, but also implicitly or indirectly limited who could participate in the R&D programmes. At the same time, the research landscape was (actively) being transformed through the introduction and/or establishment of large research centres – and at the same time their role in the value chain was strengthened. Marginalisation and exclusion manifested in several ways. First, not all countries had the funding to support this type of research (cost-shared contracts); e.g. countries with little or no R&D funding on a given topic or theme. Second, countries and actors that do not have the necessary (capital-intensive) machinery to conduct this type or research (i.e. infrastructures) or even the appropriately trained personnel to handle these machines that are crucial for laboratory research.

In sum, both the research priorities and the character of the research changed in the second period. As a direct consequence of the EU energy policy to increase the production of PV, the issue of securing an adequate supply of silicon feedstock became the focus of c-Si research activities. Research that could narrow the gap to the market was promoted. Concurrently, the research activities were reoriented to solve production issues and to deliver near-market products. Towards this end, the scope of PV research was widened to the entire PV value chain or to as many parts of the value chain as possible.

The ‘scale’ and scope of research actively supported by EU R&D programmes impacted the role and place of universities, large research centres and companies. The large research centres, understood as the link between basic research and industry, attained a central role in R&D activities. In contrast, small research groups and universities were marginalized as their participation was restricted and continuously minimized throughout the second period. The above-mentioned changes in the character of research impacted, even indirectly, the role and place of both large research centres and universities. Paraphrasing the words of the Fraunhofer interviewee, the closer we get to production, the more both the research and the prerequisites for carrying out this type of research (i.e. large machinery, equipment etc.) change. Thus, even though indirectly, imposes restrictions on who can carry out this 'upscaled' research and thus redefines the role of each actor within the R&D programmes (as well as the corresponding networks). Furthermore, this 'upscaled' research has actively reconfigured the material surroundings of the laboratory, which resembles a miniature factory. The indirect marginalization of small research groups and universities, as well as the increased role of large research centres, has implications that go beyond the question of who can participate in EU projects and networks and who has access to R&D funding. These implications concern innovation 'itself'. By actively directing the scope and priorities of research, exclusions or marginalization are not just about 'who can innovate'. It is also about which parts of the value chain we can expect to see innovations and what kind of innovations we can expect. Essentially, these last points are about who generates and forges the EU's knowledge and technical capacities and the constraints on the scope and breadth of research. In the case of PV, this also relates to who forms the EU's knowledge basis and capacity and who directs the transition to RES.

5.1.3 C-Si technoscientific research networks: the hegemony of the European North expands beyond c-Si

Tracing the patterns of collaboration and the ties between actors through specific individuals and their respective expertise, we see that the core of the EU-funded R&D on c-Si in the second period was geographically located mainly in Germany, Belgium, the Netherlands, as well as in Norway and in France to a lesser extent. We have designed Figure 5.4 (below) to trace important actors and geographies that might be overlooked by the quantitative data alone. The second period c-Si technoscientific research networks included a total of twenty-nine actors, slightly more than the first periods c-Si networks (twenty-five).

The actors from the above countries formed collaborations that expanded and connected with the following European countries: Switzerland, Sweden, Spain, the UK, and Italy. As we analyse in chapter 6, the UK, Spain, and Italy, for different reasons and following a different rationale, gradually limited their c-Si research while giving further priority to CPV R&D.[542] In contrast, Germany, the Netherlands, and Belgium placed an increasing emphasis on c-Si research throughout the second period. On a second level, we also see that actors from Norway consistently pursued research on c-Si, despite not accumulating the bulk of EU R&D funding for c-Si. French actors, on the other hand, experienced a c-Si revival towards the end of the second period and climbed to the top of R&D funding.

Actors from Greece, Cyprus, Ireland, Denmark, Austria, Bulgaria, Slovenia, Lithuania, Ukraine, the Czech Republic, Hungary, Russia, Israel and Australia took over some of the c-Si research activities of the second period. However, the actors from these countries were not continuously involved in the c-Si research projects and did not coordinate c-Si projects. Thus, the actors from these countries have neither gained a stronger position in the c-Si research, nor have they managed to become main actors in the c-Si networks.

Similar to the analysis of the first period, despite the large number of actors depicted in Figure 5.4, we can see that the majority of actors participated in a limited way (both in square and with a limited number of ties/links). Ranging from universities, research centres and their spin-offs, an electric utility and major PV cell/module manufacturers. These actors are the following: Dow Corning, Roth & Rau, Ayming, PSE, EDF, Shell, Deutsche Solar, Q-Cells, Utrecht University, EPFL, Scanwafer, BP Solar, Milano University, Photowatt, and CNRS. The majority of these actors participated in the programmes on a limited scale. Some of these actors (i.e. PSE, Roth & Rau, and EPFL) participated late in the programmes (FP7).[543] Similarly, there were actors that did not participate in c-Si research activities during FP7. These include the University of Milan, BP Solar, Scanwafer, Deutsche Solar, Shell.[544] EDF, Dow Corning and Ayming had a gap programme (i.e. FP6), whereas Q-Cells started c-Si research activities from FP6. Only a handful of actors participated continuously in EU c-Si research (i.e. Photowatt, CNRS, Utrecht University).

For an in-depth analysis of the actors, research programmes and landscape for Spain and the UK, see chapter 6. Similarly for Italy. In the following analysis, we only bring examples of actors from these countries in the context of their contribution to c-Si networks when and where necessary.

---

[542] Based on the analysis of the CPV case-study, we show that the countries of the European South that comprised the periphery of c-Si, formed the core of the CPV research.

[543] We examine the case of EPFL in the forthcoming analysis. Roth & Rau was a EPFL spin-off, which explains why the two started to enter the research activities together. PSE was a Fraunhofer ISE spin-off, for details see analysis below.

[544] Some of the companies stop embarking on c-Si research because they terminated their PV business. For example, Shell sold its assets to Siemens in 2001-2, whereas BP Solar started closing its factories in 2009.

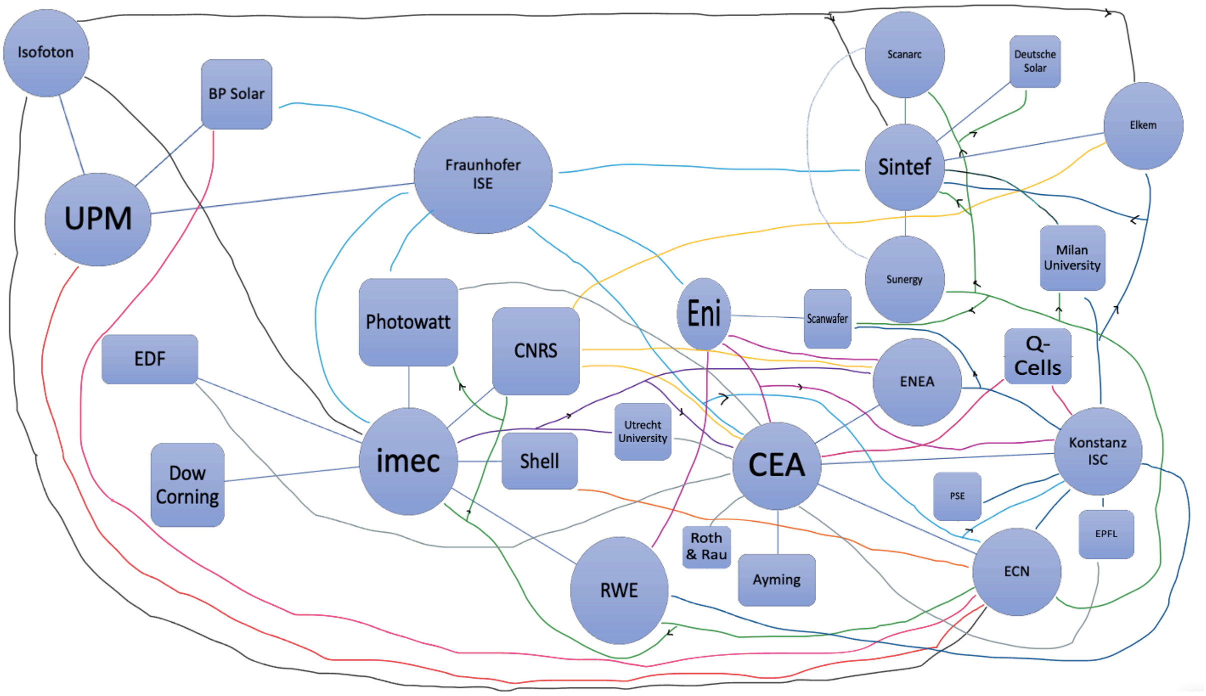


Figure 5.4 The c-Si technoscientific research networks of the second period.

A small number of actors played a central role in the c-Si research activities of the second period. As we will see in the forthcoming analysis, the actors that comprised the core of c-Si research did not all have the same influence on setting the EU research agenda (both in terms of continuity and 'type of research'). Overall, it was actors from Belgium, Germany, the Netherlands and to a lesser extend from Norway that had an impactful role in directing the research activities and agenda for c-Si. Imec, Fraunhofer ISE and Elkem continued to play a central role in the c-Si networks. ECN and Konstanz ISC attained a stronger position in the networks during this period. A new scientific 'entrant' from Norway (Sintef) managed to become core actor in the c-Si networks and research activities. In contrast, the role of former central actors from Italy, Spain, the UK, and France (i.e. Eurosolare/Eni, UPM, BP Solar, Photowatt and CNRS) was weakened. The Spanish and Italian actors gradually limited (and in some cases stopped) their c-Si research activities, which can be explained by their continuous focus on CPV R&D.[545] The situation is similar in the UK, where BP Solar increasingly focused its attention on CPV R&D. However, BP Solar closed its PV business towards the end of the second period, which further explains the absence of UK actors in research activities – both for c-Si and CPV. Lastly, the French actors exhibited a renewed thrust in c-Si research towards the

---

[545] See chapter 6 analysis.

end of the second period. However, this was through a newly established Institute at CEA and not through actors who were already continuously present in the c-Si networks.

Important (nationally and internationally) actors mainly from the European North collaborated with one another and directed the EU research agenda for (PV and) c-Si. To better comprehend the reasons why these countries have continuously pursued c-Si research, and what their priorities for c-Si research have been, we analyse them one by one. Furthermore, in line with the analysis of the first period, we provide insights into the research landscape and national networks of each country.

As we mentioned in an earlier section, the impeding silicon crisis has been given due attention in the projects funded under the EU R&D programmes. The silicon crisis in PV did not only lead to R&D funding gradually favouring thin film, but also redefined the research themes and priorities for c-Si. Direct reference was made again to the dependence on the same silicon feedstock as the electronics industry. Within this context, several projects were dedicated to finding solutions to the impeding silicon feedstock shortages.[546] In this context, research on c-Si shifted to the development of a Solar-grade Si feedstock (SoG-Si) for the field of PV, the emergence of the so-called thin film c-Si and heterojunction Si cells, as well as methods and techniques to save and/or recycle feedstock, the thinning of crystalline wafers etc. The proposed solutions reoriented the research themes for c-Si, from new production methods and processes to the development of techniques that could help reduce silicon consumption and loss.

It is worth noting that the actors leading and/or coordinating the c-Si projects of this period were not coordinating CPV projects. In other words, the leading actors in these two technologies are separate. Concurrently, the geographical location for each of these two technologies is different. C-Si research was and remained concentrated in the European North, whereas CPV research was located in the European South.[547]

5.1.3.1 C-Si in Germany: research needs to be transferred to the industry

German actors maintained their strong position in EU funded R&D activities on c-Si in the second period. In particular, German-led projects ranked first in c-Si funding in FP5 (25,83%) and FP7 (38,34%), while they ranked third in FP6 with a share of only 4,29%. The decreasing

---

[546] See the analysis of the projects below.

[547] Actors from Norway, the Netherlands, Germany, and Belgium did not coordinate any CPV projects. That is not to say that actors from some of these countries did not participate in the CPV networks. Regarding this point see the analysis in Chapter 6.

German share in FP6 can be attributed to the increasing Dutch c-Si activities, which almost monopolized c-Si funding in FP6, and the simultaneous decrease in the number of projects funded in FP6. However, German actors were included and/or involved in both the Dutch- and Norwegian-led projects and coordinated one of the (three in total) projects in FP6. Germany had both industrial and scientific actors involved in c-Si research and production and was the only country that both coordinated and participated in c-Si activities throughout the second period.

C-Si has always had enjoyed a favourable position in Germany. With large industrial actors covering many steps of the c-Si production chain and actors coming the microelectronics and telecommunications fields, German R&D in PV was built on c-Si. Within the German research landscape, there are four major R&D actors in c-Si: (i) the Fraunhofer Institute for Solar Energy Systems (Fraunhofer-ISE), (ii) the Helmholtz-Zentrum Berlin (HZB), (iii) the International Solar Energy Research Centre Konstanz (ISC-Konstanz) and (iv) the Institute for Solar Energy Research (ISFH).[548,549] We see all four actors in the EU c-Si networks, with Fraunhofer ISE and ISC-Konstanz having a more prominent place in the networks.

In the West part of Germany, close to the French and Swiss borders, is the city of Freiburg. This is also where the Fraunhofer ISE is located. Despite the rocky start and difficulties in establishing ISE in 1981, it is now he largest European and one of the largest PV Institutes worldwide and plays a central role in setting the German research agenda and activities for PV. With its long history, tradition and expertise in c-Si, Fraunhofer ISE has played a catalytic role in setting the agenda and directing the EU's c-Si research activities.[550]

> "The **Fraunhofer Institutes** are a bit different from other Institutes in a way that they **are obliged to achieve roughly a third of their income from the industry**. **The Fraunhofer Society is somehow the link between industry and fundamental research**, which is more located at universities and other type of Institutes."[551] (emphasis added)

---

[548] Information provided via interview with Fraunhofer ISE Head of Department (via Skype), 13 December 2019, London, UK.

[549] Helmholtz Zentrum Berlin formerly named Hahn-Meitner Institut Berlin.

[550] For an analysis about the Fraunhofer ISE founder, Adolf Goetzberger, and his role in directing the research activities within the Institute see the corresponding Chapter 4 section.

[551] Interview with Fraunhofer ISE Head of Department (via Skype), 13 December 2019, London, UK.

As a/the link between besic research and industry, Fraunhofer ISE essentially represents a critical node in the German innovation system. Moreover, the institutes are obliged to form collaborations with industry and are thus encouraged to transfer their know-how and expertise to industry. It is therefore not surprising that ISE flourished in Germany shortly after the FiT Law of 1999, because before that "there was no real market".[552] In particular, the FiT Law:

> "…changed things a lot and then companies came to Germany or were founded in Germany, mostly in the East of Germany they got some special regional funding and also I think the EU funded this a bit with some low-interest rates etc. So, **this was a very dynamic phase also for the Institute** that **grew from** something like **three-hundred people to more than a thousand within a few years**."[553] (emphasis added)

We have already discussed at length the impact of the FiT Law in constructing the (global) PV market and the catalytic role Scheer played in this. The favourable schemes attracted more companies to move their production to Germany. However, the above-mentioned developments also had an impact on the domestic research landscape. Given the links between research and the market that are 'necessary' to receive funding, the establishment of a PV market had a direct impact on the Institute, which flourished shortly and as a direct result of these developments. Furthermore, these developments were implemented precisely because the starting point and research focus of Fraunhofer ISE was c-Si.

Several individuals from Fraunhofer ISE were frequently and continuously involved in the EU-funded c-Si projects that we analyse in turn.[554] Martin C. Schubert joined FhG-ISE in 2008 and was appointed head of the 'Silicon Material Characterization' team one year later. He remained in this position until 2012, when he became head of the "Material and Cell Analysis' group. Since 2017, he has been promoted to head of the "Material and Cell Analysis' department. Wilhelm Warta, another FhG-ISE scientist who can often be found in the EU networks, is head of the "Characterization and Stimulation" department. Stefan Janz – Head of the 'Silicon Materials' department – specializes in minimizing kerf losses and recycling materials.

---

[552] Remark made during the interview with Fraunhofer ISE Head of Department (via Skype), 13 December 2019, London, UK.

[553] Interview with Fraunhofer ISE Head of Department (via Skype), 13 December 2019, London, UK.

[554] It is worth noting that many of the names we see 'under Fraunhofer' are PhD students. These PhD students come from a number of different institutions (e.g. Freiburg University, Konstanz University etc.). Therefore, Fraunhofer ISE comprises an active hub of knowledge generation and training of future scientists and researchers.

Maximillian Steiert – joined the FhG-ISE in 2002 as EU Project Officer, a position he held until 2019 when he became EC Policy Officer in Brussels. Ralf Preu, with a background in physics and electrical engineering, joined the Institute as head of the ‘PV Production Technology and Quality Assurance’ group after completing his PhD on innovative production technology for c-Si cells at the University of Freiburg. In 2007 he became head of the same department, in 2011 he was promoted to head of the same division, whereas since 2018 he has been appointed Director of ‘PV Production Technology and Quality Assurance’. Preu founded PSE, an FhG-ISE spin-off that we also see in the c-Si networks.

Stefan Reber was head of ‘Crystalline Silicon Materials and Thin Film Solar Cells’ department and founder of NexWafe, another FhG-ISE spin-off, working closely with the current FhG-ISE Director, Andreas Bett, to transfer the teams’ work into the commercialization stage. NexWafe is a solar wafer manufacturer based in Freiburg. The company produces kerfless PV (monocrystalline Silicon) ultra-thin wafers with high efficiency (patented technology).[555] Bett was also a member of the WG, which set the research priorities in the SRAs.

A key figure in the field of c-Si research who acted as a link between various important actors (i.e. imec, Fraunhofer and the University of Konstanz) was Gerhard Willeke. A physicist by training, he had been a project leader at imec since its inception. After leaving imec in 1989, he joined the Physics group at the University of Konstanz and become the group leader there. After spending a decade in Konstanz, he joined the Fraunhofer ISE family, first as head of the ‘Solar Cells – Materials and Technology’ department (1999-2006). Since 2007, he has been head of the Fraunhofer Centre for Silicon PV, which he helped to establish.

Two hours from Freiburg and close to the Northern part of Switzerland is the city of Konstanz. With a long tradition in c-Si PV, dating back to the 1970s, what is now the Photovoltaics Division at the University of Konstanz (Department of Physics) is internationally recognized as a knowledge-hub for PV. The Division’s advanced equipment and facilities:

> “…allows the complete processing of solar cells in industry-type and lab-type manners as well as a detailed characterization of wafers and solar cells. Numerous patents were transferred into industry.”[556]

---

[555] Regarding the exact manufacturing steps of NexWafe’s technology see: Nexwafe, *About us*, nexwafe, Available online: https://www.nexwafe.com/, (accessed 13 October 2019).

[556] Univesitat Konstanz, *Photovoltaics Division*, uni-konstanz, Available online: https://www.hahn.uni-konstanz.de/en/, (accessed 15 October 2019).

The head of the Photovoltaics Division is Pr. Dr. Giso Hahn, since 2009. Hahn obtained his PhD from the University of Konstanz and is leads the division's c-Si research activities. In an effort to expand the university's R&D activities in PV and foster links with industry, a group of physicists from the university established the International Solar Energy Research Centre (ISC) – Konstanz (e.V.) in 2006. The ISC-Konstanz is a non-profit organization covering all c-Si PV activities – from cell to system. The main funding sources of the organization are the EU (projects) and the German Ministry of Economics and Energy. In addition, ISC has the following (main) sponsors: Elkem Solar, Sunways, Centrotherm, Semilab, Rena, Baccini, PV Silicon, and Ersol.[557] ISC-Konstanz currently consists of over fifty members. Given the ISC-Konstanz funding sources, it is not surprising that many of its members are involved in the EU-funded c-Si projects. However, three individuals are frequently involved in the EU-funded projects: Peter Kristian, Radovan Kopecek and Peter Fath.

Peter Kristian was one of the founding members of ISC-Konstanz and has been managing director of the 'Applications and Systems' since 2007. He obtained his PhD in physics from the University of Konstanz. Radovan Kopecek obtained his MSc in Physics from the University of Stuttgart and subsequently completed his PhD on c-Si thin films from the University of Konstanz. He is also one of the founding members of ISC-Konstanz and has been the managing director of the 'Advanced Cell Concepts' department since 2007. Lastly, Peter Fath obtained his PhD in physics at the University of Konstanz. At that point, his path must have crossed with Kristian and Kopecek. Fath worked as a researcher at Sunways AG and is the founder of RCT Solutions GmbH. He was also member of the ETP-PV Working Group, which was responsible for writing the SRAs. Each one of these individuals worked with Fraunhofer staff mentioned above as well as with people from the companies mentioned above and with other have established collaboration ties both with the aforementioned Fraunhofer individuals and with actors analysed below.

Critical in the German innovation system is the link between research activities and industry. We see a number of German companies enter the technoscientific research networks of c-Si that have forged collaborations with a number of European research centres. The German companies the most frequently and continuously represented in EU-funded projects include Q-

---

[557] Kristian Peter, Radovan Kopecek, Roman Petres, Peter Fath, Eckard Wefringhaus, "Long-term perspective for Photovoltaic R&D activities in Konstanz", *in* Twenty second European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Milan, Italy, 3-7 September 2007, G. Willeke, H. Ossenbrink, P. Helm (eds.), WIP Renewable Energies: 2007, p. 3519-3520.

Cells, RWE Schott Solar, and Deutsche Solar/Cell. All three companies were among the top ten European PV manufacturers, throughout the second period.[558]

Q-Cells was established in 1999. The company's production line of polycrystalline-Si cells went into operation in 2001. Despite its late start, Q-Cells became one of the world's largest PV manufacturers within a few years.[559] Deutsche Solar and Deutsche Cell were manufacturers of wafer and solar cell, respectively. Both companies were subsidiaries of Solar World AG, which was founded in 1998.[560] Deutsche Cell was another top cell European manufacturer in the second period.[561] Another major industrial actor actively involved in the c-Si networks was Schott Solar/RWE. As we saw in the analysis of the first period, ASE had emerged from Nukem's PV efforts through its subsidiary RWE. The background of the company that eventually became RWE Schott Solar has a long history, going back to the late 1970s. RWE emerged from Nukem's solar business and developed from collaborations and joint ventures as well as acquisitions, including AEG's solar PV business (via ASE).[562] Schott Solar bought 50% of RWE in 2002, and the company was subsequently renamed RWE Schott Solar. Three years later, Schott bought out RWE and the company was renamed Schott Solar. The company covered the manufacturing of wafers, cells and modules. Apart from the extensive know-how and knowledge the company had acquired in the past an important figure that played a critical role in its pathway. RWE Schott's team included the first EPIA president, Dr. Winfried Hoffmann. Hoffmann has been described as "Europe's best connected solar industrialist".[563] Hoffmann is not only the company's managing director, but is also advisor to Fraunhofer ISE.[564] He also began his PV journey in thin films at Nukem, where he extensively collaborated with the Konstanz team. Along Q-Cells and Deutsche Cell, RWE Schott Solar was one of the

---

[558] For a detailed analysis of the corresponding company shares, see the Annual PV Status Reports published by the JRC.

[559] With a production of nearly 400MW in 2007, Q-Cells ranked as the leading PV company (See: Jäger-Waldau Arnulf, *PV Status Report 2008*, Publications Office of the European Union (Luxembourg: 2008, p. 10). By the end of 2010, the company's production had exceeded 1,1GW (See: Jäger-Waldau Arnulf, *PV Status Report 2008*, Publications Office of the European Union (Luxembourg: 2011, p. 27). In 2012 the company was bought by the Southern Korean conglomerate Hanwa.

[560] For more information on Solar World and its subsidiaries see the Annual PV Status Reports, published by JRC.

[561] Ranking steadily in the top ten European PV cell producers. The parent company (Solar World) filed for insolvency in the late 2010s (Jonathan Gifford, 10 May 2017, *Breaking: SolarWorld files for insolvency*, Available online: https://pv-magazine-usa.com/2017/05/10/breaking-solarworld-files-for-insolvency/, (accessed 3 November 2019).; Sandra Enkhardt, 28 March 2018, *SolarWorld files for insolvency-again*, pv-magazine, Available online: https://www.pv-magazine.com/2018/03/28/solarworld-files-for-insolvency-again/, (accessed 3 November 2019)).

[562] For a detailed analysis of ASE's background and acquisitions see the corresponding section in Chapter 4.

[563] Philip R. Wolfe, "Who's Who: Profiles of Early PV Pioneers", *in* The Solar Generation: Childhood and Adolescence of Terrestrial Photovoltaics, John Wiley & Sons Inc. (Hoboken, New Jersey: 2018), p. 161.

[564] Philip R. Wolfe, "Who's Who: Profiles of Early PV Pioneers", *in* The Solar Generation: Childhood and Adolescence of Terrestrial Photovoltaics, John Wiley & Sons Inc. (Hoboken, New Jersey: 2018), p. 139-198.

larger European PV manufacturers and was the largest German and European manufacturer in the 2000s.[565]

5.1.3.2 The Belgian framework and network

As we have seen in the analysis of the first period, Belgian actors had a long tradition in c-Si. KU Leuven and imec, which were played and still play a prominent role in the domestic research landscape. Moreover, both played a crucial role in EU-funded R&D activities on c-Si throughout the first period.[566] During FP5, Belgian actors accounted for a 13,49% share of c-Si funding, a share that increased to 23,96% in FP7. Despite the absence of Belgian-led projects in FP6, Belgian actor(s) continued to be involved in the c-Si networks.[567]

Imec had established a strong national and international position in both c-Si and PV R&D. Founded in 1984 as a spin-off from KU Leuven by Professor Roger van Overstraeten, imec is now a hub for nanoelectronics and digital technologies. A key figure at imec is Josef (Jef) Poortmans, who has coordinated several EU-funded R&D PV projects. Poortmans, who currently programme director for PV at imec, has a background in electronic engineering from KU Leuven and was one of the first to join imec when it was founded. Among his various important positions at imec, he is also a board member of EUREC and was one of the members who formed the WG for the establishment of the SRAs. Another important imec figure we often see in the EU-funded PV networks is Johan Nijs. Nijs also has an education in electrical engineering and received his PhD from KU Leuven in 1982. He joined imec in 1984 and became group leader of silicon materials and solar cell activities. Since 2002 he has been focused on the founding of Photovoltec, the spin-off from imec. The aim of the company is to transfer the knowledge attained from the R&D activities at imec to the production of solar cells and modules.[568]

---

[565] For more information of each company's production capacity see the corresponding Annual PV Status Reports, published by the JRC.

[566] See for example the analysis on Pr. Dr. Roger van Overstraeten (KU Leuven), founder of IMEC and EUREC. Overstraeten was also head of the EC's PV advisory committee, during the first period, actively shaping and directing the EU research agenda for PV.

[567] It is important to note that the Belgian activities remained almost exclusively vested in c-Si, in contrast to the majority of the other cases where we see a diversification in the PV activities.

[568] Other individuals from IMEC have been, over time, involved, in the EU-funded PV projects. Some of these individuals, the names of which are featured in the EU-funded published work or are directly affiliated in the EU-funded projects, include Guido Agostinelli that worked at IMEC from 2001 to 2007, Guy Beaucarne who was head of the 'Solar Cell Technology' group from 2003 to 2009 before joining Dow Corning, Christine van Houtven who is a public funded officer at IMEC since 1992, Ingrid de Wolf who joined IMEC in 1989 and is a Professor of Physics at KU Leuven.

Finally, Dr Jozef Szlufcik, with has a background on electronics engineering, joined imec in 1990, where he led c-Si cost-reduction activities.[569] Szlufcik was also one of the founders of Photovoltech, which was established in 2002. The company was set up "by Total, Electrabel, Soltech and imec for the manufacturing and global marketing of photovoltaic cells and modules."[570] Essentially, it is a spin-off from imec to commercialize the thin film Si wafer process. To support the immediate commercialization of imec's future research, the company had received support from major actors. Electrabel is a Belgian electric utility and energy producer, whereas Total is one of the largest multinational oil and gas companies.

5.1.3.3 The Dutch framework and network

In a previous section we saw that the Netherlands was prominent in the EU-funded PV research activities in the second period.[571] In FP5, Dutch actors accumulated a total of about 25% of c-Si funding, whereas in FP6 their share increased to a whopping 81,88%! Even though there are no Dutch-led c-Si projects in FP7, a limited number of Dutch actors from the previously formed c-Si networks (i.e. ECN and Utrecht University) were still involved in the FP7 networks. During FP7, Dutch PV activities seem to have been reoriented towards thin film research and we see that both ECN and Utrecht University have been 'transferred' to the a-Si networks.[572] Within the Dutch national R&D funding programmes, wind energy had a favourable position until the 2000s.[573] Apart from the brief promotion of PV in the 1990s, Dutch policy was reoriented towards the end of the decade.

> "In the late 1990s the government re-evaluated renewable options using two criteria: (a) contribution to greenhouse gas reduction, (b) cost-efficiency. PV

---

[569] Interuniversity Microelectronics Centre, 1 February 2017, *Harvesting sunlight from both sides of PV cells may give PV plants a significant energy boost*, imec, Available online: https://www.imec-int.com/en/imec-magazine/imec-magazine-february-2017/harvesting-sunlight-from-both-sides-of-pv-cells-may-give-pv-plants-a-significant-energy-boost, (accessed 7 November 2019).

[570] Jäger-Waldau Arnulf, *PV Status Report 2011*, Publications Office of the European Union (Luxembourg: 2011), p. 56.

[571] The bulk of the funding was dedicated for the c-Si and thin film activities. In both the c-Si and the thin-films projects the Dutch actors managed to attain large funding shares, always ranking either first or second.

[572] This 'transfer' as we argue is attributed to the launch of the c-Si thin films agenda that gradually gained prominence during the second period. We analyse these points in a forthcoming section.

[573] Maarten Wolsink, "Dutch wind energy policy – Stagnating implementation of renewables", *Energy Policy*, 1996, p. 1079-1088; Linda M. Kamp, Ruud E. H. M. Smits, Cornelis D. Andriesse, "Notions on learning applied to wind turbine development in the Netherlands and Denmark", *Energy Policy*, 2004, p. 1625-1637; Geert Verbong, Frank W. Geels and Rob Raven, "Multi-niche analysis of dynamics and policies in Dutch renewable energy innovation journeys (1970–2006): hype-cycles, closed networks and technology-focused learning", *Technology Analysis & Strategic Management,* 2008, p. 555–573.

> scored poorly on both criteria: total contribution to renewable electricity was negligible and costs were very high. As a result, policy attention shifted back to wind and biomass."[574]

Apart from the above-mentioned criteria of the Dutch government, Shell's decision to expand its production capacity by building a new production plant in Germany and to take advantage of the favourable conditions in Germany seems to have contributed to minimizing PV efforts domestically.[575] The repercussions of Shell's decision lay in the knowledge-transfer of domestic knowledge and know-how from the Netherlands to Germany. This meant that the (publicly funded) R&D efforts of Dutch universities and research centres, which were channeled to Shell would be transferred to another country.

The increasing participation of Dutch actors in EU R&D PV networks could thus be explained due to the unfavourable and unstable national framework, which led Dutch actors to seek funding through other means to continue their research activities. As mentioned earlier, Dutch universities and research centres had developed an interest in PV (and PV research) despite the unfavourable domestic situation. The research conducted until the 1990s was limited to the universities and research centres.[576] We have already analysed the role of the ECN in relation to the development of PV. In the second period, when RES was given a place on the energy policy map, ECN was tasked with researching other – non-nuclear – energy options to diversify the country's resources. With close links to the market, the research centers aims is to accelerate the Dutch (sustainable) energy transition.[577,578]

Apart from the prominent funding position the Dutch attained in both the overall EU R&D funding programmes for PV and c-Si research activities, as illustrated in Figure 5.4, ECN Solar Energy (ECN-SE) had a strong position in c-Si activities. The individuals from ECN-SE

---

[574] Geert Verbong, Frank Geels, The ongoing energy transition: Lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960–2004), *Energy Policy*, 2007, p. 1034.

[575] Geert Verbong, Frank Geels, The ongoing energy transition: Lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960–2004), *Energy Policy*, 2007, p. 1025-1037.

[576] Verbong G., Selm A. van, Knoppers R., Raven R., "Een kwestie van lange adem. De geschiedenis van duurzame energie in Nederland 1970–2000", Aeneas Technical Publishers (Boxtel: 2001), *as cited in* Geert Verbong, Frank W. Geels, Rob Raven, "Multi-niche analysis of dynamics and policies in Dutch renewable energy innovation journeys (1970-2006): hype-cycles, closed network, and technology-focused learning", *Technology Analysis & Strategic Management*, 2008, p. 555-573.

[577] Energy Research Centre of the Netherlands, ECN, *Sustainable energy: for a clean future in which ECN plays a leading role*, Available online: https://www.ecn.nl/energy-research/index.html, (accessed 2 December 2019).

[578] We have already analysed the role of ECN in the Dutch research landscape for RES and PV in the analysis of the first period. ECN was founded in 1955 as the Reactor Centre Netherlands and was renamed to ECN in 1976 following the oil crises. ECN's R&D activities focused on PV, wind energy and biomass, as well as energy efficiency etc. In 2018, ECN joined forces with TNO (Netherlands Organisation for Applied Scientific Research). In the beginning of 2020, the ECN part of TNO was renamed to Energy Transition.

collaborated with a number of actors from Norway, Germany, Belgium, Sweden etc. It is worth noting that ECN-SE and the University of Konstanz appear together in almost all projects, while ECN-SE was present in the SoG-Si projects and collaborated closely with the Norwegian network.

A handful of individuals from ECN-SE comprised the nodes between ECN-SE and the actors ECN-SE collaborated with. These individuals continuously participated in the EU-funded projects for c-Si and collaborated with each another. Some of the individuals who are constantly present in the c-Si PV networks in one way or another are G. Paul Wyers, Arthur Weeber and Wim Sinke.[579]

Dr G. Paul Wyers was the Director of ECN-SE from 2003 to 2018. Wyers specializes in geochemistry and joined ECN-SE in 1988, initially working in nuclear energy and environmental research. When he started working in PV in 1997, he became Senior Manager of Silicon PV, a position he held until 2003. Arthur Weeber has a background in physics and chemistry and obtained his PhD in physics from the University of Amsterdam. After completing his PhD, in 1988, he joined ECN-SE and focused on c-Si PV, where he remained until 2018. Wim Sinke attained his MSc and PhD in physics from Utrecht University and joined the team at ECN-SE shortly after. From 2004 to 2018, he was Program Development Manager of ECN-SE, developing the strategic research priorities and direction of the ECN. From 2009 to 2014, he was also Chairman of ETP-PV and a member of the WG3, which was tasked with writing the SRA.

5.1.3.4 PV in Norway: from a marginal place domestically to solving Europe's Si problems

Norwegian actors only coordinated c-Si projects under FP5 and FP6 and received 1,29% and 13,87% of the total c-Si funds, respectively. In FP7, Norwegian actors did not coordinate any c-Si projects. The absence of Norwegian-led c-Si projects, during FP7,can be attributed to two complementary reasons: (i) no projects supported SoG-Si research under FP7, which formed the core of the Norwegian-led projects, and (ii) the changes in c-Si research during the second

---

[579] Another individual that we repeatedly see participating in the EU c-Si projects is Lamber Johan Geerligs. Geerligs was also part of the ECN Solar Energy team during the period under examination and had filled for a number of patents on behalf of ECN. However, it was not possible to find information on his background or exact position within ECN. Based on articles he has published, he collaborated with all three individuals analysed during the examined period. Concurrently, Geerligs has published articles with a number of other individuals from Germany (Warta from Fraunhofer ISE, Kopecek and Fath from ISC-Konstanz), Belgium (Nijs from IMEC), and Italy (Pizzini, Binetti and Acciarri from Milano University, Tucci and Salza from ENEA).

period allowed Norwegian actors to 'enter' thin film activities and networks.[580] In FP7, only two Norwegian actors participated (once). The Norwegian actors that comprised the networks until FP6 are no longer involved; the only exception is Sintef. The second participation was a Norwegian company that was not part of the previous c-Si networks (i.e. NorSun). However, as we analyse in a later section, Norsun participated in the network because the company was one of the sponsors of ISC-Konstanz.

5.1.3.4.1 The Norwegian R&D landscape and c-Si networks

The Research Council of Norway (RCN), established in 1993, is the government agency responsible for domestic R&D funding and aiding Norwegian actors to access EU R&D funding programmes. Even though Norwegian actors (scientific and industrial) were involved in the silicon efforts, covering almost all steps of the production chain, there was no national funding for PV until the late 1980s. With limited funding available for PV R&D until the late 1990s, Norwegian actors started to participate in EU R&D programmes to obtain more funding and to collaborate with other European actors. Since the early 2000s, Norwegian R&D funding for PV has gradually increased.[581]

The RCN encourages collaboration between universities, research centres and the industry. In the case of c-Si PV, this involves a number of actors covering almost the entire silicon production chain. The main actors that form the backbone of c-Si activities in Norway and lead the national R&D activities are listed in Table 5.1. The Norwegian actors collaborated with each another at the national level. Similarly, in the EU-funded c-Si networks, most of these actors were part of the c-Si technoscientific networks through various collaborations (see Fig. 5.4 above). As shown in Table 5.1, the PV activities of the Norwegian actors cover the entire silicon value chain, from Si feedstock to panels.

Actor	Si value chain
Elkem*	Si feedstock
REC[582] *	Si feedstock, Panels

---

[580] Under FP7 the Norwegian actors undertook (exclusively) research on thin films Si solar cells. We explain this shift in a forthcoming section, where we examine the changes in the content of the c-Si research activities of the second period.

[581] For further details on the Norwegian R&D funding on solar energy (both thermal and photovoltaics), see: Klitkou Antje and Godoe Helge, "The Norwegian PV manufacturing industry in a Triple Helix perspective", *Energy Policy*, 2013, p. 1586-1594.

[582] ScanWafer and ScanCell are REC's subsidiaries.

ScanWafer*	Wafers
ScanCell	Cells
Institute of Energy Technology	Cell research
NTNU*	Cell research
SINTEF*	Cell research
University of Oslo*	Cell research
Fesil*	*Ferrosilicon*
NorSun*	*Ingots and Wafers*

Table 5.1 Norwegian actors, directing the national R&D activities on c-Si PV, throughout the Si value chain.[583]

On the research front, there is SINTEF and NTNU. SINTEF is one of Norway's main applied research organizations.[584] It was founded in 1950 by what is now the Norwegian University of Science and Technology (NTNU). A key role of SINTEF is to link the research conducted (both at SINTEF and NTNU) with industry. [585] SINTEF and NTNU have traditionally been linked and have worked closely for many decades. Personnel, involved in EU R&D programmes often have dual affiliations (i.e. SINTEF and NTNU). The partnership between the two is described as "…a key component of the Norwegian system…".[586]

Elkem, founded in 1904, is a Norwegian producer of silicon, silicon products and silicones. The company is one of the world's largest producers and suppliers of silicon, ferrosilicon and silane. Elkem operates quartz mines (raw material for the production of Si feedstock) and has plants in various locations in Europe, North and South America and in Asia. In addition, Elkem was one of the first supporters of the PV industry to undertake research activities to develop of SoG-Si feedstock for the PV industry. To be precise, Elkem is a unique exception in that it has continuously conducted this type of research since the 1970s. After several joint ventures with other large companies (e.g. Dow Corning, Exxon, Texas Instruments etc.) that did not yield commercial results, Elkem accumulated knowledge and expertise on the possible ways to produce a SoG-Si feedstock. The continuation of these efforts was made possible by EU R&D funding programmes. The EU-funded collaborative research projects were crucial for Elkem

---

[583] Actors with an asterisk (*) participated in the EU R&D projects for c-Si. The analysis focuses only on the actors that had a continuous participation in the c-Si research activities funded by the EU schemes.

[584] SINTEF stands for Stiftelsen for Industriell og Teknisk Forskning ved Norges Tekniske høgskole.

[585] Formerly known as the Norwegian Institute of Technology – The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology.

[586] Stiftelsen for industriell og teknisk forskning, SINTEF, *About SINTEF*, Available online: https://www.sintef.no/en/sintef-group/this-is-sintef/, (accessed 5 February 2021).

to achieve its place as one of the largest (worldwide) silicon producers for PV.[587] Furthermore, the Norwegian-led SoG-Si projects played an important role in securing additional feedstock for European PV manufacturers.[588] The impact of EU-funded R&D programmes on Norwegian SoG efforts has already been outlined by the historical actors themselves. Therefore, we will refrain from such an analysis, as it has already been done. We will only state that, according to the autobiographical narratives of the Norwegian actors, the EU R&D programmes and the corresponding c-Si networks did indeed have an impact and were helpful in the development of SoG in Norway.[589]

ScanWafer, which we also see in the illustration of the second period networks, was founded in 1994 by Alf Bjorseth. Bjorseth had previously worked for Elkem and the British Crystalox. He founded the company with the aim of producing multi c-Si wafers and ingots for PV.[590] About six years later, in 2000, ScanCell was established, which produces solar cells by using ScanWafer's wafers. Renewable Energy Corporation (REC) was established in 1996 and was the result of ScanWafer's merger with two other companies.[591] REC's strategy was "to become the most cost-efficient solar energy company in the world, with presence throughout the whole value chain."[592] Although REC is not seen in the networks illustration due to its background and collaborative ties, the company also participated in the EU-funded c-Si research activities. Regarding the Si feedstock this was achieved through acquisitions. During the silicon crisis, REC acquired ASiMi to fulfil the company's strategy of providing silicon feedstock for the PV sector.[593]

There are four prominent individuals who have been continuously involved in EU c-Si projects. Eivind Johannes Ovrelid from SINTEF Materials and Chemistry, who also worked at REC in the Silicon Division as R&D Manager. Marisa Di Sabatino, then a PhD student at NTNU, who also worked at SINTEF. And finally, Cyrus Zahedi and Erik Enebakk from Elkem's Silicon Division. The Norwegian actors collaborated with actors from other European countries (Fig. 5.4 above). In particular, the Norwegian actors collaborated with different actors in the c-Si networks (the Netherlands, Germany, France, Belgium, Sweden, Italy and Spain).

---

[587] See Chapter 7.

[588] See Chapter 7.

[589] Ceccaroli Bruno, Ovrelid Eivind, Pizzini Sergio (eds.), *Solar Silicon Processes: Technologies, Challenges and Opportunities*, Taylor & Francis Group (Boca, Raton, London, New York: 2017).

[590] Elkem held a minority share of ScanWafer.

[591] Similar to ScanWafer, Elkem also heavily invested in REC.

[592] Arnulf Jäger-Waldau, *PV Status Report 2005: Research, Solar Cell Production and Market Implementation of Photovoltaics*, Office for Official Publications of the European Communities (Luxembourg: 2005), p. 85.

[593] For more information, see Chapter 7.

An important example of how some key actors were linked was the research efforts to develop a SoG. Within this context, a number of actors joined their efforts. As part of SynErgy's efforts to develop a different process for producing SoG, the Swedish Scanarc Plasma Technology (specializing in plasma technologies), ECN and Fesil joined forces.[594,595] The collaboration between Fesil and SuneErgy led to the creation of a joint company (Fesil-SunErgy) and the commercialization of the jointly developed process (SOLSILC process).[596]

5.1.4 The c-Si periphery

In chapter 6, we analyse in depth the national research landscapes and priorities of Spain, the UK, Italy and France, as well as the main technoscientific research network actors. To avoid repetition, we will only briefly mention some Italian and French actors who have been active in c-Si research and have played an important role in c-Si research activities and the EU research agenda for PV.

We have already analysed Professor Pizzini, his background and his role both at the University of Milan and at Montedison. Pizzinni's research was industry-focused. As part of the EU-funded c-Si activities, we have seen that Pizzini has worked closely with two of his students, Dr Simona Binetti and Dr Acciarri Maurizio-Filippo. Binetti is currently an Associate Professor of physical chemistry at the Department of Materials Science at the University of Milan, and also Director of the Milano-Bicocca Solar Energy Research Centre (MIBSOLAR). Acciarri is currently working of the Laboratory for Nanostructure Epitaxy and Spintronics of Silicon (L-NESS). The research conducted at L-NESS is closely linked to important European actors including imec, ETH Zurich and Max-Plank.

Dr Mario Tucci obtained his PhD in electronic engineering from the University of Rome La Sapienza (1996) and has worked at ENEA since then.[597] He is Head of the Photovoltaics Lab of ENEA Tucci has conducted research on c-Si for a number of major European companies (i.e. Q-Cells, ENIPOWER, Helios Technology etc.). Luisa Pirozzi, a colleague of Tucci's at ENEA had established collaborative ties with the University of Milan and with a prominent figure at EniTechnology, which we will analyse shortly. The Photovoltaics Lab team working

---

[594] Regarding the ties between the two companies and how they started collaborating see: Ceccaroli Bruno, Ovrelid Eivind, Pizzini Sergio (eds.), *Solar Silicon Processes: Technologies, Challenges and Opportunities*, Taylor & Francis Group (Boca, Raton, London, New York: 2017).

[595] The collaboration between Fesil and SuneErgy resulted in the co-founding of a joint company (Fesil-SunErgy) and the commercialization of their process (SOLSILC process).

[596] Ceccaroli Bruno, Ovrelid Eivind, Pizzini Sergio (eds.), *Solar Silicon Processes: Technologies, Challenges and Opportunities*, Taylor & Francis Group (Boca, Raton, London, New York: 2017).

[597] ENEA Research Centre Casaccia, Rome, Italy.

with Tucci includes Massimo Izzi and Enrico Salza. All of the above individuals have worked on EU-funded c-Si projects. Izzi has a background in solid-state physics from the University of Rome La Sapienza and has specialized in s c-Si solar cells since joining the ENEA team.
A single individual from EniTechnologie has featured consistently in the EU c-Si projects, Dr Francesca Ferrazza.[598] Ferraza received her PhD in physics from the University of Rome La Sapienza and then started working as a researcher at Italsolar. She then became R&D Manager at Eurosolare in the early 2000s. Since 2004, she has been responsible for the company's PV activities and was head of technologies for renewable energy and environment for the rest of the second period. Apart from her various important positions within the company, she was also a member of the ETP-PV Working Group, which was responsible for the preparation of the SRAs. Due to her long expertise in this field and in the company, Ferrazza has established collaborative relationships with various key actors in the c-Si EU network (e.g. CEA, CNRS, University of Konstanz, ISFH, Q-Cells, Fraunhofer ISE, RWE Schott, ScanWafer and others).
Unlike most other countries, France was almost continuously present in all PV activities. However, unlike Germany, France has not risen continuously to the funding top. In c-Si research, French actors attained a 4,21% share under FP5 and concentrated 37,69% under FP7. As we have seen in previous cases, the number of funded projects decreased in FP6 and only a handful of projects were funded for each PV technology. However, key French actors for c-Si activities were involved in FP6 networks (i.e. CNRS and Photowatt). The push towards c-Si, evident in the increased funding shares during FP7, is due to the Commissariat a l'energie atomique et aux energies alternatives (CEA). Within the CEA, the Institut National de l'énergie solaire (INES) was established in 2006, focusing mainly on c-Si research.[599] The institute, which covers research on Si on all steps of the value chain (from feedstock to cells/module), was established to bridge the gap between research and industry and the rapid commercialization of research. By establishing an Institute that covers the entire (Si) value chain and can commercialize the research results, while having the infrastructures to conduct this type of 'upscaled research', it is not surprising that the CEA became a core in the networks towards the end of the second period. Additionally, a key figure in Photowatt, Dominique Sarti, became Director of CEA-INES. Sarti was a member of the WG that set the SRA priorities for PV during this period.

---

[598] Note that EniTechnology was formerly known as Italsolar and Eurosolare, whereas it was then renamed into Eni (Power). An analysis of the company's history has already been analysed in a previous section.
[599] *École polytechnique fédérale de Lausanne, epfl, Silicon-based heterojunction solar cells*, Available online: https://www.epfl.ch/labs/pvlab/research/heterojunction_solar_cells/, (accessed 5 February 2020).

5.1.5 Responding to the Si crisis: thin films come over to the c-Si side

To address and solve the urgent challenges of the impeding silicon crisis, c-Si research activities were reoriented. Two complementary routes were pursued: (i) the development of a SoG-Si feedstock for the PV field and (ii) the development of thin-film crystalline silicon solar cells. The first route aimed to develop a silicon feedstock for the PV sector. The second route of the thin film c-Si cells followed two different paths. The first targeted the wafer (concept of 'wafer equivalent'), while the second targeted the structure of the cells (tandem and heterojunction Si solar cells).

5.1.5.1 The research agenda for c-Si thin films: appropriating a-Si know-how

Towards the end of the first period (FP4) the concept of c-Si thin films emerged in the EU R&D programmes. A total of four projects explored research on this new technology. However, the concept was contextualized as it was in the second period. As a combination of the advantages of both technologies, it was explored in the first period mainly for its potential cell efficiency/cost advantages. In contrast, the concept was re-casted in the second period the as a direct response to the Si crisis in PV.[600]

In the early days of the first period (FP5), a consortium of (six) projects forged a collaboration to develop c-Si thin films. The coordinators included well-known actors who have traditionally been core actors in the c-Si networks (e.g. imec and Fraunhofer ISE). Apart from the central role the actors of this collaboration had in the technoscientific research networks and the commercialization of this technology, these projects led to the creation of the c-Si thin films roadmap.[601]

> "The photovoltaic market is dominated by solar cells based on crystalline Si with a market share of about 95% in 2003. Most predictions indicate this will remain the case for at least the next 2 decades. **When analyzing the cost structure of nowadays crystalline Si-modules**, **more than 50% of the costs is related with the Si- substrate** (equally distributed between material costs,

---

[600] In the analysis that follows we trace continuities in the actors comprising part of the c-Si thin films research agenda and activities.

[601] Stefan Reber, Filip Duerinckx, Mario Alvarez, Barry Garrard, Friedrich-Wilhelm Schulze, "EU project Sweet on Epitaxial Wafer Equivalents: Results and Future Topic of Interest", *in* Twenty first European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Dresden, Germany, 4-8 September 2006, J. Poortmans, H. Ossenbrink, W. Palz, P. Helm (eds.), WIP Renewable Energies: 2006, p. 570-576.

> crystallization and wafering). **The wish to reduce these costs by a reduction of the consumption of expensive EG-Si is the main driver behind the R&D of thin-film silicon-based solar cells**."[602] (emphasis added)

With the impeding silicon feedstock crisis posing the greatest challenge to the project proposals, the consortium has sought to reduce material consumption. This reduction in material in turn can reduce costs and thus promote c-Si's place in the PV market. A basic requirement was to assess the transferability of the results to production. Towards this end, several industry actors participated in the projects, covering the entire silicon value chain. These included Elkem, Dow Corning, RWE Schott Solar, Isofoton, Crystalox, Shell Solar, to name a few.

But how were thin film crystalline silicon solar cells defined in the European context? Furthermore, did this concept have technical implications that reconfigured the 'classic' or 'traditional' c-Si technology?

> "**Thin-film crystalline silicon solar cells are a term which covers a large number of approaches in which a thin active crystalline Si layer is deposited on a low-cost carrier**. This paper deals with the high- and intermediate temperature approaches for a crystalline Si thin-film technology. Over the last decade, one can observe an strongly increasing R&D-effort in this domain, especially in Europe. The **obvious drivers behind this R&D-effort are the potential cost reduction because of the reduced amount of highly pure Si and the fears for a lack of polysilicon feedstock to sustain the rapid growth of the photovoltaic market**. Despite this effort, **the introduction of its results into the photovoltaic industry proceeds relatively slow**. Therefore a critical assessment of these largely qualitative supporting arguments is justified."[603] (emphasis added)

---

[602] J. Poortmans, S. Reber, S. Gall, C. Zahedi, J. Alonso, "European cluster on high- and intermediate temperature thin-film crystalline Si solar cells R&D: Overview of running projects and underlying roadmap", *in* Nineteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Paris, France, 7-11 June 2004, W. Hoffmann, J. L. Bal, H. Ossenbrink, W. Palz, P. Helm (eds.), WIP Renewable Energies: 2004, p. 397.

[603] J. Poortmans, S. Reber, S. Gall, C. Zahedi, J. Alonso, "European cluster on high- and intermediate temperature thin-film crystalline Si solar cells R&D: Overview of running projects and underlying roadmap", *in* Nineteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Paris, France, 7-11 June 2004, W. Hoffmann, J. L. Bal, H. Ossenbrink, W. Palz, P. Helm (eds.), WIP Renewable Energies: 2004, p. 397.

The above definition of thin film crystalline silicon solar cells is crucial. First, it provides the European definition of this technology, which is being pursued through the EU-funded programmes. Second, it undoubtedly confirms the intended uses of this technology for the c-Si industry. And finally, it reinstates the fundamental challenge (i.e. silicon crisis) that this technology was intended to address and solve.

Research on c-Si thin film technology was re-casted in the second period as a direct response to the silicon crisis and eventually resulted in what became the EU R&D Roadmap for c-Si thin films. As the roadmap gradually gained momentum in the second period, the geography of a-Si also changed. Actors from the countries proposing the EU R&D Roadmap for c-Si thin films came from of c-Si backgrounds and had developed know-how and expertise in c-Si thin films, exploiting and appropriating the technical characteristics of a-Si thin films for the benefit of c-Si.

Prominent actors from the c-Si networks were behind this research agenda. Imec and Fraunhofer ISE, together with ECN, Elkem, Konstanz ISC and others, were involved in the majority of the EU-funded c-Si projects and were part of the consortium working on c-Si thin films. Furthermore, several of the individuals we analysed above (Sinke, Baliff, Bett, Fath, Ferrazza, Poortmans, Sarti), who have been continuously involved in the c-Si projects, have collaborated in the c-Si thin film projects and were part of the WG, which set the agenda and research priorities for PV.

The c-Si thin film agenda, which emerged from the consortium of FP5 projects, was incorporated into the FP6 research activities and subsequently legitimized by the SRAs and became a main research activity of the FP7 research projects. Through the SRAs, this research agenda gained legitimacy as a priority to be pursued by EU R&D funding programmes. The contents of the c-Si thin film agenda were included in the research priorities proposed by the SRAs, as they were seen as proposed routes for increasing cell efficiency and improving device performance. As we have already analysed, several of the individuals responsible for setting up the research priorities for the SRAs were the same people who were already driving and directing c-Si research in the EU programmes. During FP7, the majority of (c-Si) projects targeted the c-Si thin film agenda.[604] Either explicitly mentioning c-Si thin films, which were the core of their activities, or indirectly by focusing on the development of heterojunction solar cells. As we will show in the a-Si case study (following section), both the actors that formed

---

[604] Two thirds of the projects undertook research related to this agenda, during FP7.

the a-Si networks and the research priorities and themes for a-Si were redirected towards the end of the second period. The c-Si thin film agenda led not only to redirecting research priorities and activities for c-Si, but also to a restructuring of the geographical distribution, networks, and research activities of a-Si. The c-Si actors gained a prominent role in the a-Si research networks and funding and steered the research activities for the prevalent thin film technology. Furthermore, the development of c-Si thin films was included as a research priority for c-Si in the SRAs.

5.1.5.1.1 The Swiss network: from cutting-edge research in thin films to innovative contributions to c-Si research

Towards the end of the second period, the École Polytechnique Fédérale de Lausanne (EPFL), Institute of Microengineering (IMT) PV-lab emerged as a recurrent actor in the EU c-Si networks. The PV-Lab was founded in 1984 and specializes in thin film silicon and heterojunction Si solar cells. The lab is headed by Prof. Dr. Christophe Ballif and works closely with industry and research centres in Europe.[605] Ballif obtained his PhD at EPFL-IMT on novel PV materials, followed by postdoctoral studies at NREL (US), where he worked on compound semiconductors (CIGS and CdTe). He then worked at Fraunhofer-ISE on (mono and multi) c-Si cells before returning to Switzerland, where he worked at Empa until 2003. Baliff's versatile research, ranging from c-Si to thin films, must have been the reason he took up research on heterojunction Si solar cells. During his first years at PV-Lab, Ballif was also a member of the ETP-PV Working Group responsible for writing the SRAs.

In addition to Ballif, the PV-Lab team included Dr Stefaan De Wolf, Loris Baurraud, Dr Jonas Geissebuhler and Antoine Descoeudres, who are also involved in the FP7 c-Si projects. Barraud has been working in the PV-Lab since his diploma in 2009 as a deposition engineer specializing in heterojunction solar cells. Geissbuhler did his PhD at EPFL and is researching high efficiency Si solar cells. Descoeudres received his PhD in physics from EPFL in 2006. From 2009 to 2013, he worked on the development of Si heterojunction solar cells in the PV-Lab team. Lastly, Stefaan De Wolf started his research at imec in 1998, specializing in c-Si cells. He continued his studies on heterojunction Si cells in Japan (2005-8) before joining the PV-Lab team to lead the heterojunction Si research activities.

---

[605] Baliff has been the head of PV-Lab since 2004. The previous PV-Lab head, who was also its founder, is Prof. Arvind Shah. For more information on PV-Lab see: *École polytechnique fédérale de Lausanne - PVLab, epfl.pvlab, About us,* Available online: https://www.epfl.ch/labs/pvlab/about_us/, (accessed 5 February 2020).

With a clear research agenda aimed at 'attracting' researchers specializing in heterojunction Si solar cells, the PV-Lab's expertise on this technology comes mainly from the c-Si field. Ballif gained his knowledge on c-Si at a top institution (i.e. Fraunhofer-ISE) specializing in this technology, while he also gained experience with compound semiconductors during his studies in the USA. With the aim of transferring the lab's activities into commercialization, the lab has been active in both the establishment of companies and spin-offs (e.g. Roth & Rau and Indeotec).

Although c-Si is the dominant technology, its dominance will diminish as new technologies and design options enter the market and slowly cease to be stop being niches. In addition, Europe has invested heavily in c-Si as part of the transnational competitions. To this end, we see the following being featured in PV-Lab's website:

> "Photovoltaics (PV) energy is on the edge of becoming one of the main global source of energy, and crystalline silicon has been dominating the market with no sign of change in the near future. **Silicon-based heterojunction solar cells (Si-HJT) are a hot topic within crystalline silicon photovoltaic as it allows for solar cells with record-efficiency energy conversion up to 26.6%**."[606] (emphasis added)

According to the PV Lab's website, Si-based heterojunction solar cells are a part of the c-Si enabling further efficiency increases in the dominant technology. When *p-n* junctions are made of the same material with the same bandgap, it is called a homojunction. In contrast, in a heterojunction, the *p-n* junction is formed from two different materials with different bandgaps.[607] This 'union' allows to 'take advantage' of the different materials' bandgaps, which increases light absorption and by extension current generation and energy output. This is the case for the silicon heterojunction solar cells, as mentioned in the quote above. In this case, the c-Si wafer is combined with a-Si:H layers (on both the top and bottom of the wafer).[608] Si-based heterojunction solar cells can achieve higher efficiencies (i.e. 25,6% record efficiency by Panasonic in 2014) than the classical c-Si cells. This is essentially a technical change in the

---

[606] *École polytechnique fédérale de Lausanne, epfl, Silicon-based heterojunction solar cells*, Available online: https://www.epfl.ch/labs/pvlab/research/heterojunction_solar_cells/, (accessed 5 February 2020).

[607] I. M. Dharmadasa, "Photovoltaic Solar Energy Conversion", *in* Advances in Thin-Film Solar Cells (1st Edition), (Singapore: Pan Stanford Publishing, 2012), p. 1-24.

[608] For a schematic representation of a silicon-based heterojunction solar cell and of the Si layers see: Kleider et al., "Characterization of silicon heterojunctions for solar cells", *Nanoscale Research Letters*, 2011, p. 1-9.

Si solar cells, as it aims to close the gap between wafer-based and the thin-film technologies in favour of the former.

By using the know-how and knowledge developed in the context of thin films, and in this case with a-Si, which is part of the dominant silicon group, the PV-Lab team tried to find a way to combine and transfer this knowledge for the 'benefit' of the dominant technology. Essentially, the development of heterojunction solar cells can lead to further improvements in the dominant technology – through knowledge and technology transfer *from* thin films *to* c-Si – which can increase the efficiency of c-Si beyond theoretical limit of Shockley-Queisser.

In the case of the PV-Lab, we see that there is an effort to develop heterojunction solar cells, which essentially means combining thin-film technology and crystalline silicon technology and merging them into one to favour crystalline silicon, which is the dominant technology. On the other hand, we have the team at imec trying to do something different. That difference is essentially trying essentially to bridge the gap between the two technologies by trying to produce crystalline silicon technology in a similar way as thin films. Essentially, it is about moving developments as well as research into the processes and techniques that are being funded towards bridging this kind of gap. In both cases, we see efforts to further improve the dominant crystalline silicon technology by bringing in knowledge as well as technology from the thin films field. Despite the efforts came from different directions, i.e. imec and the PV-Lab, both offered different options, but both had a common denominator: they aimed at improvements for the dominant technology.

5.1.5.2 The directionality of c-Si to the a-Si R&D geography, networks, and research priorities

Before the introduction of the c-Si thin film agenda in FP5 c-Si projects, both the geographical distribution of R&D funding for a-Si and the a-Si networks had their own characteristics. With the introduction of the c-Si thin film agenda, the geographical distribution of a-Si R&D funding and a-Si networks started to change and strongly resembled that of c-Si.

5.1.5.2.1 The influence of the c-Si thin film agenda on the geographical distribution of the a-Si R&D funding

We have already analysed the shift to a-Si under FP1 and the simultaneous decline of a-Si in the remainder of the first period. The a-Si research under FP1 was organized around two actors (companies) from Germany and France. In the remaining time of the first period, the research funds allocated to a-Si steadily decreased. Similarly, both the French Solems and the German MBB no longer coordinate projects. This also to a greater geographical dispersion of funding for the remainder of the first period. As illustrated in Figure 5.5 (below), the geographical distribution of a-Si R&D funding from FP2 to FP4 was distributed among actors from Greece (27,3%), Finland (27,3%), Germany (18,4%), the Netherlands (17,4%), and Denmark (9,5%).[609] Even though continuities and discontinuities between FPs are not shown in Figure 5.5, we should note that the Greek actors were the only ones who continuously coordinated a-Si research projects throughout the period 1989-1998. In contrast, the Finnish and Danish actors coordinated a small number of projects only at the end of the first period.

In the second period, R&D funding were distributed to actors from the Netherlands (22,3%), Germany (22,3%), Belgium (21,1%), Switzerland (18%), Norway (8,7%), Spain (4,2%), and Greece (3,4%). Greek actors not only received a small share of funding, but also provided coordination of projects from FP6 onwards. In contrast, the Swiss started to participate in a-Si research activities from FP6 onwards. The Belgians, the Germans, the Norwegians and the Spanish started to coordinate a-Si projects under FP7. The only actors that continuously coordinated a-Si research projects throughout the second period were the Dutch.

We have already seen in the c-Si analysis that the Norwegians, Belgians, Germans as well as the Dutch were heavily involved in the c-Si technoscientific research networks. Moreover, the Dutch, German and Belgian actors concentrated most of the c-Si funding and at the same time constituted an important part of the corresponding technoscientific research networks. Although the Norwegians received a smaller share of c-Si funding, they also played an important role in c-Si research activities and networks. Even though the Spanish have shifted their research towards CPV, they were also involved in c-Si research activities and had expertise in c-Si.

---

[609] Shares may not add to 100% due to rounding up to the nearest decimal.

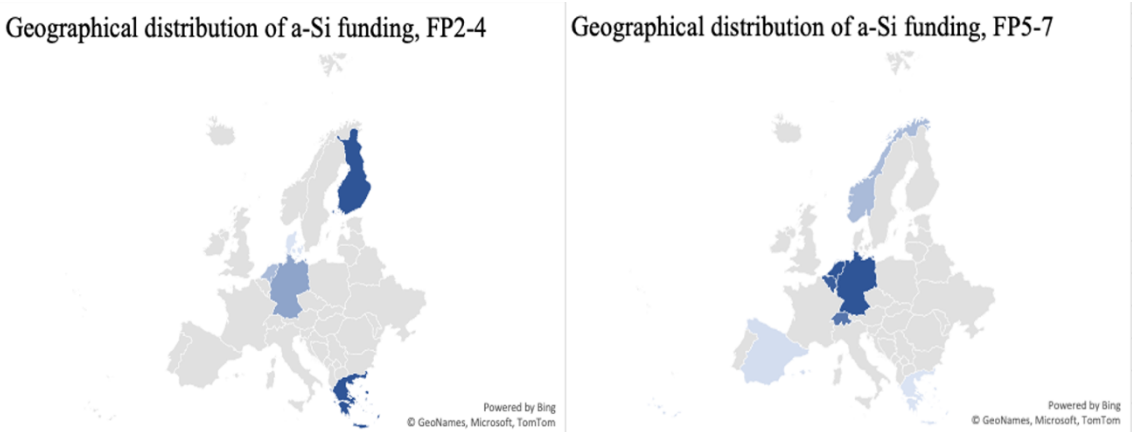
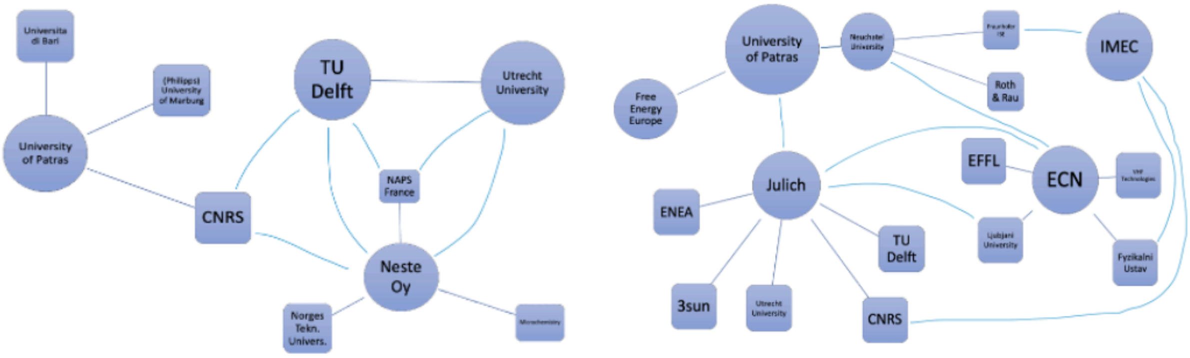


Figure 5.5 Comparison of geographical funding distribution of a-Si R&D funding (1989-2013).

Therefore, in the second period we see a gradual shift away from the actors who had 'traditionally' invested in a-Si in the first period. As the second period progresses, we see the bulk of a-Si funding shifting to actors from countries that have played a prominent role in c-Si research activities. To complement this, we now turn to the a-Si networks to show that, apart from the change in the geographical distribution of a-Si funding, which strongly resembles that of c-Si in the second period, these changes are also reflected in the a-Si networks.

5.1.5.2.2 The reformulation of the a-Si networks: mirroring the c-Si networks

As shown in Figure 5.6 (below), a-Si's technoscientific research networks grew larger from the first to the second period. In the first period, there were four actors through which all others connected to and joined the a-Si networks. These actors were: the University of Patras, TU Delft, Utrecht University and Neste Oy. Perhaps the most important actor was the University of Patras, through which most of the other actors joined the a-Si networks. As the University of Patras took a firm and continuous place in the a-Si R&D activities, other actors managed to become part of the networks (e.g. Universita di Bari and Philipps University of Marburg) and ensure a continuation of the a-Si research activities. The Dutch actors (TU Delft and Utrecht University) formed another core, sharing common links with the University of Patras (CNRS) and the Neste Oy network.



A-Si technoscientific networks, FP2-4 A-Si technoscientific networks, FP5-7

Figure 5.6 Comparison of a-Si technoscientific research networks (1989-2013).

In the second period, more and new core actors emerge, forming their own networks. Apart from the University of Patras, which only acted as a coordinator until FP5, ECN, imec, and Julich have emerged as core actors (and the Neuchatel University to a lesser extent). TU Delft and Utrecht University participated in the second period only because they were associated with Julich. They lost their insofar prominent role as core actors. The CNRS continued to participate in the a-Si networks under the coordination of projects led by Julich. Both ECN and imec were active in c-Si research and part of the c-Si thin film research agenda. They brought – as links – other actors who has played an important role in the c-Si networks, namely: Fraunhofer ISE, EPFL and Roth & Rau. Concurrently, new actors (e.g. VHF Technologies, Ljubjani University etc.) started to enter the a-Si networks due to the emergence of these new core actors in the a-Si networks.

5.1.5.2.3 An entry point for attaining larger R&D funding shares

As can be seen from the data in Table 5.2, the share of c-Si funding gradually decreased from one FP to the next, while the second period the corresponding share of thin film gradually and steadily increased. Furthermore, the share of a-Si funding continued to increase throughout the second period and accounted for the largest share of total thin film funding.

PV technology	**FP5**	**FP6**	**FP7**
c-Si	46,47%	26,37%	13,25%
Thin films	19,27%	35,76%	44,88%
a-Si	6,8%	7,96%	19,32%
a-Si share (%) in thin films	34,51%	22,25%	43,04%
a-Si share (%) in thin films (excl. projects with more than technology, including a-Si)	38,5%	38,09%	45,82%

Table 5.2 A-Si funding share and comparison, 1999-2013.

Both the increase in funding for thin films and the decrease in funding for c-Si, correlate with the continuously increasing funding for a-Si. After the launch of the c-Si thin film research agenda in FP5, the interests of c-Si actors in a-Si R&D started to be established (in FP6 and FP7). Furthermore, the role of c-Si actor was legitimized by the SRAs in FP7, where we can observe a reorientation of the research activities for both for c-Si and a-Si. For a-Si, one of the research priorities that served as a pathway to achieve higher cell efficiencies was “PV technology merging”.[610] This essentially paved the way for the c-Si thin film agenda to be transferred to a-Si. These changes are reflected both in the geography of a-Si networks, which was gradually reconfigured in the second period to closely resemble the geography of c-Si funding and in the a-Si networks of the second period.

The research agenda for c-Si thin films was created in response to the silicon crisis. This helps us to both understand and explain why the changes observed in the a-Si networks were gradually introduced from FP6 onwards and prevailed in FP7. This is consistent with the gradual shift towards a-Si that coincides with shrinking c-Si funding. This shift allowed the c-Si actors to secure their position and thus their share of R&D funding through the a-Si projects. As this technological ‘marriage’ allows the transfer of both knowledge and know-how from c-Si to a-Si and vice versa, the c-Si actors were able to secure their position in the EU funding programmes, while innovating in/for two separate technologies. The reorientation of c-Si research due to the silicon crisis has reshaped both the scientific fields of a-Si and c-Si as well as the research priorities and activities for both technologies. Moreover, these changes have reconfigured the geography of a-Si research networks and reproduced the Northern European hegemonic geography of c-Si networks.

5.1.6 The view from the market: the PV sector becomes industrial

PV is the favorite child of EU R&D funding programmes among all other RES. Among all other PV technologies, c-Si has ‘traditionally’ enjoyed the funding lead.[611] Emerging as the dominant technology of the semiconductor electronics actors, c-Si has dominated the global

---

[610] Photovoltaic Technology Platform, *A Strategic Research Agenda for Photovoltaic Solar Energy Technology*, Office for Official Publications of the European Communities (Luxembourg: 2007).; Photovoltaic Technology Platform, *A Strategic Research Agenda for Photovoltaic Solar Energy Technology*, 2nd Edition, Office for Official Publications of the European Communities (Luxembourg: 2011).

[611] As the PV field gradually became industrial during the second period, the EU R&D funding schemes started prioritized other RES. Accordingly, c-Si funding gradually declined during the second period.

PV market. In the second period, as the field of PV gradually became industrial, c-Si was able to maintain and further expand its dominance in the market.

As we have already highlighted, the importance of PV (and flat-plate c-Si in particular) lies in the unique system integration option it offers. Flat-plate PV provided energy policy with a unique alternative system integration option that paved the way for a different way of generating and consuming energy 'leading to' smart grids, the reconfiguration of electricity production, transmission and distribution systems, while constructing different users (e.g. producers consumers). The inclusion of RES and especially PV pn the energy policy map by the EC was detrimental to the industrialization of this sector. Furthermore, the Treaty of Lisbon (2007) defined energy policy "[…] as an area of priority action by primary (i.e. treaty) law […]", hence a common EU energy policy, centrally regulated.[612] With these enhanced powers, the EU placed RES at the heart of its energy policy and its (RES) transition vision and commitments. Most recently, the '2050 long-term strategy' set the goal for the EU to become 'climate-neutral' by 2050; RES play a central role in this.[613] The impact of including RES on the energy policy map became visible in the second period, when PV production grew at an unprecedented pace. During the 1998 World Conference for PV, Palz remarked:

> "For the first time we shall see **industrial production chains** for cells and modules, which really deserve their name."[614] (emphasis added)

It is neither accidental nor negligent that Palz used the term 'industrial production chains'. This is indeed the key to the above statement. This was meant to inaugurate the long-awaited industrialization of the PV sector in terms of upscaled production and by extension upscaled industrial actors. Global annual PV production increased from 33,6 MW in 1988, to 69,44 MW in 1994.[615]

---

[612] Jale Tosun, Sophie Biesenbender, Kai Schulze (eds.), *Energy Policy Making in the EU: Building the Agenda* (London: Springer, 2015), 22.

[613] This is part of the European Green Deal. See: European Commission, Europa, *Climate Action – 2050 long-term targets*, Available online: https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2050-long-term-strategy_en, (accessed 10 April 2021).

[614] W. Palz, "PV Highlights from a European Perspective", *in* Second World Conference on Photovoltaic Solar Energy Conversion, Fifteenth European PV Solar Energy Conference, Twenty Seventh US IEEE Photovoltaics Specialists Conference, Tenth Asia/Pacific PV Science and Engineering Conference, Proceedings of the International Conference held at Vienna, Austria, 6-10 July 1998, J. Schmid, H. A. Ossenbrink, P. Helm, H. Ehmann, E. D. Dunlop (eds.), Vol. I, WIP Renewable Energies: 1998, [CD-ROM], p. xciii.

[615] Arnulf Jager-Waldau, *Status of PV Research, Solar Cell Production and Market Implementation in Japan, USA and the European Union*, Office for Official Publications of the European Communities (Luxembourg: 2002), p. 4.

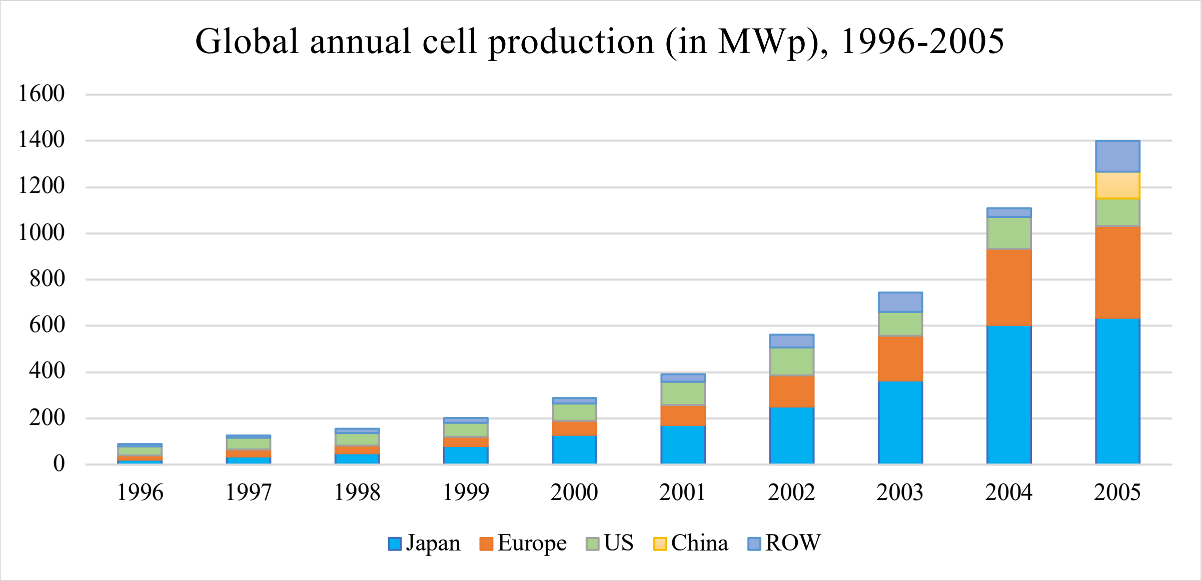


Figure 5.7 Global annual cell production (in MWp), 1996-2005. Adapted from: Greenpeace and EPIA, *Solar Generation: Solar Electricity for Over one billion people and two million jobs by 2020*, September 2006, p. 19.

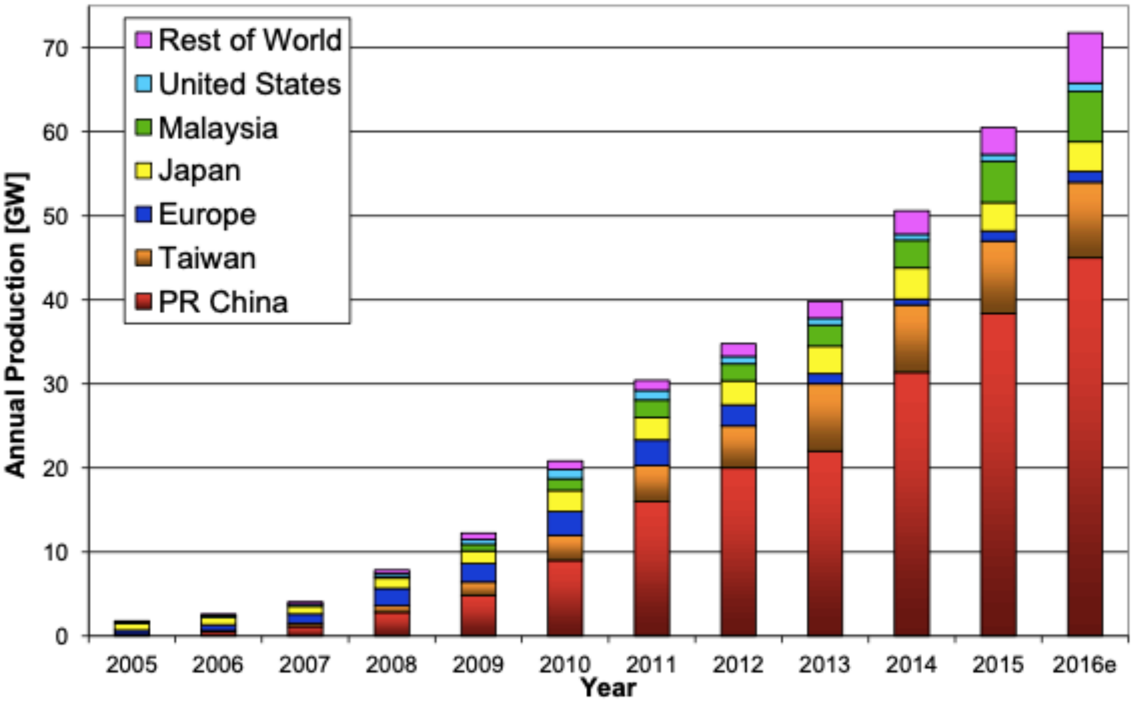


Figure 5.8 Global annual cell/module production, 2005-2016e. Source: Arnulf Jager-Waldau, *PV Status Report 2016*, Publications Office of the European Union (Luxembourg: 2016), p. 11.

As shown in Figures 5.7 and 5.8 (above), global production of PV cells/modules increased dramatically in the second period.[616] For example, global annual PV production grew from less than 200 MW in 1998 to a just over 1 GW at the beginning of the silicon crisis in 2004, to about 8 GW at the end of the silicon crisis in 2008, and finally to over 70 GW in 2013![617] In just five years, in 2018, production passed 500 GW mark.[618] China's market entry has been a major factor contributing to the rapid global expansion of PV production, with consequences for European's position in the market and their international competitive position.

5.1.6.1 International competition in PV: the rise and fall of the EU

We have already analysed how the EC instrumentalized R&D programmes in the first period to help European industry to compete internationally. Either by actively constructing the first European market for PV, or by a 'U-turn' in R&D funding towards a 'new' PV technology (i.e. a-Si) or by a return to the 'basics' (i.e. c-Si), the research policy of the Commission has always directly helped the European industry to compete internationally.[619] In the second period, research policy had to respond to a raw material crisis that was the result of the EC's decision to include RES in its energy policy. From the development a PV-exclusive Si feedstock to the appropriation of thin films know-how and expertise, research policy continued to support the international competitiveness of the European industry. In the second period, the geographical location gradually shifted to respond to Chinese competition.

Before China's entry into the PV business (2004-5), competition was between Japan, Europe, and the USA was fierce. Until 1998, the US led in production, followed by Japan. From 1999 to 2006, Japan took over the production lead, while Europe climbed to the second place from 2002. After China's dynamic entry into the PV business, China finally displaced Japan from first place in 2007. Europe maintained its second position – ahead of Japan – until around 2009. There is no doubt that the targets set by the EU have helped to create a 'stable' market environment necessary for upscaling PV production. By extension, the EU energy policy targets for PV have been very successful in supporting the industrialization of the PV sector by continuously increasing production. This is not to say that Germany's role has not been critical

---

[616] Please note that in the JRC PV Status Reports, the author notes that the reported production data vary for several reasons (e.g. competitiveness and secrecy on behalf of the companies, how each company gathers this data, what each company counts etc.). However, given the diversity and the legitimacy of the sources these reports use to compile the data, we consider the JRC Reports as trustworthy and well-informed sources.

[617] Arnulf Jager-Waldau, *PV Status Report 2014*, Publications Office of the European Union (Luxembourg: 2014).

[618] Arnulf Jager-Waldau, *PV Status Report 2019*, Publications Office of the European Union (Luxembourg: 2019).

[619] During the first period, the major a-Si competitor was Japan. Accordingly, the major c-Si competitor was the US.

to these developments. Without the strong political support of key actors in implementing these EU targets, with contestations and obstacles along the way, the story of the PV sector would not have been the same.[620] The EU's energy policy goals, encouraged and supported by EU R&D funding schemes, have been extremely successful in making the European PV sector competitive. Europe has not only increased its PV production, but also surpassed that of the USA and Japan. During the silicon crisis in PV, the European PV industry really flourished.

Equally important to the geographical distribution of PV production is the corresponding distribution of installations and the type of installations (i.e. the uses and applications). In the 1970s and 1980s, PV systems were mainly installed in remote and rural areas. During the 1990s, PV systems were explicitly installed on building for the first time as part of the first roof programmes. Within this context, the German and Spanish programmes and incentives created large domestic markets for PV in the second period.

Alongside the annual European PV production, the annual installed PV capacity in the EU has also increased continuously. The annual PV capacity installed in Europe (in GWp) has wlasys been always the highest and accounted for over 80% of the annual PV capacity installed worldwide in 2010. Not surprisingly, the EU also leads in cumulative installed PV capacity (GWp), accounting for more than 50% of global cumulative installed PV capacity by 2013.[621] During the silicon crisis, the EU increased PV installations, which led to Europe overtaking Japan. Germany accounted for the largest share of PV installations both in EU and globally.[622] Germany was the leader in PV installations in 2001, with 80 MW installed annually.[623] By 2001, a total of about 300 MW had been installed in Europe.[624] Furthermore, Germany had a total installed capacity of 194.7 MWp in 2001, while Japan had a total installed capacity of 452.2 MWp.[625] In 2008, Spanish PV installations (in MW) exceeded even those of Germany.

---

[620] See analysis in corresponding sections in chapter 3 and in present chapter.

[621] The percentages have been estimated based on the data provided by the following sources: Jäger-Waldau Arnulf, *PV Status Report 2009*, Publications Office of the European Union (Luxembourg: 2009); Jäger-Waldau Arnulf, *PV Status Report 2014,* Publications Office of the European Union (Luxembourg: 2014); Jäger-Waldau Arnulf, *PV Status Report 2016,* Publications Office of the European Union (Luxembourg: 2016).

[622] EPIA, *Global Market Outlook: For Photovoltaics 2014-2018*, 2014.; Jäger-Waldau Arnulf, *PV Status Report 2016,* Publications Office of the European Union (Luxembourg: 2016), p. 11.

[623] Wolfgang Palz, "Keynote Speech: Photovoltaics in Europe and the World", *in* PV in Europe - From PV Technology to Energy Solutions Proceedings of the International Conference held in Rome, Italy, 7-11 October 2002, J. L. Bal, G. Silvestrini, A. Grassi, W. Palz, R. Vigotti, M. Gamberale, P. Helm (eds.), WIP-Munich & ETA-Florence, 2002, p. xxxix.; EPIA, *Global Market Outlook: For Photovoltaics 2014-2018*, 2014, p. 21.

[624] Wolfgang Palz, "Keynote Speech: Photovoltaics in Europe and the World", *in* PV in Europe - From PV Technology to Energy Solutions, Proceedings of the International Conference held in Rome, Italy, 7-11 October 2002, J. L. Bal, G. Silvestrini, A. Grassi, W. Palz, R. Vigotti, M. Gamberale, P. Helm (eds.), WIP-Munich & ETA-Florence, 2002, p. xxxix.; EPIA, *Global Market Outlook: For Photovoltaics 2014-2018*, 2014, p. 21.

[625] Thomas Nordmann, "Subsidies Versus Rate based Incentives; For Technology – Economical – and Market-Development of PV. The European Experience", *in* Proceedings of Third World Conference on Photovoltaic Solar

Within a single year, about 2,6 GW of PV systems were installed in Spain.[626,627] The majority of Spanish PV installations were of large-scale systems (i.e. large, centralized plants of over 10 MW each) and included the installation of CPV.[628,629] From 2009 to 2013, Italy followed Germany in PV installations. Since the early 2010s, the EU's share has steadily continuously declined, as China, Japan and the USA have increased their installed PV capacity.

The EU played a catalytic role in stimulating global PV production and in constructing and fostering a (stable) market for PV. Policy objectives and commitments, both at EU and member state level, have played a crucial role in these developments. As mentioned above, the majority of EU PV installations concerned grid-connected applications. In contrast to the previous period, where PV had a variety of uses and applications, in the second period the primary use or application of PV was electricity generation.

5.1.7 The uses for PV: the unique options for integration offered by small-scale PV

Solar PV, can be installed either in solar farms or on rooftops, depending on the scale of the system.[630] This potential of PV was realised early on, also by (important) actors from the European research networks for PV.[631] Early research supported small-scale PV systems because it was recognized that they could be mounted on rooftops (e.g. for households).[632] This

---

Energy Conversion, Joint Conference of Thirteenth PV Science and Engineering Conference, Thirtieth IEEE PV Specialists Conference, Eighteenth European PV Solar Energy Conference, Osaka, Japan, 11-18 May 2003, Kosuke Kurokawa, Lawrence L. Kazmerski, Bernard McNelis, Masafumi Yamaguchi, Christopher Wronski, Wim C. Sinke (eds.), IEEE: 2003, [CD-ROM, file number: 8OD1102, pdf p. 2].

[626] Jäger-Waldau Arnulf, *PV Status Report 2009,* Publications Office of the European Union (Luxembourg: 2009).

[627] This corresponds to fifteen times more PV than the Spanish produced. (Steven Hegedus and Antonio Luque, "Achievements and Challenges of Solar Electricity from Photovoltaics", *in* Handbook of Photovoltaic Science and Engineering, Antonio Luque and Steven Hegebus (eds.), Wiley & Sons (Second Edition, UK: 2011), p. 1-38).

[628] Steven Hegedus and Antonio Luque, "Achievements and Challenges of Solar Electricity from Photovoltaics", *in* Handbook of Photovoltaic Science and Engineering, Antonio Luque and Steven Hegebus (eds.), Wiley & Sons (Second Edition, UK: 2011), p. 1-38.

[629] Regarding the Spanish CPV installations see chapter 6.

[630] Small-scale PV can be mounted on rooftops, whereas large-scale installations of PV can result in solar farms. G. J. Vachtsevanos, A. P. Meliopoulos, B. K. Paraskevopoulos, "Distributed photovoltaic system impact upon utility load/supply management practices", *in* Fifth EC Photovoltaic Energy Conference, Proceedings of the International Conference held at Kavouri, Athens, Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 383-392.; J. Schmid, "Photovoltaic System Design", *in* Fifth EC Photovoltaic Energy Conference, Proceedings of the International Conference held at Kavouri, Athens, Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 410-416.; S. I. Firstman and G. J. Vachtsevanos, "Distributed Photovoltaic Systems: addressing the utility interface issues", *in* Fifth EC Photovoltaic Energy Conference, Proceedings of the International Conference held at Kavouri, Athens, Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 424-431.

[632] Selectively see: Makios V., "Feasibility study for small solar cell operated units", *in* Photovoltaic Power Conversion, Proceedings of the EC Contractors' Meeting held in Brussels, 16-17 November 1982, Roger van Overstraeten and Wolfgang Palz (eds.), Vol. III, D. Reidel Publishing Company (Dordrecht Holland, Bolton USA, London England: 1983), p. 236-244.

unique option for rooftop installations enabled by PV, and thus their integration into the urban environment, was the politics of the networks of the first period. Moreover, this unique option was further promoted in the second period by several key actors from the networks and the European PV community. For example, the founder of Fraunhofer ISE, Prof. Goetzberger referred to solar energy as "citizen's energy".[633] Goetzberger's understanding of this unique option offered by PV and RES was directly linked to a different understanding of the market. In particular, he referred to a customer-oriented market in which consumers (in a liberalized market) have a choice of where they purchase their electricity. This was contrasted with centrally generated fossil fuels and nuclear energy, where the market was monopolized. Similar comments were made by Herman Scheer, who stated:

> "**Energy consumption is always decentralized**. The supply of conventional energies is, beginning from its source, centralized. The global energy economic system, with its infrastructure is tailored to the utilization of conventional energy sources of energy. […] **If past choices had been issued in favour of renewable energies, a different energy system would exist today**. […] **The necessity and opportunity of renewable energies is to change the energy structures**, from the present split between the areas where energy is produced and the places where energy is consumed – the conventional system bringing both together."[634] (emphasis added)

Scheer spoke about the differences between the two systems and addressed how the infrastructures required for conventional energy sources and RES differ. He also expressed his vision and conviction that RES can change energy structures, as they are inherently local energy sources. In this context, the networks have selected the technological frontrunner (i.e. c-Si). Accordingly, in this context, the Commission included PV in the White Paper for RES and placed them directly on rooftops.

Schmid J., "Photovoltaic System for a Solar House", *in* Photovoltaic Power Conversion, Proceedings of the EC Contractors' Meeting held in Brussels, 16-17 November 1982, Roger van Overstraeten and Wolfgang Palz (eds.), Vol. III, D. Reidel Publishing Company (Dordrecht Holland, Bolton USA, London England: 1983), p. 245-250.

[633] Goetzberger Adolf, "Solar Energy, the Citizen's Energy", *in* Fourteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Barcelona, Spain, 30 June – 4 July 1997, H. A. Ossenbrink, P. Helm and H. Ehmann (eds.), Vol. I, H. S. Stephens & Associates (Oxfordshire, UK: 1997), p. xxxvii-xl.

[634] Scheer Hermann, "Keynote Speech, *in* Sixteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Glasgow, UK, 1-5 May 2000, H. Scheer, B. McNelis, W. Palz, H.A. Ossenbrink and P. Helm (eds.), Vol. I, James and James (London, UK: 2000), p. xxiv.

Until the mid-1990s, demonstration activities were mainly about the installation of stand-alone PV systems with a focus on rural electrification. Grid integration gradually became an issue from the mid-1990s onwards, when electricity utilities started to support the installation of grid-connected PV systems for centrally generated electricity, i.e. large-scale PV system installations of around 1 MW or more. Therefore, system integration issues were not part of the demonstration activities until the mid-1990s, as the majority of PV systems were stand-alone. In the second period, the pilot component was no longer a separate category of the research programmes. This component became an integral part of the research projects, which, however, did not involve the installation of PV systems. Rather, as we have seen, this component was integrated into the projects by delivering pilot production lines, etc. Overall, the PV research community did not consider the system integration dimension in the second period.[635] Although research projects focused on the integration of PV systems into buildings, the 'next step' (system integration) was never considered. An exception were the rare and few research activities that dealt with inverters.

In the second period, the Commission supported and promoted research that focused on solving system integration problems.[636] The research focused on "large-scale integration of distributed energy sources" and sought to identify and solve not only the technical issues (e.g. quality of supply, current power quality, reliability etc.) but also the non-technical issues (e.g. legislative and regulatory).[637] In this context, research included the development of new converters, inverters, energy storage, high temperature superconducting cables etc.

The majority of these projects dealt with all RES. Essentially, integration for the needs of specific RES technologies such as PV remained limited. The actors forming the networks of this research do not share similarities with those of PV, with the exception of the large research centres (e.g. ECN and CEA), which were conducting research for all RES. The majority of the actors forming these networks were electric utilities, distribution and transmission system operators, companies, national RES centres and energy regulatory bodies and to a lesser extent

---

[635] In the first ETP-PV SRA (2007) the issue of integration to the grid was included but it was not until the second SRA (2011) that this dimension received more attention. The 'timing' seems to suggest that the establishment of the ETP SmartGrids played an important role for this dimension to receive more attention. However, despite integration being incorporated in the PV SRA, it was not fully incorporated in the PV research projects (see analysis). This can be explained by the ETP SmartGrids establishment, which was directly focused on resolving such issues.

[636] See for example the action "Cleaner Energy Systems, including RES" under FP5.

[637] See for example DG-Facts and SUSTELNET.

universities.[638] The projects explicitly refer to the deregulation of the European energy market and the opportunities that distributed energy sources offer to make it more competitive.[639]

The vision published by ETP SmartGrids did not include any PV-specific remarks. Smart grid research followed the formation of this ETP and became part of the EU R&D programmes during FP7.[640] However, these actions remained distinct or separate from the research conducted for PV and we do not see a dialogue between the two ETPs to support the potential of synergies between them.

This branch of research activities shows the Commissions' commitment to promote and foster the transition to RES by helping to overcome the technical and non-technical barriers to its integration into the energy system. It also shows that in the second period, the Commission's energy policy goals for RES also became commitments for research policy. At the same time, we also see that the artifacts and the network were not configured or designed together. Rather, we see a fragmentation of research activities, as the coordination of the two areas was not considered in the design phase.

We argue that the two sets of EU policies (i.e. research and energy) moved in the same direction, jointly co-producing the energy market and trying to promote the liberalization of the energy market and system (and its infrastructures). The further liberalization of the energy market was made possible by the material possibilities that arose from the technological choices of the networks, which made their selections through this exact realization. The actors of the networks made their choices based on the realization of how these technologies could reconfigure the architecture of the energy system and further liberalize the energy market. It was this reasoning that the Commission embraced when setting the energy policy targets for rooftop PV. The desire to further liberalize the energy market led to the promotion of the system integration research branch, which brings us back full circle to research. Given the actors of the system integration networks, primarily from the energy sector, we argue that this research led them to accept and materialize the further liberalization of the energy market. However, the design of the artifacts and the network were not a mutual undertaking, nor were the corresponding research efforts.

---

[638] Notable examples include Tractbell, EDF and Iberdrola.

[639] See for example DISPOWER.

[640] See for example the research actions under the FP7 Energy area of "Smart Cities and Communities".

5.2 Conclusions

A handful of countries from the European North and a small number of actors set the research agenda, priorities and funding of EU PV. These countries and their actors had a tradition in semiconductor electronics and expertise and know-how in working with c-Si, which comprises the founding (and dominant) semiconductor for the electronics industry. Therefore, apart from the tradition these countries (and their actors) had in electronics, they also had vested interests in c-Si, both industrially and scientifically. These vested interests were prevalent in-the-making of the PV sector and not only determined the research activities of EU PV, but also the choice of the dominant technology: flat plate c-Si PV.

Towards the end of the first period, the EC published the White Paper for RES. This meant the inclusion of RES on the energy policy map, while giving the PV sector the green light towards becoming industrial. Based on the technological frontrunner of the first period (i.e. c-Si flat plate), the White Paper acknowledged the unique system integration c-Si flat plate PV offered: enabling the move towards a distributed electricity production, distribution, and consumption. In turn, in the second period, energy policy goals redirected research towards solving the presupposed problems of upscaled production, as well as an impending crisis that resulted from this upscaled production: the silicon crisis in PV. With the focus shifting to cover as many or all steps the value chain as possible, the scope of research activities was expanded in the second period. The changed scope of research was accompanied by the need to narrow the gap between research and the market in order to achieve energy policy goals.

This increased 'need' in turn led also to an increased number of spin-offs by these large research centres, which were also present in the EU-funded c-Si networks. Promoting 'upscaled research', during the second period, also led to a re-structuring of the networks. A small number of large research networks comprised the main core of the networks, followed by a smaller number of companies. This also led, even though indirectly, to the marginalization of small research groups and universities in the c-Si research activities. In the c-Si technoscientific research networks of the second period, not only has a small number of actors prevailed, but behind these actors is a small number of individuals, resulting in an anthropocentric hegemony too, and form hegemonic patterns of collaboration. These individuals have directed the EU research agenda for PV and form the knowledge capacity for a major energy source to transition to RES, while determining how the EU innovates.

In response to the silicon crisis in PV, some of the leading actors proposed the c-Si thin film agenda, which gained prominence in c-Si research. The appropriation of thin films for the benefit of the dominant technology had another consequence. It redirected research for a-Si thin films. Not only did it reconfigure the geographical distribution of a-Si research funds, but it allowed c-Si actors to enter a-Si networks and direct research priorities. Essentially, the 'power' of c-Si actors was expanded in thin films.

The geography of hegemonic networks defines the boundary between the countries that form the core and the countries that form the periphery. Moreover, the hegemony of the European North goes beyond who sets the agenda, priorities and research themes and who constructs the EU knowledge capacity(-ies) for c-Si. Concurrently, this divide excludes the role of these countries in the ongoing energy transformation.

The dominance of c-Si as **the** technology on which the PV goals were envisioned to take place, directed the material and social technological reconfiguration of the alternative design option (i.e. CPV). As a 'way-out' of the prevalence of the hegemonic c-Si networks and as a departure from the dominant semiconductor (i.e. c-Si) the actors of the CPV networks differentiated themselves and their technology by switching from c-Si to other semiconductors. This also led to the countries that formed the periphery of c-Si research becoming the core of the development of a technology developed by the European South and for hotter climates.

The changing character of research during the second period led to small research groups being marginalized from networks, which also limited their access to R&D funding. Thus, in addition to the geographical marginalization of Southern European countries from the c-Si technoscientific research networks, there is another marginalization that results directly from the changing character of research and knows no geographical boundaries. With the reorientation of research priorities and activities by EU energy policy towards solving production issues and delivering near market products, the 'scale' of research has shifted. As we move towards production, research requires large machinery, equipment, large areas/spaces and specialized personnel. This 'upscaled' research cannot be done by small research groups or universities, leading to an indirect marginalization of these actors from c-Si research and the corresponding technoscientific research networks. This in turn explains the emergence of the large research centres as the dominant actors of the second period, which form the core of technoscientific research networks.

In this way, albeit indirectly, who is allowed to conduct this 'upscaled' research is restricted and the role of individual actors within R&D programmes (as well as the corresponding networks) is redefined. Furthermore, this 'upscaled' research has actively resconfigured the material surroundings of the laboratory, which resemble a miniature factory. The indirect marginalization of small research groups and universities, and the augmented role of large research centres, has implications that go beyond the question of who participates in EU projects and networks and who has access to R&D funding. These impacts concern innovation 'itself'. By actively directing the scope and priorities of research, the exclusions or marginalization do not solely concern 'who can innovate'. They also about the parts of the value chain where we can anticipate or expect innovations and the kinds of innovations we can expect see. Essentially, these last points are about who generates and forges the EU's knowledge and technical capacities and the constraints on the scope and breadth of research. In the case of PV, this also related to who forms the EU's knowledge basis and capacity and who directs the transition to RES.

The installations goals set by the EC and the simultaneous developments in Germany helped to foster a strong PV market. The PV sector became industrial as global production of PV cell/module grew from less than 200 MW in 1998 to a just over 1 GW at the beginning of the silicon crisis in 2004 to around 8 GW by the end of the silicon crisis in 2008 and finally to over 70 GW in 2013. The EU maintained its strong position in the global market. In 2010, EU accounted for over 80% of the globally installed annual PV capacity. The EU and Germany played a catalytic role in stimulating global PV production and in constructing and fostering a (stable) market for PV. Policy goals and commitments, both at EU and member state level, have played a crucial role in these developments. However, China's dynamic entry into the production of PV cell/module has led to the EU being displaced from its former strong position and eventually the demise of many European PV companies.

During this period, the Commission showed its commitment to promoting the transition for RES, by supporting a branch of research activities for the "large-scale integration of distributed energy sources", which was in line with the corresponding energy policy installation goals. We argue that Es energy and research policies were moving in the same direction during the second period, pursuing further liberalization of the energy market and the energy system. The further liberalization of the energy market was made by possible by the material opportunities offered by the technological choices of the networks, which made their choices through this very realization. The actors of the networks made their selections based on the understanding of how these technologies can reconfigure the architecture of the energy system and further liberalize the energy market. The Commission embraced this thinking when setting the energy policy goals for PV, placing them on the rooftops. The desire for further liberalize of the energy market eventually led to the promotion research activities for the system integration, which brings us back full circle to research. Given the actors in system integration networks, who are primarily from the energy sector, we argue that this research led them to accept and materialize the further liberalization of the energy market.

References

Automated photovoltaic cell and Module industrial Protocol to regain and secure European - Renewable Energy market, ampere-h2020, *CEA-INES*, Available online: https://www.ampere-h2020.eu/partners/cea-ines-ampere-h2020.html, (accessed 2 February 2020).

Ceccaroli Bruno, Ovrelid Eivind, Pizzini Sergio (eds.), *Solar Silicon Processes: Technologies, Challenges and Opportunities*, Taylor & Francis Group (Boca, Raton, London, New York: 2017).

Dharmadasa I. M., "Photovoltaic Solar Energy Conversion", *in* Advances in Thin-Film Solar Cells (1st Edition), Pan Stanford Publishing (Singapore: 2012), p. 1-24.

Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity, Official Journal of the European Communities (30.1.1997).

École polytechnique fédérale de Lausanne, epfl, *Silicon-based heterojunction solar cells*, Available online: https://www.epfl.ch/labs/pvlab/research/heterojunction_solar_cells/, (accessed 5 February 2020).

École polytechnique fédérale de Lausanne - PVLab, epfl.pvlab, *About us*, Available online: https://www.epfl.ch/labs/pvlab/about_us/, (accessed 5 February 2020).

Energy Research Centre of the Netherlands, ECN, *Sustainable energy: for a clean future in which ECN plays a leading role*, Available online: https://www.ecn.nl/energy-research/index.html, (accessed 2 December 2019).

Enkhardt Sandra, 28 March 2018, *SolarWorld files for insolvency-again*, pv-magazine, Available online: https://www.pv-magazine.com/2018/03/28/solarworld-files-for-insolvency-again/, (accessed 3 November 2019).

European Photovoltaic Industry Association, "Global Market Outlook: For Photovoltaics 2014-2018", 2014.

European Commission, *Energy for the Future: Renewable Sources of Energy White Paper for a Community Strategy and Action Plan*, COM (97)599 final, 1997.

European Commission – Directorate General for Energy, *THERMIE-ALTENER: Renewable Energy Report*, Office for Official Publications of the European Communities (Luxembourg: 1998).

European Commission, Europa, *Climate Action – 2050 long-term targets*, Available online: https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2050-long-term-strategy_en, (accessed 10 April 2021).

Firstman S. I. and Vachtsevanos G. J., “Distributed Photovoltaic Systems: addressing the utility interface issues”, *in* Fifth EC Photovoltaic Energy Conference, Proceedings of the International Conference held at Kavouri, Athens, Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 424-431.

Gifford Jonathan, 10 May 2017, *Breaking: SolarWorld files for insolvency*, Available online: https://pv-magazine-usa.com/2017/05/10/breaking-solarworld-files-for-insolvency/, (accessed 3 November 2019).

Goetzberger Adolf, “Solar Energy, the Citizen’s Energy”, *in* Fourteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Barcelona, Spain, 30 June – 4 July 1997, H. A. Ossenbrink, P. Helm and H. Ehmann (eds.), Vol. I, H. S. Stephens & Associates (Oxfordshire, UK: 1997), p. xxxvii-xl.

Greenpeace and EPIA, *Solar Generation: Solar Electricity for Over one billion people and two million jobs by 2020*, September 2006.

Hegedus Steven and Luque Antonio, “Achievements and Challenges of Solar Electricity from Photovoltaics”, *in* Handbook of Photovoltaic Science and Engineering, Antonio Luque and Steven Hegebus (eds.), Wiley & Sons (Second Edition, UK: 2011), p. 1-38.

Interuniversity Microelectronics Centre, 1 February 2017, *Harvesting sunlight from both sides of PV cells may give PV plants a significant energy boost*, imec, Available online: https://www.imec-int.com/en/imec-magazine/imec-magazine-february-2017/harvesting-sunlight-from-both-sides-of-pv-cells-may-give-pv-plants-a-significant-energy-boost, (accessed 7 November 2019).

Jäger-Waldau Arnulf, *Status of PV Research, Solar Cell Production and Market Implementation in Japan, USA and the European Union*, Office for Official Publications of the European Communities (Luxembourg: 2002).

Jäger-Waldau Arnulf, *PV Status Report 2005: Research, Solar Cell Production and Market Implementation of Photovoltaics*, Office for Official Publications of the European Communities (Luxembourg: 2005).

Jäger-Waldau Arnulf, *PV Status Report 2008*, Office for Official Publications Office of the European Communities (Luxembourg: 2008).

Jäger-Waldau Arnulf, *PV Status Report 2009,* Office for Official Publications of the European Union (Luxembourg: 2009).

Jäger-Waldau Arnulf, *PV Status Report 2011,* Office for Official Publications of the European Union (Luxembourg: 2011).

Jäger-Waldau Arnulf, *PV Status Report 2014,* Publications Office of the European Union (Luxembourg: 2014).

Jäger-Waldau Arnulf, *PV Status Report 2016*, Publications Office of the European Union (Luxembourg: 2016).

Jäger-Waldau Arnulf, *PV Status Report 2019*, Publications Office of the European Union (Luxembourg: 2019).

Jegen Maya, "Energy policy in the European Union: The power and limits of discourse", *Les cahiers européens de Sciences Po*, n°2, 2014, p. 1-22.

Kamp Linda M., Smits Ruud E. H. M., Andriesse Cornelis D., "Notions on learning applied to wind turbine development in the Netherlands and Denmark", *Energy Policy*, 2004, p. 1625-1637.

Kleider Jean Paul, Alvarez Jose, Ankudinov Alexander Vitalievitch, Gudovskikh Alexander Sergeevitch, Gushchina Ekaterina Vladimirovna, Labrune Martin, Maslova Olga Alexandrovna, Favre Wilfried, Gueunier-Farret Marie-Estelle, Cabarrocas Pere Roca i, Terukov Eugene Ivanovitch, "Characterization of silicon heterojunctions for solar cells", *Nanoscale Research Letters*, 2011, p. 1-9.

Klitkou Antje and Godoe Helge, "The Norwegian PV manufacturing industry in a Triple Helix perspective", *Energy Policy*, 2013, p. 1586-1594.

Makios V., "Feasibility study for small solar cell operated units", *in* Photovoltaic Power Conversion, Proceedings of the EC Contractors' Meeting held in Brussels, 17-17 November 1982, Roger van Overstraeten and Wolfgang Palz (eds.), Vol. III, D. Reidel Publishing Company (Dordrecht Holland, Bolton USA, London England: 1983), p. 236-244.

Nakopoulou Efi and Arapostathis Stathis, "Reconfiguring Technologies by Funding Transitions: priorities, policies, and the renewable energy sources in the European Community funding schemes", *Journal of Energy History/Revue d'Histoire de l'Énergie* [Online], n°4, published 27 July 2020.

Nexwafe, nexwafe, *About us*, Available online: https://www.nexwafe.com/, (accessed 13 October 2019).

Nordmann Thomas, "Subsidies Versus Rate based Incentives; For Technology – Economical – and Market-Development of PV. The European Experience", *in* Proceedings of Third World Conference on Photovoltaic Solar Energy Conversion, Joint Conference of Thirteenth PV Science and Engineering Conference, Thirtieth IEEE PV Specialists Conference, Eighteenth European PV Solar Energy Conference, Osaka, Japan, 11-18 May 2003, Kosuke Kurokawa, Lawrence L. Kazmerski, Bernard McNelis, Masafumi Yamaguchi, Christopher Wronski and Wim C. Sinke (eds.), IEEE: 2003, [CD-ROM, file number: 8OD1102], (pdf) p. 1-4.

Palz W., “PV Highlights from a European Perspective”, *in* Second World Conference on Photovoltaic Solar Energy Conversion, Fifteenth European PV Solar Energy Conference, Twenty Seventh US IEEE Photovoltaics Specialists Conference, Tenth Asia/Pacific PV Science and Engineering Conference, Proceedings of the International Conference held at Vienna, Austria, 6-10 July 1998, J. Schmid, H. A. Ossenbrink, P. Helm, H. Ehmann and E. D. Dunlop (eds.), Vol. I, WIP Renewable Energies: 1998, [CD-ROM], p. xciii-xcv.

Palz Wolfgang, “Keynote Speech: Photovoltaics in Europe and the World”, *in* PV in Europe - From PV Technology to Energy Solutions Proceedings of the International Conference held in Rome, Italy, 7-11 October 2002, J. L. Bal, G. Silvestrini, A. Grassi, W. Palz, R. Vigotti, M. Gamberale and P. Helm (eds.), WIP-Munich & ETA-Florence, 2002, p. xxxix-xl.

Pamblad Linus, Jacobsson Staffan, Sanden Bjorn, and Hall Maria, “Dynamics of the Swedish PV Innovation System – The impact of a recent market formation programme”, *in* Twenty first European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Dresden Germany, 4-8 September 2006, J. Poortmans, H. Ossenbrink, W. Palz and P. Helm (eds.), WIP Renewable Energies (Germany: 2006), p. 3136-3151.

Papoutsis Christos, [Introductory conference speech], *in* Second World Conference on Photovoltaic Solar Energy Conversion, Fifteenth European PV Solar Energy Conference, Twenty Seventh US IEEE Photovoltaics Specialists Conference, Tenth Asia/Pacific PV Science and Engineering Conference, Proceedings of the International Conference held at Vienna, Austria, 6-10 July 1998, J. Schmid, H. A. Ossenbrink, P. Helm, H. Ehmann and E. D. Dunlop (eds.), Vol. II, WIP Renewable Energies: 1998, [CD-ROM], p. xl-xliii.

Peter Kristian, Kopecek Radovan, Petres Roman, Fath Peter, Wefringhaus Eckard, “Long-term perspective for Photovoltaic R&D activities in Konstanz”, *in* Twenty second European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Milan, Italy, 3-7 September 2007, G. Willeke, H. Ossenbrink and P. Helm (eds.), WIP Renewable Energies: 2007, p. 3519-3520.

Photovoltaic Technology Platform, *A Strategic Research Agenda for Photovoltaic Solar Energy Technology*, Office for Official Publications of the European Communities (Luxembourg: 2007).

Photovoltaic Technology Platform, *A Strategic Research Agenda for Photovoltaic Solar Energy Technology*, 2nd Edition, Office for Official Publications of the European Communities (Luxembourg: 2011).

Poortmans J., Reber S., Gall S., Zahedi C., Alonso J., “European cluster on high- and intermediate temperature thin-film crystalline Si solar cells R&D: Overview of running projects and underlying roadmap”, *in* Nineteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Paris, France, 7-11 June 2004, W. Hoffmann, J. L. Bal, H. Ossenbrink, W. Palz and P. Helm (eds.), WIP Renewable Energies: 2004, p. 397-402.

Reber Stefan, Duerinckx Filip, Alvarez Mario, Garrard Barry, Schulze Friedrich-Wilhelm, “EU project Sweet on Epitaxial Wafer Equivalents: Results and Future Topic of Interest”, *in* Twenty first European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Dresden, Germany, 4-8 September 2006, J. Poortmans, H. Ossenbrink, W. Palz and P. Helm (eds.), WIP Renewable Energies: 2006, p. 570-576.

Scheer Hermann, “Keynote Speech, *in* Sixteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Glasgow, UK, 1-5 May 2000, H. Scheer, B. McNelis, W. Palz, H.A. Ossenbrink and P. Helm (eds.), Vol. I, James and James (London, UK: 2000), p. xxv-xxviii.

Schmid J., “Photovoltaic System for a Solar House”, *in* Photovoltaic Power Conversion, Proceedings of the EC Contractors’ Meeting held in Brussels, 17-17 November 1982, Roger van Overstraeten and Wolfgang Palz (eds.), Vol. III, D. Reidel Publishing Company (Dordrecht Holland, Bolton USA, London England: 1983), p. 245-250.

Schmid J., “Photovoltaic System Design”, *in* Fifth EC Photovoltaic Energy Conference, Proceedings of the International Conference held at Kavouri, Athens, Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 410-416.

Stiftelsen for industriell og teknisk forskning, SINTEF, *About SINTEF*, Available online: https://www.sintef.no/en/sintef-group/this-is-sintef/, (accessed 5 February 2021).

Tonini Alberto, “The EEC Commission and European Energy Policy: A Historical Appraisal”, *in* Rosella Bardazzi, Maria Grazia Pazienza, Alberto Tonini (eds.), *European Energy and Climate Security: Public Policies, Energy Sources, and Eastern Partners*, Springer (New York, London: 2016), p. 13-35.

Tosun Jale, Biesenbender Sophie, Schulze Kai (eds.), *Energy Policy Making in the EU: Building the Agenda*, Springer (London: 2015).

Univesitat Konstanz, uni-konstanz, *Photovoltaics Division*, Available online: https://www.hahn.uni-konstanz.de/en/, (accessed 15 October 2019).

Wolfe Philip R., *The Solar Generation: Childhood and adolescence of terrestrial photovoltaics*, John Wiley & Sons (Hoboken, New Jersey), 2018.

Wolsink Maarten, “Dutch wind power policy: Stagnating implementation of renewables”, *Energy Policy*, 1996, p. 1079-1088.

Vachtsevanos G. J., Meliopoulos A. P., Paraskevopoulos B. K., “Distributed photovoltaic system impact upon utility load/supply management practices”, *in* Fifth EC Photovoltaic Energy Conference, Proceedings of the International Conference held at Kavouri, Athens, Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 383-392.

Verbong G., Selm A. van, Knoppers R., Raven R., “Een kwestie van lange adem. De geschiedenis van duurzame energie in Nederland 1970–2000”, Aeneas Technical Publishers (Boxtel: 2001).

Verbong Geert and Geels Frank, “The ongoing energy transition: Lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960–2004)”, *Energy Policy*, 2007, p. 1025-1037.

Verbong Geert and Geels Frank W., Raven Rob, “Multi-niche analysis of dynamics and policies in Dutch renewable energy innovation journeys (1970-2006): hype-cycles, closed networks and technology-focused learning”, *Technology Analysis & Strategic Management*, 2008, p. 555-573.

Chapter 6. The marginalized alternative of CPV: the Southern option for large-scale power plants

6.1 The first steps of CPV: from marginalization to limited inclusion with the aid of the European North

Concentrator photovoltaics (CPV) comprised **the** alternative design option to the dominant c-Si flat place PV. CPV was considered as a technology best suited to the southern climates and utilizing the same semiconductor for the solar cells (i.e. c-Si) as the dominant technology, CPV struggled to find support both by the industrial and/or private sector actors and by the EC R&D funding programmes, during the first period. The industrial actors had vested interests in c-Si and actively supported the dominant c-Si flat plate design. This support manifested not only by the increasing participation of these actors in the c-Si networks, but also by the lack of supply of (modified) cells for the alternative design option (i.e. CPV). Due to this shortage, the first CPV demonstration project was not completed. Because the supply of CPV cells was inadequate for more than twenty-five years, the measurements, tests and standards that would enable its commercialization were delayed. Amid the EEC enlargements to the European South, CPV research was excluded from FP1, with the EC justifying this exclusion on geographical and climatic. It was not until the 1990s, when an industrial actor from the European North developed interests in CPV, that R&D funding for this technology increased; alas, without surpassing c-Si or thin films.

Section 6.1 covers the analysis of the first period, while section 6.2 focuses on the second period. The analysis of the first period is divided into three parts. From 1975 to 1984, there were neither networks nor continuities in the actors carrying out CPV activities. In FP1 (1985-9) CPV were excluded from the R&D activities. For the rest of the first period, CPV was again included in the EU R&D activities and the first networks were formed. At the beginning of the sections of each period, we address the technical aspects that are important for linking CPV systems to their respective uses and applications, explicitly addressing the system integration that each system enables. In section 6.3 we summarize the main findings of the analysis and draw our conclusions.

6.1.1. Classifying the CPV systems: different scales for different applications and uses

There are different CPV systems that operate under different conditions and result in different scale artefacts and installations, that allow for different uses and applications as well as system integration options.

> "It is usual to **classify the CPV systems according to the concentration ratio of the solar radiation incident onto the cel**l. This ratio indicates the number of times that the solar light is concentrated and it is usually known as 'Suns'."[641] (emphasis added)

Based on the above classification, three CPV systems are distinguished: (a) low concentration PV (LCPV), (b) medium concentration PV (MCPV) and (c) high concentration PV (HCPV). Despite the way CPV systems are classified, we should note that the concentration ratio corresponding to each system has changed over time. Moreover, there does not seem to be a single concentration ratio that could be agreed upon for each system. For LCPV, the ratios vary from 1-40 suns to 1-100 suns, while for HCPV the ratios vary from 300 suns to either 1000 or 2000 suns.[642] The ratios in between (usually) correspond to the MCPV systems. This inconsistency can be attributed to the lack of standards for CPV systems.

The first standardization processes started in 2007 with the publication of IEC 62108:2007, which was the first standard for CPV technology. The aim of this standard was "to guarantee the durability and reliability of the CPV systems."[643] However, important gaps related to performance rating and tracking systems were not covered by this standard.[644] It took almost ten more years to develop the next standard for CPV (i.e. IEC 62108: 2016), which has significantly hindered the industrial deployment of this alternative PV technology. Apart from the classification mentioned above, these systems have other differences:

> "**Medium- and high-concentration systems require accurate tracking to maintain the focus of the light on the solar cells as the sun moves throughout the day**. **This adds extra costs and complexity to the system and** also **increases the maintenance burden** during operation. For systems with

---

[641] P. Perez-Higueras, E. Munoz, G. Almonacid and P.G. Vidal, "High Concentrator PhotoVoltaics efficiencies: Present status and forecast", *Renewable and Sustainable Energy Reviews*, 2011, p. 1810.

[642] In the analysis of each period, we provide insights as to how the historical actors defined each scale.

[643] E. Munoz, P. G. Vidal, G. Nofuentes, L. Hontoria, P. Perez-Higueras, J. Terrados, G. Almonacid, J. Aguilera, "CPV standardization: An overview", *Renewable and Sustainable Energy Reviews*, 2010, p. 519.

[644] E. Munoz, P. G. Vidal, G. Nofuentes, L. Hontoria, P. Perez-Higueras, J. Terrados, G. Almonacid, J. Aguilera, "CPV standardization: An overview", *Renewable and Sustainable Energy Reviews*, 2010, p. 518-523.

> small solar cells, or using low concentration, passive cooling (interchange of heat with the surrounding air) is feasible."[645] (emphasis added)

To maximize the electricity output, both MCPV and HCPV systems typically have tracking systems that allow them to follow the sun throughout the day, increasing the electricity output. However, this leads to more complex systems and increases the cost of these technologies. In addition, these systems are very large, which limits their installation location (i.e. covering large areas, cannot be integrated into the urban environment). In contrast, LCPV systems can be stationary and small-scale.[646] Their cost is lower as they do not require tracking systems and use cheaper semiconductors (i.e. c-Si). This allows them to be integrated into the urban. In other words, a direct competitor for the dominant c-Si flat plate PV technology.

As we analyse below, already in the first period, all three different CPV system designs were part of the actors' research activities. Even though c-Si was the dominant semiconductor for the CPV cells, a variety of other semiconductors were used. In the second period, in response to the silicon crisis in PV, the coupling of cell material and the corresponding CPV system were established. CPV work (best) with direct radiation, which makes them a technology best suited for sunny areas and the Global South. Apart from the system configuration indicating the 'best' geographical and climatic conditions for CPV, we revive the voice of our historical actors to understand how they perceived this alternative design option.

6.1.2 CPV research priorities: the directionality of industrial policy

During the first period, research activities for CPV focused on the following: (i) designing and developing prototype systems to measure, test and evaluate the prospects of the technology, (ii) conducting studies, primarily theoretical and design models to predict the optimal cell efficiency, (iii) solving key technological problems. An overarching goal that pertains the majority of the projects was the need to increase cell efficiency while reducing the respective cost(s). Throughout this period, despite building prototypes, the focus was on the cell. The cell comprised the focal point of research, especially for the universities and research centres that carried out studies and tests, designed models and made measurements. The emphasis was on

---

[645] G. Sala and A. Luque, "Past Experiences and New Challenges of PV Concentrators", *in* Concentrator Photovoltaics, Antonio L. Luque and Viacheslav M. Andreev (eds.), Springer (Verlag, Berlin, Heidelberg: 2007), p. 1.

[646] This corresponds to contemporary LCPV systems, as we will see in the next section this was not the case for the original CPV systems developed in the first period.

the cell efficiency-cost relationship, which was an industrial rationale. This rationale were incorporated in the research activities of the universities and research centres and comprised the point of directionality of the industrial policy on research policy.

The scale of the CPV system(s) and the semiconductors used for the cells had not yet been determined. Rather, a variety of cell semiconductors – and combinations – were being researched. C-Si (monocrystalline) remained the dominant cell material, but other options were also being explored (e.g. GaAs, CdTe, CdS). Accordingly, the concentration ratios ranged from 1 sun to 1000 suns (low to very high concentration). The respective uses and applications of the CPV systems had also not yet been determined. The actors that made direct references to the applications of the CPV systems remained limited and came primarily from the private sector. Towards the end of the first period, we see two universities also making such connections.[647]

It is important to note that when CPV were first introduced, they were "originally conceived of as a technology for large power plants".[648] In the early days of CPV development, the applications of this alternative design were in direct contrast to the applications of the dominant technology. For rooftop and building-integrated applications, CPV were "found generally unsuitable", in contrast to the dominant technology.[649]As we have argued, the actors of the c-Si networks conducted research and actively promoted this technology through an understanding of how this technology because it could reconfigure the architecture of the energy system. To this end, CPV was opposite of the main technology actors' logic as it would lead to the installation of large-scale power plants. Towards the end of the first period, a limited number of CPV actors referred to the potential application of CPV systems to roofs and building facades, and more generally to their potential applications in households, emphasizing the need to deploy small-scale CPV systems.

The focal point of research, during this period, was the solar cell. Evident by the lack of complete systems studies, or research covering more system components. While the universities and research centres were concerned with the industrial process(es), the two 'spaces' remained separate. Priority was given to strengthening the scientific and technological base of the European industry, which was the core aim of the R&D programmes. Towards this

---

[647] We are referring to the Polytechnic University of Madrid and the University of Reading. This point is further analysed in the section covering the FP2-4.

[648] Swanson Richard M., "Photovoltaic Concentrators", *in* Handbook of Photovoltaic Science and Engineering, Antonio Luque and Steven Hegebus (eds.), John Wiley & Sons (England: 2003), p. 450.

[649] Swanson Richard M., "Photovoltaic Concentrators", *in* Handbook of Photovoltaic Science and Engineering, Antonio Luque and Steven Hegebus (eds.), John Wiley & Sons (England: 2003), p. 451.

end, specific uses and applications were not placed centre stage in the projects. Rather, they remained as a 'reference' in a limited number of projects (four projects in total).

6.1.3 The first two energy R&D programmes: lack of adequate cell supply

Throughout the first period and during the first two energy R&D programmes, c-Si was the R&D funding frontrunner.[650] Thin films and CPV retained a share of R&D funding, which enabled the continuation of related research activities. As Palz noted in relation to the CPV activities of the second energy programme, when presenting the EC's R&D activities on PV during the fourth EC Photovoltaic Solar Energy Conference: "The effort on concentration systems was never very big and has been decreasing again with respect to the first programme."[651]

During the first two energy R&D programmes (1975-1984), a total of fifteen (15) CPV projects were funded.[652,653] The actors conducting this research were primarily companies (47%). The remaining actors conducting CPV research were universities (33%), research centres (13%) and an electric utility (7%). CPV research activities were coordinated by actors from Germany, Belgium, the UK, France and Italy.

From the first to the second energy R&D programme, there is no continuity in the actors implementing the CPV projects. This suggests the lack of well-established interests in CPV. Rather, different actors were researching CPV, using different CPV designs with different semiconductors for the cell(s). The dominant semiconductor used for the CPV cells was c-Si, but other semiconductors were also tested (e.g. (Si/)Ga(Al)As and CdTe). The scale of CPV was always large when compared to the c-Si flat-plate PV. However, there are a variety of CPV system, ranging from then small scale (i.e. 1-20), to the medium scale (i.e. 20-50 suns) to the (very) large concentration scale (i.e. 800-1000 suns).[654] C-Si cells have been used for small and medium CPV systems, while Ga(Al)As cells have been used for large CPV systems.

---

[650] See corresponding R&D funding distribution Figures in Chapter 4.

[651] W. Palz, "Overview of the European Community's Activities in Photovoltaics", *in* Fourth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Stresa, Italy, 10-14 May 1982, W. H. Bloss and G. Grassi (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London, England: 1982), p. 7.

[652] Nine projects under the first energy R&D programme and six projects under the second energy R&D programme.

[653] We do not include the projects that focused on hybrid systems, comprising of concentrating PV and solar thermal collectors, since these projects aimed at developing systems for the production of both thermal and electric power.

[654] During the period under examination, a well-defined or 'set' delineation between the CPV systems did not exist. It was not until the 2010s that the CPV systems were classified concretely, along with the establishment of

The majority of CPV projects focused on c-Si concentrator solar cells. The French, Belgian and UK actors focused exclusively on c-Si for CPV. In contrast, the Italian and German actors undertook research for both c-Si and GaAs (and Si/Ga(Al)As) cells, while a single German actor investigated the potential of CdTe cells for CPV. The actors embarking on c-Si research for CPV reported various problems that led to the termination of their CPV activities. Towards this end, the conclusions drawn by private sector actors were important. The teams from the Katholieke Universiteit Leuven (KU Leuven) and the Laboratoire de Marcoussis (LEP) conducted joint research on the potential use of c-Si cells for CPV. From Italy and the UK, only private sector actors have explored the potential of c-Si for CPV.[655] Ferranti Electronics from the UK and Montedison from Italy both tried to use c-Si cells for CPV. Finally, from Germany, the Fraunhofer ISE and Schlaich & Pa. used c-Si for CPV. The conclusions reached by the different actors were different. There were positive and negative results for the future development of CPV, but also inconclusive reports given the lack of cells supply.

The Franco-Belgian collaborative duo (i.e. LEP and KU Leuven) reported problems with the resistance series of the cell(s).[656] In particular, when presenting their findings at the first EC Photovoltaic Solar Energy Conference, they reported:

> "The efficiency of solar cells working under concentrated sunlight is to a large extent limited by the series resistance of the cell. […] Even for medium concentrations it can be seen that the influence of the resistance is very important."[657]

LEP, with the help of the KU Leuven team, tried to configure the properties of the optimized c-Si cells for CPV. However, due to the aforementioned problems with the cells and despite

---

CPV standards. Throughout the analysis we present each system's envisioned uses and applications – where applicable.

[655] Ferranti Electronics was the sole actor from the UK that conducted a project for CPV. In contrast, the Italian actors conducted more projects on CPV but only the Montedison-led project concerned c-Si cells. Rather, the Italians expressed more interest on Ga(Al)As cells for CPV.

[656] For an extensive analysis of the technical problems reported by LEP, see: E. Fabre, L. De Smet, R. Mertens, "High Intensity Silicon Solar Cells", *in* Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Luxembourg, September 27-30, 1977, D. Reidel Publishing Company, (Dordrecht Holland, Boston USA: 1978), p. 249-258; J. Belluque and J. Michel, "Optimisation d'un ensemble concentrateur cellules solaires au silicium", CECA-CEE-CEEA, (Brussels, Luxembourg: 1982).

[657] E. Fabre, L. De Smet, R. Mertens, "High Intensity Silicon Solar Cells", *in* Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Luxembourg, September 27-30, 1977, D. Reidel Publishing Company, (Dordrecht Holland, Boston USA: 1978), p. 250.

the good efficiencies reported when using c-Si cells, which exceeded the teams' initial hypotheses, the actors of LEP concluded that:

> "Toutefois les multiples essais faits sur le concentrateur dans ses différentes variantes ont été très décevants du fait des limitations technologiques. Il serait déraisonnable d'envisager le développement industriel d'un tel système. [However, the multiple tests carried out on the concentrator in its different variants were very disappointing because of the technological limitations. It would be unreasonable to contemplate the industrial development of such a system.]"[658]

With the main motive of determining the industrial development of these systems, the team of LEP decided to terminate the CPV activities. The efficiency was not 'enough', despite the problems and limitations faced in the CPV study, did not suffice. The Fraunhofer ISE team came to the following conclusions:

> "It is clear that this type of cell is not ideal for use with a concentrating device, but more appropriate cells were not available to us in sufficient quantities when this series of measurements was begun."[659]

The lack of suitable cells for carrying out measurements was also reported by other actors as a critical problem. For the Fraunhofer team, the lack of adequate cells – on time – to carry out the measurements was as an obstacle to completing their study. The other private sector actors reported more optimistic results for the future use of c-Si cells for CPV. Ferranti did not use modified c-Si concentrator cells and modules, but its standard modules (MST-300). As expected, the modules suffered electrical failures and resulted in poor measurements. Ferranti's team suggested that the modifications needed to overcome these problems were not severe, but they did not announce whether CPV activities would continue. Schlaich & Pa. and Montedison used modified c-Si cells. In the case of Montedison, the reported cell efficiencies were higher

---

[658] J. Belluque and J. Michel, "Optimisation d'un ensemble concentrateur cellules solaires au silicium", CECA-CEE-CEEA, (Brussels, Luxembourg: 1982), p. 11.

[659] H. R. Wilson and V. Wittwer, "Conversion of Solar Energy Using Fluorescent Collectors: Installation of a Test Collector to Deliver Several Watts Power", *in* Photovoltaic Power Generation, Proceedings of the EC Contractors' Meeting held in Brussels, 16-17 November 1982, R. Van Overstraeten and W. Palz (eds.), Vol III, D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London, England: 1983), p. 269.

than originally expected. Equally positive was Schlaich & Pa.'s report, which noted the potential applicability of small CPV for decentralized power supply. However, as the team noted, the overall cost of small CPV was higher than the cost of 'traditional' c-Si flat-plate PV. Limited efforts to use different semiconductors for the CPV cells have been carried out by Italian and German actors. We briefly review the main points regarding the use of (Si/)Ga(Al)As cells for large-scale CPV systems.[660] The teams from the University of Stuttgart and ENEL, both reported problems with cell supply.[661] The HCPV systems were intended for warmer climates (i.e. Southern Europe and the so-called 'developing' countries). Despite the projects' original aim to work with tandem or multijunction cells of Si and GaAlAs, which were hypothesized to be the optimal semiconductor cell for HCPV systems, they were unable to achieve this. Instead, they investigated the potential use of GaAs cells for HCPV, which were also used to hypothesize the potential efficiencies of the optimal cell configuration. Moreover, indoor measurements were limited by the solar simulators, which could not 'count' the required solar spectrum. Despite these two obstacles, the teams concluded that the Si-GaAlAs cell could have higher efficiencies for HCPV.

In sum, during the first two energy R&D programmes, different actors conducted research on CPV. Each actor conducted research to apply their existing technology or expertise to this alternative design option. For example, the Battelle Institute, which specializes in CdTe investigated the potential applicability of these semiconductors for CPV, while ENEL used the cells from CISE for HCPV systems. Accordingly, the majority of actors specialized in c-Si (e.g. LEP, KU Leuven, Fraunhofer etc.) experimented with the potential applicability of the dominant semiconductor for this alternative design option. In both cases, the lack of adequate cell supply was mentioned as a limiting factor for the completion of measurements and/or studies. The lack of continuity among the actors conducting CPV research, from the first to the second energy R&D programme suggests the absence of a well-established interests and/or commitment to the alternative design option. In addition, the declining enthusiasm of the private sector actors, as well as conclusions regarding the inadequate industrial development of CPV, seem to have contributed to the exclusion of CPV from the R&D activities of FP1.

---

[660] The efforts by the Battelle Institut team were not conclusive regarding the future and potential deployment of CdTe cells for CPV. Hence, we only focus on the efforts for the utilization of (Si/)Ga(Al)As cells.

[661] The project coordinated by ENEL utilized GaAs cells by CESI for a small size and very high concentration module (1000 suns). Regarding CESI's know-how and expertise, as well as the relationship between ENEL and CESI see the analysis of the second period's Italian actors for CPV.

6.1.4 PV as a technological option for all?: the exclusion of (Southern European) CPV from R&D funding

During FP1, research priorities and activities were reoriented to respond to Japanese competition. In this context, R&D funds were redirected to thin films, especially a-Si. During this shift, CPV was excluded from R&D funding. This alternative design option, which was an alternative technological option best suited to southern climates, was excluded based on geographical reasons. Spain was one of the pioneers in CPV research, both nationally and internationally. CPV R&D started in Spain in the 1970s by a small group at the Polytechnic University of Madrid.[662] Thus, the exclusion of CPV essentially meant a Southern European exclusion from PV R&D funding and research activities. Moreover, the timing of the exclusion has a different significance for understanding the European research politics. In the midst of the Southern EEC enlargements, the Commission decided to exclude the Southern CPV technology and its actors from the R&D programmes and funding. To attain a better insight into the underlying reasons for this exclusion, we examine three complementary points. First, the failure of the first CPV demonstration project. Second, the justification of the exclusion by the Commission's Director General for Research, Science and Education (DG XII), G. Schuster, during his keynote speech at the Photovoltaic Solar Energy Conference in 1980. Finally, we analyse the vested interests of the actors that formed the basis for c-Si as another stumbling block for the further development of CPV, at a time when the silicon feedstock shortage was perceived as **the** bottleneck for the future of PV.

6.1.4.1 Failure to complete: the vested interests of c-Si industrial actors stand in the way of completing the first CPV demonstration project

CPV were directly and always linked to southern climates. From the pilot projects realised between 1970 and 1989, it appears that no projects for CPV or flat-plate PV with other semiconductors were installed. An explanation for the (exclusion of a) different design option could be provided by a demonstration project funded under the first EC demonstration

---

[662] For an in-depth analysis of the UPM-IES activities and actors involved, as well as their place regarding CPV research nationally and internationally, see the forthcoming analysis of the CPV Spanish framework and network.

programme.[663] In particular, a single contract was signed for CPV, but the project was never completed.[664]

> "Initial design of all generator components and sub-systems completed. Other than the solar cells, all components are ready for the construction of 4 kWp prototype for design qualification. **But only 1kWp of solar cells are available and Ansaldo, the suppliers, do now wish to manufacture any more**. Because of the difficulties of solar cell procurement and serious technological problems with the concentrating system, it is unlikely that the projects as it stands can be brought to a successful conclusion. In retrospect, a flat-plate array would have been a better choice. Such an array providing power for an agricultural cold store, would be a good demonstration, having the necessary elements of innovation, good publicity impact and good market potential in the near future."[665] (emphasis added)

Despite the technological problems that are a risk with all novel and/or niche technologies, the lack of adequate cell supply has prevented the project from being completed. Moreover, we have argued elsewhere that the EC R&D funding programmes supported 'high-risk' research, implying that the risk was too high for the companies to undertake such research alone.[666] Therefore, the EC R&D programmes were built on this rationale as an incremental part of the research they supported. The failure of the project was rather due to the lack of cells needed to complete the system. In particular, completion failed due to the unwillingness of the solar cell manufacturer (Ansaldo) to continue manufacturing the cells needed to complete the demonstration project. Thus, the unwillingness of the cell manufacturers to produce CPV cells seems to have been the catalyst as to why CPV development lacked behind in Europe. We have no record of European cell manufacturers producing such cells. This in turn would require significant investment and long-term commitment from industrial actors. As Sala and Luque

---

[663] The first EC demonstration programme launched in 1979 and funded a total of four PV projects. However, as we will see only three projects were completed. The fourth project, concerning the installation of a CPV, did not materialize.

[664] The project coordinator was Officine Galileo, an Italian producer of optics and optoelectronics instruments; contract number 17/79/IT.

[665] Commission of the European Communities, *Assessment Report on the Community Demonstration Projects in the fields of Energy Saving and Alternative Energy Sources*, COM (82) 324 final/3, Brussels, 17 June 1982, p. 66.

[666] Efi Nakopoulou and Stathis Arapostathis, "Reconfiguring technologies by funding transitions: priorities, policies, and the renewable energy sources in the European Community funding schemes", Journal of Energy History / Revue d' Histoire de l' Énergie [Online], n°4, published 27 July 2020.

wrote in 2007, the lack of supply of solar cells has been the main limiting factor for the CPV commercialization and deployment for about 25 years.[667]

Given the aim of the EC R&D programmes – to strengthen the scientific and technological basis of the European industry – the support of industrial actors in a technology could determine its inclusion in the programmes. Therefore, the unwillingness of industrial actors to manufacture and supply cells for CPV was one of the reasons that led to their exclusion from FP1. This is one of the ways we see that the dominant actors from the semiconductor electronics industry determined which materials and technologies will dominate the PV market, while at the same time this has also led in the marginalization of research communities and potential new entrants into the PV field and market. These actors had vested interests in the semiconductor electronics industry and were interested in a single technology. In this way research conducted for the c-Si flat-plate could also be used for semiconductor electronics and the results could be incorporated into production. The cells used for CPV, as we have already analysed, had to be adapted in order to be manufactured. Thus, they did not fullfill the criterion mentioned above.

Furthermore, since the standards were based on c-Si – the technology that the semiconductor electronics actors had experience with due to their background and tradition in the field – they had a strong say in determining who could enter the PV field and with which technologies. This gave the 'original', semiconductor electronics actors, an advantage in setting the 'rules' and the future research agenda.

6.1.4.2 Geography as an exclusion criterion: EC excluded the Southern European technological option

In the EC call for proposals for the pilot programme that preceded FP1, we see, in addition to the clear prioritization of c-Si flat-plate PV, the following:

> "**Flat-plate silicon panels should be employed in general. For the sake of comparison a small fraction of the overall capacity may include**: alternative cells, namely CdS cells; **concentrator arrays (in the south of Europe)**; flat mirror boosters."[668] (emphasis added)

---

[667] We examine this point extensively in the sections that correspond to the analysis of the second period.

[668] Call for tenders (C50), 28 February 1980, Official Journal of the European Communities, p. 8.

Apart from the fact that the call included all other technologies "for the sake of comparison", we see that CPV were placed directly in Southern Europe. Since the geographical and climatological distribution of CPV in Southern Europe is clearly defined, CPV were excluded from FP1. As the Commission's Director General for Research, Science and Education (DG XII), G. Schuster, during his keynote speech at the 1980 EC Photovoltaic Solar Energy Conference, stated:

> "Light concentration, which is less promising in the European climate, was restricted to some proof of concept studies."[669] (emphasis added)

In a very public and influential setting, Schuster used geography as the basis for justifying the EC's rationale for the exclusion of CPV. When Schuster speaks of concentration, he means CPV. The 'European climate' for which CPV was less promising (and thus its R&D would be 'restricted'), was the Northern European climate. PV was prioritized in R&D funding because it was understood to be as a technology for the Northern-Western European climate.[670] Therefore, CPV was excluded from the forthcoming (FP1) R&D activities as a Southern European technology because it did not meet the main criterion that this technology was envisioned to fulfil. Amid the Southern EEC enlargements (Greece in 1981, Portugal and Spain in 1986), the research agenda for PV was reconfigured in a way that marginalized a technological option best suited to these climates.[671] As we mentioned in an earlier section, the Spanish team of UPM-IES carried out research on CPV and comprised an important European knowledge centre for this technology. As an extension, the exclusion of CPV – as no CPV projects were funded under FP1 – also meant the marginalization of the Southern European research communities from R&D funding.

This action, however, received criticism. About three years later, during the Fifth E.C. Photovoltaic Solar Energy Conference, held in Athens, we see the following summary of the words of a key figure in the European PV Community, with extensive expertise in c-Si cells, and with a key position in directing the EC research agenda for PV:

---

[669] G. Schuster, "The Future of Photovoltaics in Europe", *in* Third EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes France, 27-31 October 1980, W. Palz (eds.), D. Reidel Publishing Company, (Dordrecht Holland, Boston USA, London England: 1981), p. 8.

[670] Regarding this point see Chapters 2 and 3.

[671] We remind the reader that FP1 run from 1985 to 1989.

> "Prof. van Overstraeten pointed out that the price of modules had not gone down as quickly as had been predicted. He suspected that **the cut in R&D work on concentration might prove to have been a mistake**. In his opinion, R&D programme planners should continue to support the three approaches of concentration, crystalline silicon flat-plate and thin-film in the quest for low cost."[672] (emphasis added)

Professor Dr. Roger van Overstraeten was a very influential actor in Europe and the EC. Overstraeten was head of the Advisory Committee of the EC's PV R&D programme, so we understand the above as (potentially) reflective critique. Apart from the choice of words like 'suspected' and 'might prove to have been a mistake', which downplay the seriousness of the exclusion imposed by the research politics followed, we turn to the justifications provided. The criterion used by Overstraeten to justify why the CPV exclusion might have been a mistake was a purely economic one. Overstraeten argued that all three (technological) options should be supported because they could help to reduce the costs – of the dominant technology.

6.1.4.3 One person's trash is another's treasure: Si feedstock shortage

At the time Schuster made his statement about 'restricting' the further CPV research supported by the EC R&D programmes, there was a silicon feedstock shortage underway.[673] This silicon feedstock shortage was recognized by the EC as a bottleneck for the future development of PV and did not lead to research into options that could replace or move away from c-Si production. Moreover, the shortage was not sufficient in persuading the actors to shift to CPV, which required much smaller amounts of raw materials for the cells.

The silicon feedstock shortage, reported by various key actors during the late 1970s and early 1980s, was recognized as a bottleneck for the further development of PV. The shortage was caused by the rapid development of the personal computer, which flourished during this period and required large quantities of silicon feedstock to meet the expansive needs of the electronics industry. At this time, the PV industry was making its first infant steps into terrestrial applications. The actors undertaking c-Si research were actors from the electronics industry

---

[672] F. C. Treble, "The future of Photovoltaics: A Report on the Panel Discussions", *in* Fifth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Kavouri (Athens), Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 27.

[673] Regarding the analysis of the Si feedstock shortages of the period under examination see chapter 7.

who supplied the PV actors with their ‘reject’ or ‘waste’ silicon feedstock to meet the production needs of the PV industry. Essentially, these actors found a way ‘into’ the newly emerging field of PV, which enabled these actors to enter the energy market through PV. Moreover, they found a new and profitable market for their ‘reject’ feedstock. These actors were unwilling to diversify their production lines to produce the modified c-Si cells needed for CPV. Diversifying production would mean additional costs and capital investment for a technology that can only be used for a single purpose. In contrast, flat-place c-Si cells allowed them to (i) convert their ‘reject’ feedstock into a profitable commodity, (ii) transfer know-how from one field to the other, and (iii) keep the same production machinery, equipment etc. to produce a product that could be used in two discrete fields/sectors. The above comprised – at least part of the – reason why CPV was not considered as an option when the silicon feedstock shortages occurred. Although less raw material is needed for the cell(s), the silicon feedstock shortage was essentially solved by the same actors who had vested interests in c-Si flat-plate.

6.1.5 Geographical distribution of CPV funding: a collaboration between the European South and the European North

Although CPV was excluded from R&D funding during FP1, it was included in the research programmes for the rest of the first period and received only 7,46% of the research funding for PV.[674] We should note that the funding CPV increased from FP3 when BP Solar joined the networks. CPV received 7,6% under FP2, 15,33% under FP3 and 4,92% under FP4.[675] It was only when an industrial actor from Northern Europe expressed interest in CPV that funding for this technological option increased. Despite the low funding shares, CPV regained a place in the EU R&D funding programmes that could support the research activities of the relevant actors while contributing to the development of this alternative technological option.

As shown in Figure 6.1 (below), a handful of countries coordinated the eleven (11) CPV projects from FP2 to FP4. CPV R&D funding was distributed among actors from Spain (41,7%), Belgium (34,98%) and the UK (23,23%). As we analyse in detail below, Spanish and British actors collaborated in the development of CPV. Actors from both countries continuously coordinated the CPV projects throughout the first period, with the sole exception of FP3. In FP3, two CPV projects were coordinated by EUREC, while the third project was

---

[674] The share corresponds to CPV’s funding from FP2 to FP4.

[675] Despite the declining share in FP4, the actual amount dedicated to CPV was similar to FP3 funding (i.e. approximately 3,7 mil EUR).

coordinated by a UK actor (BP Solar). However, we see that important Spanish and British actors are part of the EUREC-led project networks. This helps us to explain the Belgian participation (EUREC), which, as we have analysed, was an association of large European research centres and universities.

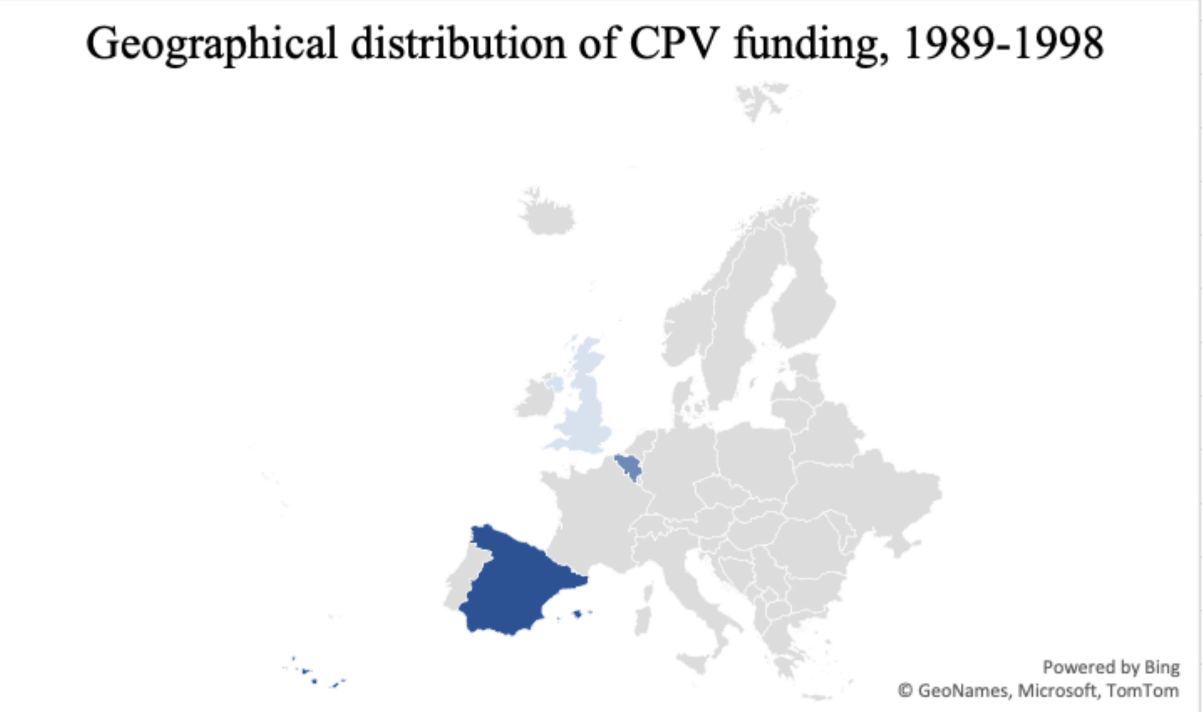


Figure 6.1 Geographical distribution of CPV funding, 1989-1998.

Therefore, CPV R&D funding was concentrated in two countries. Spain and the UK formed the core of CPV research. Apart from this core, the networks extended geographically from the European North to the European South and included seven other countries: Belgium, Germany, France, Italy, Greece, Ukraine and Russia. These countries formed the periphery of the CPV technoscientific research networks. Actors from these countries 'entered' the networks because they collaborated with actors from Spain and the UK. In addition, a Southern European country that had been part of the c-Si periphery formed the CPV core.

6.1.6 The UK and Spanish national research landscape

Spanish R&D activities on RES, including PV, have been organized through the Plan de Energías Renovables (PER) and the Plan de Fomento de las Energías Renovables en España

(PFER).[676] During the period studied, there were two PV companies in Spain, Isofotón and BP Solar. Isofotón was founded as a spin-off company of the Polytechnic University of Madrid (UPM) - Institute of Solar Energy (IES) to commercialize the bifacial solar cell invented by Professor Antonio Luque. Luque, whom we analyse in a forthcoming section, established IES at the UPM and was the founder of Isofotón. Luque was a pivotal figure in the development of CPV, both nationally and internationally. Shortly after Isofotón was founded, with the aim of commercializing Luque's invention (i.e. the bifacial cell), the company expanded its production to monofacial cells, using ARCO's technology.

UPM-IES, Isofotón and BP Solar began to collaborate on CPV development in the 1980s. BP Solar built a factory in Madrid in 1985 to manufacture c-Si modules. BP's move to build one of their factories in Madrid further strengthened the UK-Spanish cooperation while ensuring a closer and faster knowledge transfer between the relevant actors.[677] As a result, the Spanish-based companies manufactured cells and modules from imported Si wafers.[678]

The Spanish national research activities focused on (i) reducing PV costs, (ii) increasing PV (plants) installations to support rural electrification. The latter received a lot of attention and attracted the interest of the electric utilities (e.g. Hidrola and Sevillana). The electric utilities focused on large-scale PV systems, mostly with a capacity of 100kW (each plant), as part of electrifying rural areas.[679] In addition to the companies, there were three major actors from the research community, each specializing in different PV technologies. On the CPV front, the team from UPM-IES, led by Luque, undertook and led the research for this technology.[680] The UPM-IES was the first PV-specific institute in Spain. Similarly, Isofotón was the first Spanish PV company. The person behind both initiatives was Luque.[681]

---

[676] For more information on the Plan de Energías Renovables, covering the first period see: L. Crespo, "Spanish National Photovoltaic Program", *in* Seventh EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Sevilla, Spain, 27-31 October 1986, A. Goetzberger, W. Palz, G. Willeke 9eds.), Kluwer Academic Publishers, (Dordrecht, Boston, Lancaster, Tokyo: 1987), p. 1177-1184.; Fernando Sanchez, "Spanish National Photovoltaic Program", *in* Ninth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Freiburg, Fed. Rep. of Germany, 25-29 September 1989, W. Palz, G. T. Wrixon, P. Helm (eds.), Kluwer Academic Publishers, (Dordrecht, Boston, London: 1989), p. 1195-1196.

[677] Apart from Spain, BP also had factories in Australia and in the US.

[678] L. Crespo, "Spanish National Photovoltaic Program", *in* Seventh EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Sevilla, Spain, 27-31 October 1986, A. Goetzberger, W. Palz, G. Willeke (eds.), Kluwer Academic Publishers, (Dordrecht, Boston, Lancaster, Tokyo: 1987), p. 1177-1184.

[679] The installations concerned flat-plate c-Si PV, in large numbers.

[680] On the thin films front, the Institute of Renewable Energies was conducted research primarily on a-Si, while collaborating with Spanish universities and institutions. On the components quality control, CIEMAT oversaw and conducted the corresponding research.

[681] Antonio Luque, "Photovoltaics and its Research and Development Structure in Spain: the situation in 1988", *Solar Cells*, 1989, p. 107-123.

The UK did not have a specific R&D plan for RES. Rather, the R&D activities were fragmented and primarily carried out by the private sector with (limited) financial support from the government. In chapters 2 and 4, we showed how funding for RES gradually declined in the 1980s and 1990s crude oil prices fell. When we discussed the situation in the UK with a critical stakeholder, they commented:

> "UK energy research had fallen to a particularly disastrously low level. Every IEA member country had a decline in energy research throughout the 1980s and the 1990s. And in the UK, it was as if everything had shifted towards the zero end of the axis, and it had fallen to something like 30 million pounds a year (annually), which is nothing for a country like the UK."[682]

The above confirms both the general situation of R&D funding situation in the energy sector and the prevailing situation in the UK until the 1990s, and at the same time explains the absence of contributions to UK RES R&D at the European Photovoltaic Solar Energy Conferences. For PV the situation was much worse. A limited number of companies and research teams tried to continue their research activities in an unfavourable environment. Therefore, the financial support of companies was crucial to sustain the research groups and PV research activities.

This situation gradually changed in the 2000s, largely due to the climate change agenda and the persistence of certain individuals such as Prof. Sir David King, who advocated for increasing funding for energy research and the establishment of an Energy Research Centre.[683] These efforts led to the restructuring of the UK energy research system in the 2000s. However, it is worth noting that PV was not the focus of the UK R&I energy system at the time.[684] Unlike the Spanish case, where the scientific community set the research agenda and established a company to commercialize the research outcome, the UK followed a different route. It was the companies that drove the early development of PV in the UK and helped sustain research activities in PV during the first period.

*6.1.7 A Spanish, university-driven, network: UPM as **the** core of the CPV network*

---

[682] Interview with former UK (high-level) research policy maker, December 12th, 2019, London, UK.
[683] Interview with former UK (high-level) research policy maker, December 12th, 2019, London, UK.
[684] Interview with former UK (high-level) research policy maker, December 12th, 2019, London, UK.

Spanish actors accumulated 41,68% of R&D funds, while the corresponding share for the UK actors was 23,42%. The EUREC-led projects under FP3 accounted for the remaining share.[685] BP Solar, which entered the networks for the first time under FP3, attained 17,86% under FP4. The corresponding share for Isofotón, which entered the networks for the first time under FP4, was 30,2%. The University of Reading received 11,64% of CPV funding in FP4, while the University of Southampton received 5,56% of the total CPV R&D funding in FP2. Finally, UPM-IES accumulated 94,43% of CPV funding in FP2 and 40,3% in FP4.

Apart from the quantitative data indicating UPM's leading role in CPV R&D funding, UPM-IES, as illustrated in Figure 6.2 (below), is **the** core actor of the CPV technoscientific networks and research activities. It is around or through UPM-IES that all other actors got connected or participated and collaborated in the networks supported under the EU R&D programmes.

As we have seen in the analysis of the Spanish research landscape, UPM-IES has been the main actor in CPV research. Professor Antonio Luque Lopez founded the Institute of Solar Energy I (ETSI Sistemas de Telecomunicación) at UPM in 1979. Luque obtained his PhD on Telecommunications Engineering and is a Professor of Electronic Technology. He is the inventor of the bifacial cell (1976) and the founder of Isofotón.[686] Professor Luque, with a background in electronics and telecommunications, has been extensively interested in CPV and has devoted a large part of his work to its development.

As shown in Figure 6.2, Luque and his team from UPM formed the core of the CPV technoscientific research networks funded by the EU R&D programmes. Working alongside the UPM team were their colleagues at Isofotón and BP Solar. UPM was a unique case, as we have not seen any other university that has continuously played a central role in EU-funded technoscientific research networks. This is due to the unique links UPM has established – through Luque –with the private sector actors (Isofotón and BP Solar), as well as the crucial role that UPM has played at both the domestic and European level for CPV research.

BP Solar entered the PV business in 1981 by acquiring 50% of Lucas. Lucas, which we saw in the analysis of the c-Si case, entered the solar business in 1975 and was one of the first European private sector actors actively involved in the development of c-Si. The company founded within Lucas by Philip Wolfe, BP Solar, was the leading PV company at the end of

---

[685] Through the network analysis we show how behind EUREC was in fact the well-established Anglo-Spanish networks, comprising the core for linking other actors to the network.

[686] Isofotón was a spin-off company of UPM, established to commercialise the bifacial cell. This effort was supported and/or associated with BP Solar (see: Instituto de Energia Solar (Universidad Politecnica de Madrid), ies.upm, *40 years leading PV solar energy: History*, Available online: https://www.ies.upm.es/IES_UPM/History, (accessed 13 May 2021)).

the first period.[687] Philip Wolfe comprised one of the pioneers in the UK PV industry, was one of the EPIA founders, and served as Director General in the British RE Association in the 2000s.[688] Wolfe was one of the proponents of adopting a FiT law in the UK for RES. BP Solar was active also in the solar thermal collectors business, which may partly explain the company's interest in CPV.[689] In 1985, Isofotón expanded its business to include solar thermal collectors. Apart from the CPV cooperation, BP Solar had established additional links with UPM and Isofotón.

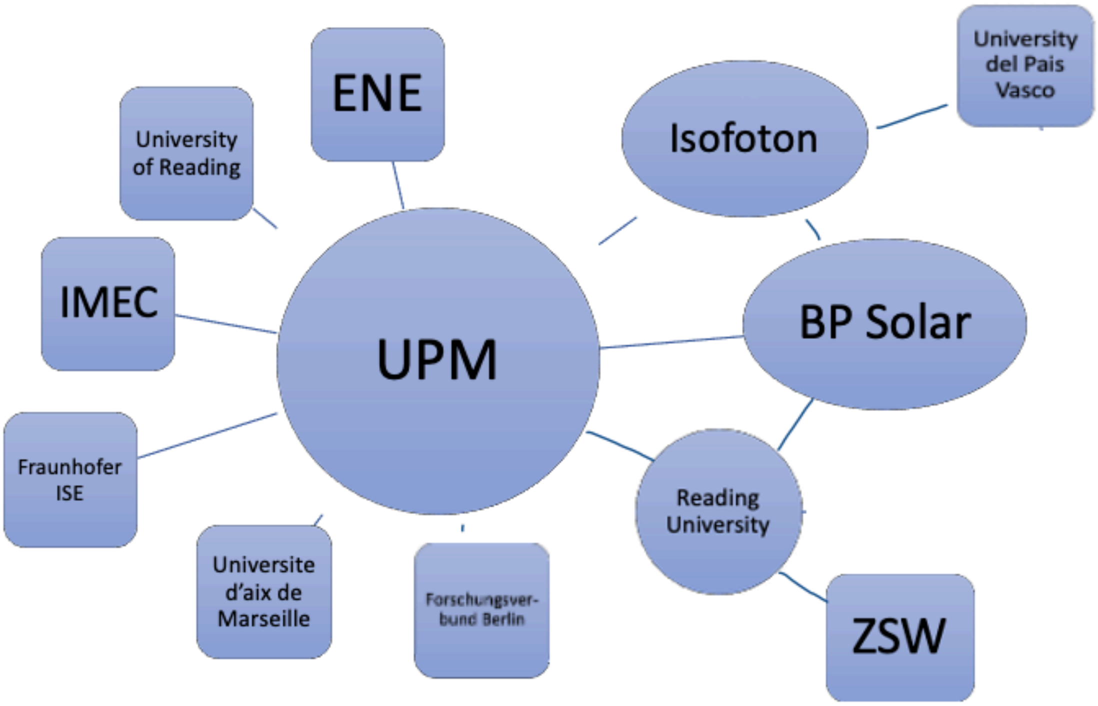


Figure 6.2 The CPV networks, 1989-1998.[690]

During FP3, the budget for CPV quadrupled. This budget increase can be attributed to the explicit interests of an industrial actor from the European North. BP Solar first entered the CPV

---

[687] Philip R. Wolfe, "Profiles of Early PV Companies and Organizations", *in* The Solar Generation: Childhood and Adolescence of Terrestrial Photovoltaics, John Wiley & Sons, Inc. (Hoboken, New Jersey: 2018), p. 207-208.
[688] Philip R. Wolfe, "Profiles of Early PV Companies and Organizations", *in* The Solar Generation: Childhood and Adolescence of Terrestrial Photovoltaics, John Wiley & Sons, Inc. (Hoboken, New Jersey: 2018), p. 192-3.
[689] We analyse this point in a later section, we well as the links between the CPV research and the CSP research.
[690] Towards creating Figure 6.2, we established continuities and discontinuities in the CPV projects, both within each FP and in-between them. The actors depicted in Figure 6.2, comprise the continuities. Essentially, only actors that participated more than once in the CPV projects have been included. Moreover, towards making the links (lines connecting the actors) we examined the collaboration patterns. The actors depicted within a circle comprised project coordinators, in contrast to those in a square that only participated in the projects.

projects under FP3. It was only when an industrial actor from the European North expressed interest in this alternative design option that R&D funding increased. BP Solar, as we saw in chapter 4, first entered the PV business through acquisitions in the 1980s. The company made its entry into the PV field with c-Si. However, BP Solar diversified its business to include thin film and CPV.[691] This diversification of BP Solar's PV activities can be understood as the company's commitment to this field, eagerly exploring different technologies.

As we mentioned at the beginning of this chapter, CPV research was very diverse in the early days. UPM's research projects are no exception to this. At UPM-IES, both (mono) c-Si and GaAs solar cells were research for concentration ratios ranging from 1 sun to 80-100 suns to 1000 suns. Typically, GaAs cells were coupled with high concentration ratios (i.e. 1000 suns), while c-Si was coupled with the low concentration ratios (1-100 suns). In contrast to UPM, both BP Solar and Isofotón carried out projects that focused exclusively on c-Si and participated in UPM's the c-Si projects. Moreover, the scale of these projects remained small (up to 30 suns).

BP Solar was interested in developing c-Si CPV modules that could be used for building facades. This made BP Solar one of the first actors to 'place' CPV as an integral part of buildings. Concurrently, the company was interested in developing a technology for the Mediterranean climate and the so-called 'developing' countries. As we have already analysed, CPV was perceived as a technological design for the southern climates. C-Si CPV modules were larger than flat-plate c-Si modules but were understood by a major PV actor and a powerful industrial actor as an alternative to distributed electricity production for the southern climates. We should note that the projects complemented each other and represented a continuity in activities to develop different aspects of CPV technology. For example, the research conducted by UPM during FP2 formed the basis for FP3 activities. The FP3 projects targeted different 'parts' of the CPV (i.e. cell, module) so that the projects could transfer knowledge among one another. Essentially, the projects complemented each other and built on each other's knowledge. BP Solar supplied the cells needed for the studies and developments of the projects, while assuring that the resulting knowledge would be fed back into the company. Moreover, BP Solar had extensive know-how in manufacturing of modules.

---

[691] According to Philip Wolfe that established BP Solar, the company's thin film endeavours have been deemed as the reason for its demise.

6.2 The CPV technoscientific research networks: a technological pathway *by* the South and *for* the South

The share of R&D funding for CPV gradually increased in the second period.[692] As illustrated in Figure 6.3 (below), a handful of countries coordinated the sixteen (16) CPV projects in the second period. Spain, followed by Italy, Austria, France and the UK coordinated the CPV projects in that order based on the funding they received. Spain not only maintained its dominant position in the CPV research activities, but further strengthened its position by receiving half of the total CPV R&D funding of the second period; 50,32% to be exact. Consecutively, Italy attained a share of 32,96%, Austria a funding share of 13,52%, France a share of 2,77% and the UK a share of only 1,34%.

The geographical scope of CPV networks has expanded to include several EU and non-EU members. Overall, the number of countries participating in the networks increased steadily from one FP to the next. In particular, the geographical coverage of the networks grew from eight countries in FP5 to ten in FP6 and to fifteen in FP7. Despite the widened geography of the actors participating in the CPV research activities, we have an uneven geographical concentration of funding. Spain and Italy concentrated a total of 83,28% of the total CPV funding. In contrast to the geographical distribution of c-Si funding, in the case of CPV we see that the countries dominating and accumulating funding are from the European/EU South and in particular from the Mediterranean region. CPV is a design 'best suited' to the southern climate.[693] So, we can talk about a technology or a PV design option developed *by* the European South and for the South, incorporating the needs and ideas of certain Southern European countries.

But is the geographical distribution of CPV funds different from that of the first period? In other words, does the dominance of Southern European countries represent a continuity? Which countries were traditionally involved in CPV research? Were there countries that continuously held a dominant position in CPV research? Who were the actors that set the agenda of CPV research?[694]

---

[692] Even though the CPV funding shares can be found in Chapter 5, we included them here for the readers' convenience. The CPV funding increased from 12,76% in FP5 to 14,89% under FP6 to 16,48% under FP7.

[693] We have analysed this point in a previous section but do further analyse it in a forthcoming section based on the different semiconductors that dominated during the second period.

[694] We directly compare the geographical distribution of the CPV funding between the two periods. We have already analysed the distribution for the first period, in the corresponding CPV section. Here we directly juxtapose and compare the changes and similarities, with a focus on interpreting the changes for the second period.

In contrast to the first period, where the UK was strongly represented, in the second period only one project was coordinated by a UK actor, namely the University of Reading.[695] There are two reasons that can help us interpret the shift in the UK's declining position in CPV R&D activities. First, the main (industrial) actor from the UK, BP Solar, ceased to exist; hence, we see only BP Solar in a single (FP5) CPV project (i.e. IDEOCONTE).[696] Secondly, during the second period a national (UK) research policy was established for PV, prioritising thin films. However, as we pointed out in the previous section, CPV received increased R&D funding when a private actor from the European North expressed interest (i.e. BP Solar). It was the collaboration of BP Solar with UPM and Isofotón that put CPV on the EU R&D map. Given the lack of support from this crucial private actor we will see through what changes in the design and the material, CPV continued to receive funding during this period. As we analyse in the following sections, these changes were a direct outcome of the silicon crisis in PV.

Another difference with the first period is the absence of Belgium. However, the Belgian actor coordinating the first period project was EUREC, an association of large European research centres.[697] Unsurprisingly, UPM was part of EUREC and participated in the aforementioned project. Moreover, as we have in the corresponding first period section, the project coordinated by EUREC was essentially a continuation – and a combination – of the FP2 networks, which were split into smaller networks in FP4. Furthermore, the main actors of the EUREC-led project were the same as those that coordinated the FP4 projects. As EUREC does not appear in the PV R&D projects in the second period, Belgium did not coordinate any projects.

Another difference compared to the first period is the inclusion of Austria in the R&D activities of CPV. Austria has not entered into system or material/cell and module research. The project coordinated by an Austrian actor (Voestalpine Metal Forming GmbH) was rather concerned with the construction and assembly of CPV components that could support the mass production of the technology.

---

[695] The University of Reading coordinated one project during the first period and was collaborating with UPM.

[696] BP Solar started shutting down its factories in Spain, Australia and later in the US too in the late 2000s. In 2011 BP Solar ceased to exist, attributed to the increasing manufacturing Asian activities with which the company could not compete. For more information see: LaMonica Martin, 21 December 2011, CNET, *Another one bites the dust: BP Solar shuts down*, Available online: https://www.cnet.com/news/another-one-bites-the-dust-bp-solar-shuts-down/, (accessed 7 April 2021) and Pfeifer Sylvia and Clark Pilita, 21 December 2011, Financial Times, *BP to exit solar business after 40 years*, Available online https://www.ft.com/content/80cd4a08-2b42-11e1-9fd0-00144feabdc0, (accessed 7 April 2021).

[697] We have analysed EUREC and its participation in the EU-funded projects in depth, in previous sections (both for c-Si and CPV).

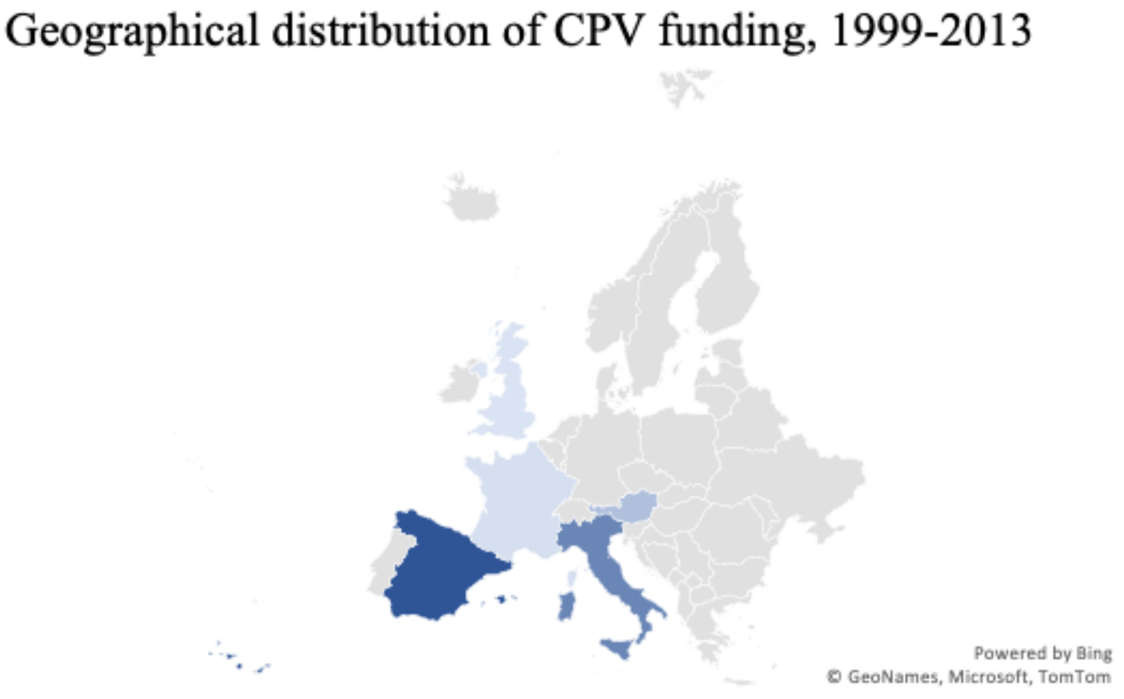


Figure 6.3 Geographical distribution of CPV based on funding, 1999-2013.

Italy had expressed some limited interest in CPV since the early days of Community R&D programmes. ENEL and Montedison coordinated projects during the first two energy R&D programmes (1975-1983). From the actors that coordinated these projects, we see that the private sector was interested in CPV R&D activities. Then, we see only one Italian participation in the CPV networks under the three Joule programmes.[698,699] Apart from the R&D programmes, we remind the reader that the first CPV demonstration project failed to be completed due to Ansaldo's lack of interest in the production of CPV cells. It is thus clear that Italian interests in CPV R&D remained limited, as they were halted by the private actors who had well-established interests in the development of c-Si flat plate PV. During most of the second period, the scene remained unchanged. During FP7, Italian actors coordinated CPV projects – for the first time since the 1980s – who received the bulk of CPV funding. As we explain in a following section, this newfound interest in CPV by Italian actors is due to the

---

[698] Euroinks srl participated in the project coordinated by Isofotón. Based on the limited information available on the company, it seems that they produce "thick film printing inks", which are distributed also for the photovoltaics industry (Bloomberg, *Euroinks srl*, Bloomberg. Available online: https://www.bloomberg.com/profile/company/1523Z:IM, (accessed 10 May 2021)).

[699] For more information see the corresponding first period. In summary, we remind the reader that the Italian actors involved in the CPV R&D activities were involved in only a single project. As such, there is not a continuous interest, rather the Italian efforts can be characterised as dispersed.

joint interests of ENEA and ENEL in using domestic experience with III-V cells for space applications through CESI, which were commercialised through a joint venture.

French activity on CPV had always been modest. LEP and SEP participated in CPV research during the first Community programme and sought to use c-Si cells. For the rest of the first period, the limited projects involving French actors included efforts by public sector actors (universities), mainly in collaboration with UPM-IES. During the second period, the situation remained unchanged, with limited French participation in CPV research, mainly in collaboration with UPM-IES. A notable exception was the (limited) involvement of EDF, who opposed the utilization of small-scale PV installations. Therefore, EDF's involvement in CPV research can be interpreted as a means for finding a PV technology that could be integrated to the already existing energy system and allowing her to maintain control in the supply of electricity. EDF's involvement in CPV research ceased as soon as the 2006 French FiTs law was passed, which favoured and promoted the installation BIPVs.[700]

Spanish participation was a constant from the first period. The Spanish actors whom we analyse in a detail in a forthcoming section, had extensive experience and expertise in CPV. We note that in the second period, the Spanish actors further established their dominant position in the research networks.

Apart from the increasing EU R&D funding for CPV, we see three changes in CPV R&D during the second period. First, R&D shifted to HCPV, which became the sole recipient of funding from FP6 onwards. Second, this was accompanied by a shift in the materials used for the HCPV cells (i.e. multi-junction III-V semiconductors), which also meant a move away from c-Si. Third, we see that the above two changes are incorporated in the EU Roadmap and the SRAs. In parallel, we see that the installation of HCPV systems using III-V multi-junction solar cells dominate the installations from 2008 onwards. Essentially, the technology only became commercial with the shift to HCPV. The shift also meant a change in the respective uses and applications of CPV. By extension, this shift to HCPV had implications regarding the energy policy options that this system enabled. HCPV redirected and constrained the use of CPV to large-scale systems. In the following section, we analyse the system-cell coupling promoted in the second period and provide insights into the commercialization constraints before this shift.

---

[700] Duvauchelle Christophe, Fraisse Jean-Luc, Barlier Yves, "Photovoltaic Integration in the Distribution Grid French Regulation and Network Requirements", *in* Twenty second European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Milan, Italy, 3-7 September 2007, G. Willeke, H. Ossenbrink, P. Helm (eds.), WIP Renewable Energies: 2007, p. 3505-3511.

6.2.1 CPV system and material coupling shift: a response to the Si crisis in PV and a technology for the Global South

As the reader may recall, a variety of semiconductors were used for the CPV cells in the first period. Most prominent was c-Si, which was also used for the dominant flat-plate PV technology. In the second period, and in direct response to the silicon crisis in PV, the preferred cell semiconductor for CPV changed. This change was implemented not only in the CPV projects funded by the EU R&D programmes but later also incorporated in the manufactured CPV technologies.

> "**HCPV systems were mostly equipped with c-Si concentrator cells before 2008**, **but III-V multi-junction solar cells have since become standard**. LCPV systems still employ either slightly modified standard or high-efficiency c-Si cells."[701] (emphasis added)

The shift of HCPV systems away from c-Si cells took place before the silicon crisis in PV. A prominent R&D proponent behind this shift was UPM-IES, which aimed to use III-V multi-junction solar cells for HCPV. From FP6 onwards, HCPV systems became the sole recipient of EU R&D funding.

> "…**HCPV is advantageous in hot climates in particular**, since the **output of the solar cells used does not decline as severely at high temperatures** as that of conventional c-Si solar modules."[702] (emphasis added)

CPV is a technology best suited to southern, sunny areas. Both the design and the choice of material for the cells, especially the semiconductors used for HCPV, make CPV a southern technology. In terms of design configuration, the use of tracking systems allows it to 'follow' the sun throughout the day. The solar cells used in HCPV systems (i.e. III-V multijunction) are more efficient at high temperatures than conventional c-Si cells. Also, unlike conventional c-Si solar cells and thin-film cells, HCPV cannot use diffuse radiation, but use direct normal

---

[701] Simon P. Philipps, Andreas W. Bett, Kelsey Horowitz, Sarah Kurtz, *Current Status of Concentrator Photovoltaic (CPV) Technology*, Fraunhofer ISE and NREL, Version 1.2, February 2016, p. 10.

[702] Simon P. Philipps, Andreas W. Bett, Kelsey Horowitz, Sarah Kurtz, *Current Status of Concentrator Photovoltaic (CPV) Technology*, Fraunhofer ISE and NREL, Version 1.2, February 2016, p. 7.

irradiance (DNI).[703,704] Drawing from all this technical information about CPV systems and HCPV in particular, we can conclude that this system is most suitable for the climate of the south.

As can be seen in Figure 6.4, the commercialisation of CPV began in the mid-2000s. LCPV and HCPV systems are most commonly installed and/or deployed, with preference seeming to be given to the latter. This preference is also observed in the CPV R&D projects funded in second period. However, this shift was made possible by the inclusion of the so-called III-V multijunction solar cells in CPV, which were first used for space applications.

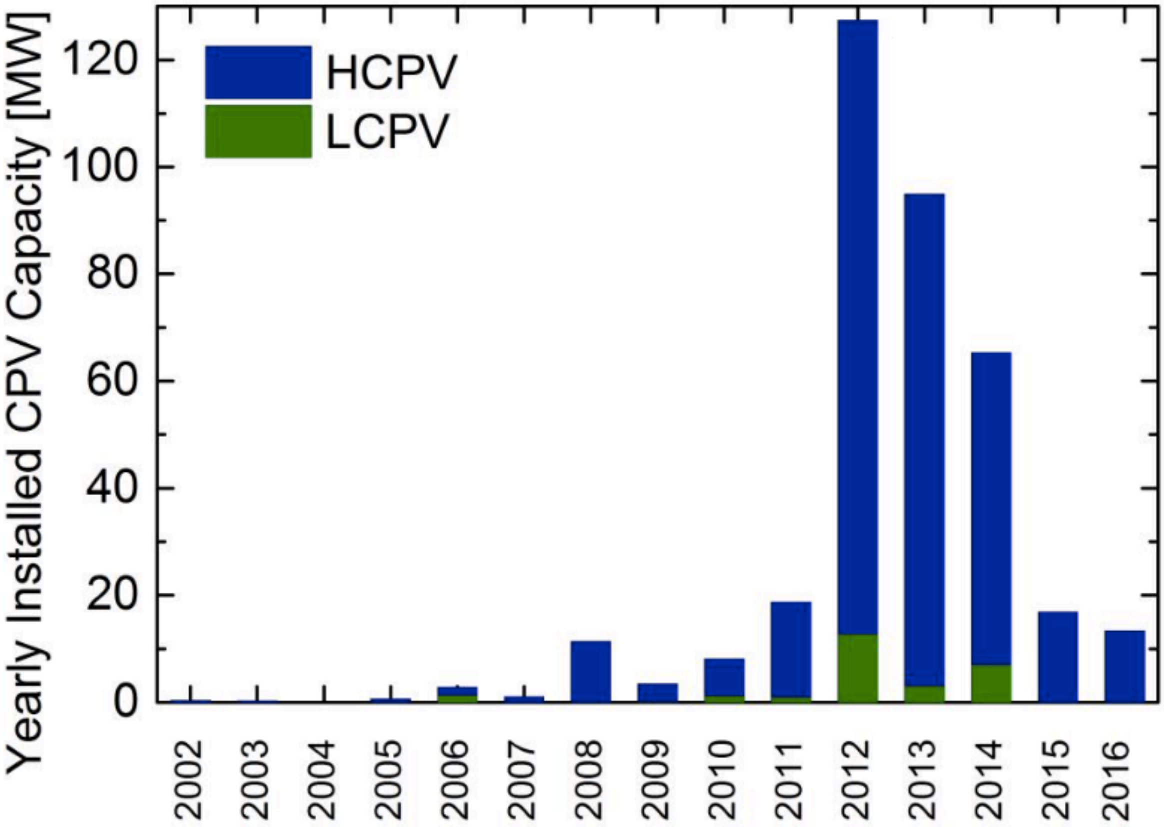


Figure 6.4 Annually installed CPV capacity (in MW). Source: Maike Wiesenfarth, Simon P. Philipps, Andreas W. Bett, Kelsey Horowitz, and Sarah Kurtz, “Current status of concentrator photovoltaic (CPV) technology”, April 2017 (version 1.3), Fraunhofer ISE and NREL. Reproduction permission granted by Andreas W. Bett & Simon P. Philipps.

---

[703] Simon P. Philipps, Andreas W. Bett, Kelsey Horowitz, Sarah Kurtz, *Current Status of Concentrator Photovoltaic (CPV) Technology*, Fraunhofer ISE and NREL, Version 1.2, February 2016, p. 1-26.

[704] LCPV are similar to HCPV in that respect, since they “…can only utilise a fraction of diffuse irradiation”. (Simon P. Philipps, Andreas W. Bett, Kelsey Horowitz, Sarah Kurtz, *Current Status of Concentrator Photovoltaic (CPV) Technology*, Fraunhofer ISE and NREL, Version 1.2, February 2016, p. 8).

Multijunction solar cells, as the name suggests, are cells that consist of multiple p-n junctions, in contrast to the conventional single junction (c-Si) solar cells. Multijunction cells use different semiconductor materials that can take advantage of their different bandgaps, resulting in higher electricity production.[705] Based on the Shockley-Queisser limit there is a theoretical maximum for the efficiency of single junction solar cell (30%). However, this theorem refers to single junction (c-Si) solar cells. All cells that exceed this theorem are considered second or third generation solar cells.

As shown in Figure 6.4 (above), CPV installations started to gradually increase towards the end of the silicon crisis and peaked in 2012, when over 120MW were installed. Most of the installations were of HCPV systems, mainly in Spain, which flourished in the (Spanish-led) market until 2010-1. From 2012 onwards, the number of annual installations expanded to China, the USA, South Africa and Italy, as well as other countries (e.g. France, Portugal, Australia, Saudi Arabia etc.).

The slow uptake of CPV systems, which is also evident from the lack of standards, can be attributed to at least one important factor. As Dr. Sala and Prof. Luque wrote in 2007:

> "Although there were several concentration cells developed in the world, with efficiencies ranging from 19.6% at the UPM to 27% by Swanson et al., **the production capacity was poor and concentrator cells were difficult to find for 25 years**. **The rare investors** that were **interested in** the **PV concentration** 'miracle' **were discouraged when they discovered that concentration cells were not available**, or that the cost ratio with flat-module cells was larger than the concentrator gain."[706] (emphasis added)

Since the 1980s, supply restrictions on concentrator cells came from cell producers. Based on the analysis of the previous chapter, we have seen how (i) electronics industry actors entered the PV endeavours, (ii) c-Si became the dominant technology and R&D funding frontrunner due to its links to the electronics industry, and (iii) the prioritisation of both PV among all RES and c-Si among PV technologies was justified by climatic conditions (i.e. a technology for the northern European climate).

---

[705] Each semiconductor has a different bandgap.

[706] Sala G., and Luque A., "Past Experience and New Challenges of PV Concentrators", *in* Concentrator Photovoltaics, Antonio Luque and Viacheslav M. Andreev (eds.), Springer: 2007, p. 4.

In view of the above, without the willingness of industrial actors from the electronics industry to supply those interested in developing CPV, it would have been almost impossible to produce the cells required for CPV; and this was the case. The alternative would have been to enter into production of c-Si concentrator cells from scratch. However, this option would mean a heavy commitment in terms of time and capital, and at a time when PV was still in its infancy. It would therefore require an actor willing to make a long-term, capital-intensive, and high-risk investment at a time when PV was just taking its first steps on Earth. Moreover, this actor would have to compete with electronics industry conglomerates that clearly has an interest in c-Si flat-plate PV. In other words, a very tough competition.

Given the scenery Sala and Luque sketch, efforts to develop CPV were blocked for twenty-five years by the cell suppliers who – coming from the electronics industry – had embarked on and were committed in the development of c-Si flat plate PV. The interests of the electronics industry not only determined the dominant technological path for PV, but also, with the blessing of the Commission, hindered the development of this – southern – alternative PV design option.

Limited and restricted access to concentrator cell supply delayed further CPV development. Without an adequate supply of cells, the installation of CPV systems remained limited for almost thirty years. This, in turn had the effect of limiting the measurements the performance, stability and reliability of this alternative design option, as well as the development of the relevant standards and the subsequent commercialization of CPV.

6.2.2 The reorientation of research: towards 'upscaled research'

In the second period, we see a shift in R&D in both the CPV design funded and the corresponding cell materials. More specifically, we refer to the shift from LCPV systems using c-Si cells to HCPV systems using multijunction III-V solar cells. The latter became the sole recipient of EU research funding from FP6 onwards.

This shift and the concurrent use of multijunction III-V cells for HCPV systems was legitimised in the SRAs.[707] However, the first time that the use of multijunction solar cells was directly associated with HCPV systems was in the context of a UPM-coordinated FP5 project, while the rationale for this choice was articulated in a UPM-led FP6 project. Professor Luque (UPM-IES) justified the feasibility of using more expensive materials for the solar cells based on the

---

[707] We remind the reader that the first SRA for PV (including CPV) was published in 2007. Consecutively, the updated version of the SRA was published in 2011.

maximum energy output made possible by their incorporation into the CPV design. The smaller surface area of CPV cells ‘allowed’ the use of these expensive materials for this technological design but for economic reasons they had to be used in HCPV systems. The choice of HCPV systems over LCPV systems has had a direct impact on the applications and use of this technology, and therefore on the options it enables for energy policy.

At the same time with the above changes in CPV R&D, we see a shift in the character of the CPV R&D projects funded. Some of the projects (i) made direct reference to cost and/or included specific cost targets (e.g. EUR/Wp), (ii) aimed to stimulate (mass) production by including either a pre-production of CPV cells or pre-commercial production lines. The changing objectives of the projects – by including mass production, pre-production of cells and pre-commercial production lines – in the research projects undoubtably testify to the changing character and use of research policy in the second period. In this way, research moved closer to the market and significantly narrowed the gap between the two. Research that could shorten the value chain was prioritised (i.e. the development of near-market products directly from research projects). This was expressed primarily through the constant emphasis on innovation and the linking of research with the market and industrial production. This is also reflected in research policy through the recurrent efforts to facilitate the integration of RES technologies into electricity grids and the implementation of PV (i.e. increasing cell efficiency). Apart from the emphasis placed on delivering near-market products or production lines and the general emphasis placed on resolving production issues, the projects sought to cover the entire value chain. In the case of CPV, feedstock was not a problem to be researched. Rather, the shift to III-V semiconductors was the CPV network’s response to the silicon crisis. Nevertheless, the projects covered a broader spectrum of the value chain, similar to the case of c-Si in the second period.

Efforts were also made to find the possible and perhaps most suitable applications for CPV. In other words, the research projects actively tried to link each CPV system to specific markets by trying to link them to their potential applications. Applications vary, ranging from large-scale grid-connected power plants to (stand-alone) water pumping and irrigation, to the use of CPV in industrial and residential areas, as well as (limited) BIPV-specific references. Efforts to determine the best uses for CPV in terms of the materials used for the cells and the corresponding costs concerned the R&D projects of the second period.

The division of research into short-, medium- and long-term research and the goals that each type of research should achieve were set out in the SRAs. The SRAs established a direct link between the short-term research, that was conducted under the FPs, and the achievement of the cost goals. As we have already analysed in chapter 2, the SRAs essentially legitimised the changes that have taken place since FP5. The cost targets of the EU-funded CPV R&D projects and the reorientation of research towards resolving production issues pertain the second period CPV projects, which are in line with the CPV priorities set by the SRAs.

From the first to the second period the number of projects coordinated by universities decreased slightly (from 44% to 43,75%). Projects coordinated by research centres decreased (from 16% to 12,5%), while the role of companies augmented (from 36% to 43,75%). In contrast to the case of c-Si, we find that universities and companies played a stronger role in CPV networks, while the role of the research centers was disproportionally smaller. These differences can be attributed to the respective characteristics of the networks. As we have already seen in the network analysis of the first period, the CPV networks were built around a single dominant actor. UPM comprised a unique case – it always had an eye on the commercialization of the team's research. Luque played a catalytic role in this regard. Because of his entrepreneurial spirit, he helped UPM maintain its dominant position in the networks. This university had established close relationships with companies, one of which was the university's spin-off company. In the case of c-Si, the universities established research centres (e.g. imec from KU Leuven, ISC Konstanz from Konstanz University etc.) that enabled them to establish closer collaborative relationships with companies and/or through which they created spin-off companies. Essentially, they followed different commercialization paths, which in turn lead to different networks and network dynamics.

The participation rate of universities decreased from the first to the second period (from 42,18% to 26,56%). In contrast, the participation rate of both companies (from 35,93% to 42,18%) and that of research centres (from 20% to 25,78%) increased. The increasing share of companies and the simultaneous decrease in the share of universities is very similar to the case of c-Si. As we have already noted, the CPV projects of the second period aimed at solving production issues, moving closer to production and extended the value chain steps included in the research projects. Despite the differences between two case studies c-Si moved closer to upscaled production (i.e. became industrial), while CPV was on its wat to commercialization. These findings are similar for both cases and relate to the general reorientation of research during the second period. This is directly related to the upscaled research, which can be primarily conducted by large research centres, which in turn minimizes the role of universities and other small research groups in the networks.

6.2.3 The Spanish framework and network

As shown in Figure 6.5, actors from Spain received the largest share of CPV R&D funding from FP5 to FP6. In particular, CPV projects led by the Spanish actors received 73,21% of CPV funding in FP5, 100% in FP6 and in FP7 the funding share shrank to 27,36%, mainly due to the entry of Italian actors.

Moreover, until FP6, the majority of Spanish funding came from CPV projects, 64% in FP5 and 100% in FP6. This changed in FP7, when the corresponding share shrank to about 24%. This change is attributed to the expansion of Spanish research to other PV materials, which was made possible by the know-how and experience that the Spanish actors had developed through their focus on III-V multijunction HCPV systems. This allowed them to work with the same semiconductors for different PV technologies.

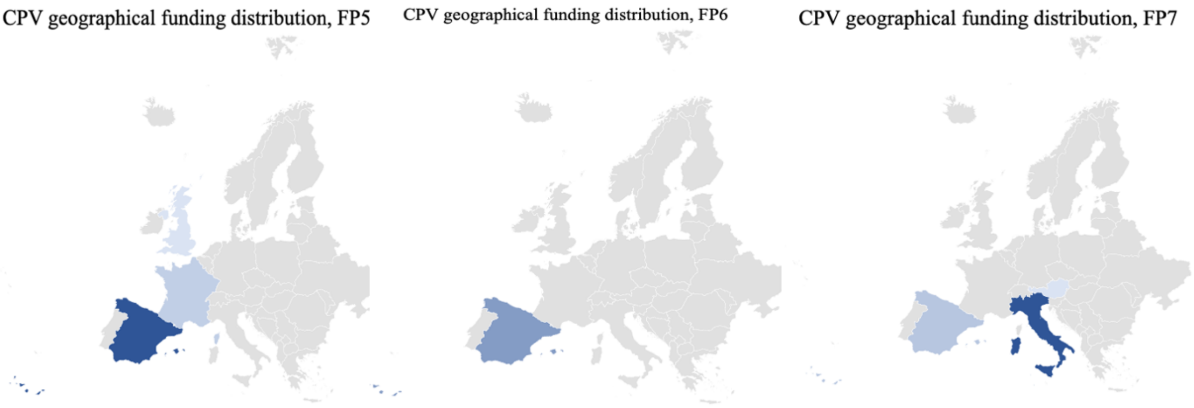


Figure 6.5 CPV geographical funding distribution by FP, 1999-2013.

During the second period, the Spanish National R&D Plan did not include a PV programme. Rather, R&D priorities for all RES were included in the National Energy Plan.[708] In the three Spanish Renewable Energy Plans (Plan de Energías Renovables - PER), covering the period from 1999 to 2020, R&D activities for RES were formulated in line with changing energy policies.[709] To be exact, the EU's energy policy goals formed the basis for setting R&D priorities. In the second PER, the technological R&D priorities for PV were defined in more detail and at the same time concrete links were made to the main barriers and challenges that

---

[708] Salas V., Olias E., "Overview of the photovoltaic technology status and perspective in Spain", *Renewable and Sustainable Energy Reviews*, 2009, p. 1049-1057.

[709] Plan de Energías Renovables (PER). The first PER was published in 1999, covering the period 2000-2010. The second PER was published in 2005, covering the period 2005-2010. It comprised an update to the first PER, taking into consideration the developments in energy policy (i.e. Directive 2001/77/EC and Directive 2003/33/EC). The third PER was published in 2011, covering the period 2011-2020.

needed to be overcome. In this context, the issue of the silicon feedstock shortage was identified as a potential obstacle for the future development of PV. To this end, the following was proposed:

> "Tecnologías innovadoras como la concentración, que para igualdad de potencia utilizan silicio de grado electrónico, procedente de la propia industria electrónica pero en mucha menor intensidad y con mayor valor añadido, pueden contribuir a resolver el problema de la materia prima." [Innovative technologies such as concentration, which for equal power use electronic grade silicon, from the electronics industry itself but in much less intensity and with greater added value, can help resolve the problem of the raw material(s).][710]

Concentration, i.e. CPV, as an alternative technological pathway was casted in the Spanish context as a possible solution to the problems with the silicon feedstock – especially HCPV, because this option significantly reduces the amount of raw material needed for the cells.[711] In addition, a complete shift away from silicon-based technologies was proposed, which could be achieved through HCPV systems, which not only reduce the use of raw materials but also require other semiconductors for the solar cells (i.e. III-V).

In essence, the Spanish PER sought to take advantage of the domestic know-how and expertise, both academic and industrial, that had already made a U-turn in R&D towards HCPV. The inclusion of this bottom-up R&D strategy in the PER explicitly placed HCPV at the centre of Spanish R&D activities and in the context of overcoming the silicon feedstock shortage. This turn was further justified by the inclusion of a map of Spain, which was divided into zones on the basis of solar radiation. Based on this map, the use of PV was considered favourable for the country's climate, especially given the large areas of high solar irradiance. Given the characteristics of CPV that we analysed in an earlier section, this map provided further justification for the CPV turn based on the country's specific climatic conditions.

The Spanish commitment and prioritization to CPV is also evident in two other developments. First, the Institute for Concentration Photovoltaic Systems (ISFOC) was established in Spain in 2006 with the aim of developing CPV. ISFOC was the result of the joint efforts of UPM-

---

[710] Ministerio de Industria, Turismo y Comercio - Instituto para la Diverficación y Ahorro de la Energía, *Plan de Energías Renovables en España 2005-2010*, Agosto de 2005, p. 163.

[711] As mentioned in the PER, HCPV could use 250-1000 times less material (see: Ministerio de Industria, Turismo y Comercio - Instituto para la Diverficación y Ahorro de la Energía, *Plan de Energías Renovables en España 2005-2010*, Agosto de 2005, p. 186.)

IES, the Castilla La Mancha government and the Spanish Ministry of Education and Science.[712] Second, a regulatory framework for CPV was proposed in Spain in 2010, which included the introduction of policy instruments (i.e. FiTs) to support the deployment of CPV.[713]

6.2.3.1 The Spanish-led technoscientific research network

If we look at the actors that coordinated the EU R&D projects, as shown in Figure 6.6 (below), we see that UPM played a central role in the CPV R&D activities. During FP5, CPV projects coordinated by UPM received a large share of funding (39,17%). Another important and central actor was the UPM spin-off, Isofotón, while another Spanish actor, Solucar, also received significant amounts of funding (12,11%). In FP6, the UPM-led project received the largest share of CPV R&D funding (75,54%), while Solucar received the remaining share. In FP7, UPM-led projects received 27,36% of the funding, while Italian actors took the lead with slightly more than half of the total CPV R&D funding.[714]

Apart from the geographical distribution of CPV funding, which indicates Spain's central role in R&D activities, this is also further confirmed by looking at the CPV technoscientific research networks. As can be seen in Figure 6.6, Spanish actors played a central role in the CPV networks.

Most important is the collaborative duo consisting of UPM and Isofotón. UPM has consistently collaborated with Isofotón in both periods. Isofotón joined the networks only when UPM was present, and UPM was always part of the projects led by Isofotón. At this point we must remind the reader that Isofotón was a spin-off company foudned by Luque, who also founded UPM's ETSI laboratory.[715,716] Isofotón was acquired by the Bergé group in 1997 and was sold to Affirma and Toptec in 2010.[717,718] Despite these changes, Isofotón continued to work closely

---

[712] Institute for Concentration Photovoltaics Systems, isfoc, *History*, Available online: http://www.isfoc.net/index.php/en/isfoc-2/global-presentation/history, (accessed 13 April 2021).

[713] Perez-Higueras P. J., et al., "A Spanish CPV Regulatory Framework: Proposal of a Feed-in Tarriff", *in* 25th European Photovoltaic Solar Energy Conference and Exhibition/5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Valencia, Spain, De Santi G. F., Ossenbrink H., Helm P. (eds.), WIP Renewable Energies: 2010, p. 5421-5424.

[714] We analyse the Italian-led network and the respective actors in a forthcoming section. An explanation for the funding shift, under FP7, is explained in detail in that section.

[715] For further information on Isofotón, see the corresponding section in the first period analysis.

[716] Isofotón went bankrupt in 2015, after continuous competitions pressures by the Chinese PV actors. See Barciela Fernando, 17 June 2013, El Pais, *Total eclipse of the sun*, Available online: https://english.elpais.com/elpais/2013/06/17/inenglish/1371471362_164500.html, (accessed 13 April 2021).

[717] Philip R. Wolfe, *The Solar Generation: Childhood and Adolescence of Terrestrial Photovoltaics*, John Wiley & Sons, Inc (Hoboken, New Jersey: 2018).

[718] The Spanish Bergé group, established in 1870, provides automotive and logistic services. In the late 1990s, the group expanded their entrepreneurial interest in the field of renewable energy and acquired Isofotón and Ecolmare.

with UPM until the closure of the company in 2015, as evidenced by the continuity of the people responsible for the projects.[719]

UPM received a total of 39,10% of the CPV R&D funds in the second period, i.e. almost two-fifths of the total funds.[720] This illustrates once again the dominant and central role that UPM – and its expertise – played in the EU-funded R&D CPV networks. Moreover, UPM was the only actor continuously involved in CPV R&D activities from FP2 to FP7.[721] By this we mean that only UPM consistently and continuously coordinated and participated in the EU-funded CPV R&D projects from 1989 to 2013.[722]

During the second period, UPM coordinated a total of six projects and participated in another four projects. This makes UPM the only actor with such a strong presence in the CPV projects. Looking at the ties and/or collaboration patterns (Figure 6.6), we also see that UPM was the core of the CPV research networks – until FP6. Actors followed UPM from one project to the next when UPM was coordinating projects. Moreover, we observe that certain actors followed UPM on projects in which UPM was involved as a participant. Essentially, UPM established collaborative ties with actors and these actors follow UPM in the networks that UPM either coordinated or participated in.

---

[719] Due to the continuous Chinese competition pressures, which affected several European companies, Isofotón went bankrupt in 2015. See: Barciela Fernando, 17 June 2013, El Pais, *Total eclipse of the sun*, Available online: https://english.elpais.com/elpais/2013/06/17/inenglish/1371471362_164500.html, (accessed 13 April 2021).

[720] When referring to UPM, the projects were coordinated by the team at ETSI de Telecomunicación, Department de Ingeniería de Sistemas Telemáticos.

[721] As we have already noted CPV was marginalised in FP1, which is the first programme in which Spain participated since joining the EEC in 1986.

[722] UPM continuously coordinated projects throughout the majority of the 1989-2012 period. The only 'gap' is during FP3 (Joule II), when a single CPV project was funded and was coordinated by EUREC. However, as we have already noted in the first period analysis section and in the present analysis, UPM was part of this projects' network.

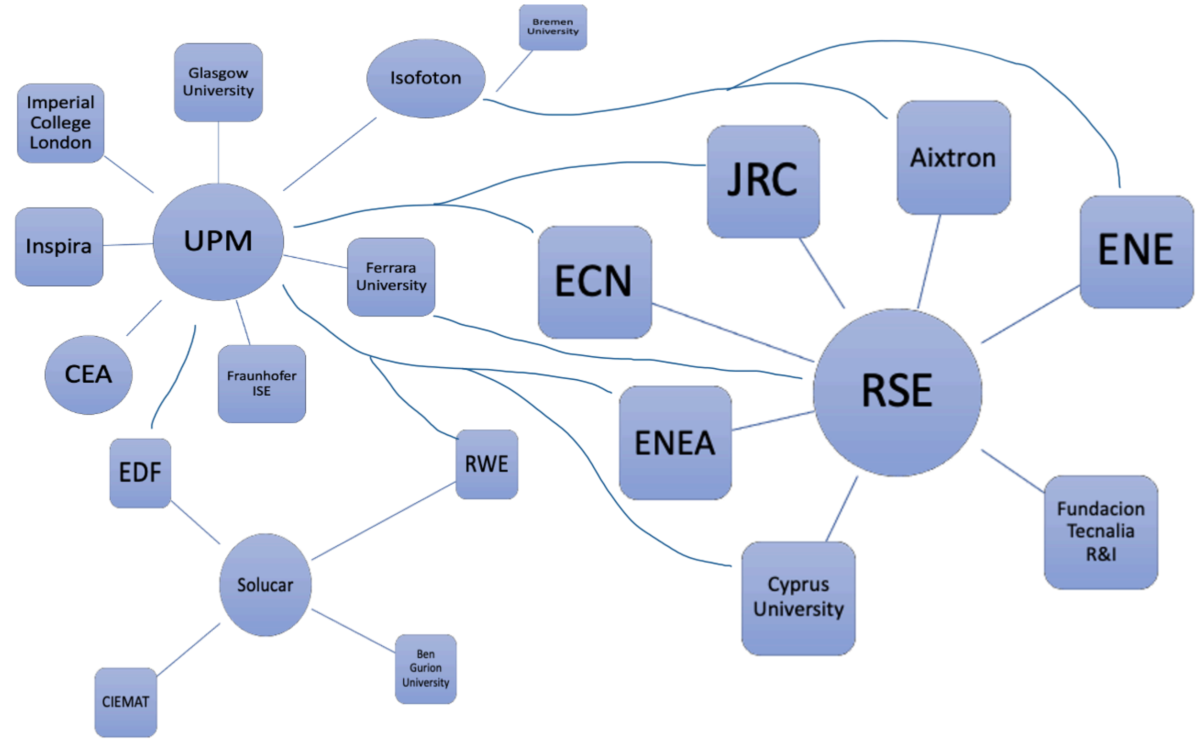


Figure 6.6 CPV networks, 1999-2013.

Behind UPM-IES is Professor Antonio Luque and his group.[723,724] To avoid repetition, we remind the reader that Luque founded the IES in 1979 and established Isofotón in 1981 as a spin-off of UPM-IES.[725] Luque, thus played a crucial role in shaping the R&D activities at UPM and in transferring the know-how and knowledge developed at UPM to Isofotón. In addition, UPM-IES is a key Spanish actor in setting the national research priorities for PV and, at the same time, a European and international leader for CPV.

Professor Luque, as we analysed a few pages earlier, introduced the use of III-V multijunction solar cells for HCPV systems in EU R&D programmes. Given the role that both UPM-IES and Luque played in the development of CPV systems, Luque established collaborative relationships with various actors who could help in the further develop and commercialisation of CPV technology. Luque's collaborators at Isofotón were Jesus Alonso, the company's director of R&D, and Vicente Diaz, who had obtained his PhD from UPM and was Isofotón's director of Innovation and Engineering. Alonso worked at UPM before taking the position of director at Isofotón. Luque also collaborated with the Spanish company Inspira and with the

---

[723] Some of the other project coordinators include Luque's students (e.g. G. Sala and A. Marti).

[724] We searched the European Solar Photovoltaic Energy Conference Proceedings for papers presenting the progress of the findings of the EU funded. Upon conducting this research, we were able to confirm the remaining – various – participants from UPM-IES. Similarly, this type of research was conducted for all other actors for all the analysed PV technologies and projects.

[725] For more information on Luque and his background see the corresponding section in the first period analysis.

German company RWE Space Solar Power. Inspira was a company active in the development of equipment and the installation of industrial machinery and equipment. It contributed its expertise to the development of the machinery and equipment needed to commercialise CPV. RWE Space Solar Power, now AZUR SPACE Solar Power, traces its roots to AEG Telefunken and DASA.[726] It is a company specializing in the development of solar cells for both terrestrial and space applications and is 'the European leader … in development and production of multijunction solar cells for space PV and terrestrial CPV applications."[727] AZUR SPACE was until the late 2000s the only European company – and one of three in the world – to supply CPV cells.[728,729]

Another important actor in the UPM network was Fraunhofer ISE. In chapter 4 we saw how Adolf Goetzberger's determination and persistence led to the establishment of ISE at Fraunhofer. Although the primary research focus of Fraunhofer-ISE was always on c-Si, given (i) the role of ISE in the PV field – both in Europe and internationally – and (ii) the involvement of certain individuals, the R&D activities of ISE expanded to other semiconductors and PV technologies. Professor Goetzberger, in addition to his long and extensive research on c-Si within Fraunhofer ISE and the international c-Si community, also had close ties to UPM.[730] Goetzberger "was a member of the scientific advisory board of the Instituto de Energía Solar at the Universidad Politécnica de Madrid, as well as the Spanish Institute for Concentration Photovoltaics Systems ISFOC.", which illustrates the friendly approach to CPV at Fraunhofer ISE.[731] Besides Goetzberger's interest and support, another important person for III-V and CPV at Fraunhofer ISE is Professor Andreas Bett.

Bett attained his Bachelor and Master degrees at the University of Freiburg. He completed his doctoral thesis at the University of Konstanz, which focused on the development of GaAs solar cells. After completing his PhD, he returned to Fraunhofer ISE (Freiburg) and became the Head of III-V Epitaxy and Solar Cells in 1993. Under his leadership, the group developed the FLATCON technology for CPV, which was commercialized though the establishment of

---

[726] For an in-depth analysis of the company's background see the corresponding section in the first period analysis.

[727] Azur Space, azurspace, *Welcome*, Available online: http://www.azurspace.com/index.php/en/, (accessed 11 May 2021).

[728] The other two companies, both based in the US, are Spectrolab and Emcore.

[729] Kurtz S., *Opportunities and Challenges for Development of a Mature Concentrating Photovoltaic Power Industry*, Technical Report NREL/TP-520-43208, November 2009.

[730] He was the project coordinator of the first Fraunhofer ISE project for CPV, funded under the 2nd energy R&D programme of the EC.

[731] Fraunhofer ISE Press Release, 30 November 2018, ise.fraunhofer, Professor Adolf Goetzberger turns 90: Pioneer of the Energy Transformation and Founder of Fraunhofer ISE, Available online: https://www.ise.fraunhofer.de/en/press-media/press-releases/2018/professor-adolf-goetzberger-turns-90-pioneer-of-the-energy-transformation-and-founder-of-fraunhofer-ise.html, (accessed 12 May 2021).

Concentrix Solar GmbH; a Fraunhofer ISE spin-off company. In 2009 Bett was appointed as Deputy Director of ISE.[732] Outside Fraunhofer ISE, Bett is a member of IEC TC82 WG7, which works on the development of (international) standards for CPV. Bett's name appears in all CPV projects, which Fraunhofer ISE is involved.

Another constant collaborator of the UPM networks was the Commissariat a l'energie atomique et aux energies alternatives (CEA). More precisely, this was the CEA's research institute for electronics and information technologies (CEA-Leti), founded in Grenoble in 1967. Clause Jaussaud and Gilles Fanget, both engineers, worked with the team from UPM-IES.

Electricite de France (EDF), the French public utility, was involved to a lesser extent in CPV R&D activities. However, as we mentioned in the introductory section, EDF was also the biggest opponent of grid-connected PV (and net metering) in France until the early 2000s.[733] The situation in France changed in 2006 when a new FiT law came into force that promoted BIPV installations. EDF was involved in a French CIGS consortium (Institut de Recherche et Développement sur l'Énergie Photovoltaïque - IRDEP) created in 2005 to start the commercialization of CIGS cells, a BIPV technology. EDF was able to redirect knowledge from CPV to CIGS and develop a technology suitable for BIPV applications, thus securing a market share that was preferred domestically. This may also explain why EDF did not participate in CPV research projects under FP7 while was involved in CIGS research activities. Therefore, EDF's participation, albeit limited, in the CPV research activities can be seen as a means to prevent the transition to small-scale PV installations, as HCPV installations are large-scale.

6.2.4 The Italian framework and network

In FP5 there was only one Italian participation, namely that of the University of Ferrara. Accordingly, in FP6 there is also only one Italian participation by the JRC. However, this situation changed rapidly in FP7 when we see (i) an increased participation of Italian actors

---

[732] In 2016, Andreas Bett and Frank Dimroth became the Directors of Fraunhofer ISE.

[733] B. Gaiddon, "New legal framework and market perspective for grid connected PV in France", *in* Seventeenth Photovoltaic Solar Energy Conference, Proceeding of the International Conference held in Munich, Germany, 22-26 October 2001, B. McNelis, W. Palz, H. A. Ossenbrink, P. Helm (eds.), Vol. I, WIP-Munich and ETA-Florence: 2002, p. 911-913.; B. Gaiddon, M. de l'Epine, M. Jediczka, "The Photovoltaic Market in France", *in* Twentieth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Barcelona, Spain, 6-10 June 2005, W. Palz, H. Ossenbrink, P. Helm (eds.), WIP Renewable Energies (Germany: 2005), p. 3064-3067.

and (ii) Italian-led projects receiving the largest share of CPV R&D funding, pushing Spain into second place.

This is a notable difference from the first period, which, as we analysed in an earlier section, was limited to the early days of EC PV R&D. Moreover, this limited interest in CPV was largely guided by the interests of industrial actors, who gave priority to c-Si flat-plate and stopped the first attempt at a CPV demonstration project. So what changed in the second period and how can we understand this renewed Italian interest in CPV?

From 1996 to 2000, the Italian national R&D plan for PV was not continued. This drastic decrease in R&D funding "caused an almost immediate drop out of dedicated resources especially in universities, and a general reduced interest for PV."[734] In these turbulent times, EU R&D funding for PV came as a relief, providing a means to continue PV R&D activities in Italy. R&D spending on PV remained low throughout most of the 2000s (around EUR 5 mil. annually). The lack of national R&D funding for PV from the mid-1990s to 2000, followed by the silicon crisis and limited national R&D funding for PV, formed the backbone of what can best be described as an unfavourable climate for PV in Italy – for about 15 years.

Following the implementation of EU energy policy provisions, in particular the 1997 White Paper for RES, the Roof-tops programme was initiated in 2001.[735] This programme created a favourable environment for small-scale grid-connected PV system installations on rooftops.[736] In continuation of the Roof-tops programme, the Conto-Energia programme was launched in 2005.[737] The programme aimed to increase the number of grid-connected PV systems.

Italy did not have domestic production of silicon feedstock, ingots and wafers.[738] Initiatives for such production were announced for 2010. At the same time, the big Italian manufacturers of c-Si modules were dependent on the international market for the supply of cells. Due to the

---

[734] Ferrazza F., De Lillo A., Farinelli U., "The Italian PV R&D Programme: Status and Perspectives", *in* 29th IEEE Photovoltaic Specialists Conference, 19-24 May 2002, New Orleans, USA, p. 15.

[735] Silvestrini G., Gamberale M., Frankl P., "Italian PV Roof Programme: First Results", *in* 17th European Photovoltaic Solar Energy Conference, Munich, Germany, 22-26 October 2001, McNelis B., Palz W., Ossenbrink H. A., Help P. (eds.), Vol. III, WIP Renewable Energies and ETA: 2002, p. 2371-2374; De Lillo A., Li Causi S., Castelllo S., Guastella S., "PV activities and future development in Italy", *in* 20th European Photovoltaic Solar Energy Conference, 6-10 June 2005, Barcelona, Spain, Palz W., Ossenbrink H., Helm P. (eds.), WIP-Renewable Energies: 2005, p. 3099-3102.

[736] The small scale of PV installations ranges from 1kW up to 20kW.

[737] De Lillo A., Castello S., De Lia F., Guastella S., Paletta F., "Status and Perspectives of PV in Italy", *in* 25th European Photovoltaic Solar Energy Conference and Exhibition/5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Valencia, Spain, De Santi G. F., Ossenbrink H., Helm P. (eds.), WIP Renewable Energies: 2010, p. 5344-5347.; Castello S., De Lillo A., Li Causi L., De Lia F., Tucci M., Guastella S., Paletta F., "PV Market, Industry and Research in Italy", *in* 24th European Photovoltaic Solar Energy Conference, 21-25 September 2009, Hamburg, Germany, Sinke W., Ossenbrink H., Helm P. (eds.), WIP Renewable Energies: 2009, p. 4427-4430.

[738] The joint Italian-US polysilicon activities came to a halt when the Chinese GLC-Poly acquired MEMC/SunEdison in the 2010s. For more details, see chapter 7.

situation described above, the Italian actors were practically defenseless against the pressure created by the price increases of the silicon feedstock. As the Italian networks only emerged under FP7, it is difficult to trace the main actors and their connections historically. However, if we follow the initiatives of the Italian actors in the Italian-national framework, we can reconfigure the historical links of the Italian actors.

ENEA, the main organization for R&D in PV in Italy, played a catalytic role in the reorienting of national R&D activities in the second period.[739] In 2001, ENEA launched the PhoCUS project. This project dealt with the R&D of CPV systems, using c-Si solar cells for large-scale generation of electricity in close cooperation with the industry.[740] We can interpret this newfound interest in CPV as a means to overcome or limit the impact of the impeding silicon crisis, especially given the vulnerable position of Italian industrial actors.

Centro Elettrotecnico Sperimentale Italiano (CESI) is one of the leading European companies in the production of GaAs cells. It comprises one of the oldest companies developing GaAs cells for space applications since 1984, receiving R&D funding from both the Italian and the European Space Agencies (Italian Space Agency (ASI) and European Space Agency (ESA), respectively). Moreover, CESI's GaAs cells were the first European cells to reach space.[741] In addition to GaAs cells, CESI has been developing multi-junction III-V solar cells for terrestrial (concentrator) applications since the mid-2000s. In 2005, just in time for the launch of the Conto-Energia programme, ENEA became the main stakeholder of CESI, which was renamed CESI RICERCA SpA.[742] This 'move' gave ENEA direct access to CESI's expertise and know-in GaAs single junction cells and on III-V multijunction solar cells, enabling the development of HCPV systems. The Conto-Energia initiatives, which promoted the installation of small and large-scale PV systems, created a favourable environment for HCPV systems. The Italian actors involved in CPV, 'took advantage' of the changes in the national energy policy, which (in 2005) also promoted large-scale PV system installations. Given the Italian bottom-up research landscape, the above changes are not accidental. Rather, it was a matter of using national know-how to respond to the silicon crisis while supporting the industrial actors. HCPV is a technology suitable for large-scale installations. Faced with a weakened c-Si flat plate

---

[739] ENEA was in charge for both setting-up the R&D agenda and of the R&D funding distribution, during the first period.

[740] Sarno A., Apicella F., Cancro C., Fucci R., Pascarella F., Pellegrino M., Privato C., Roca F., The PhoCUS Standard Unit: Design, Realization and Preliminary Performance Analysis, *in* 20th European Photovoltaic Solar Energy Conference, 6-10 June 2005, Barcelona, Spain, Palz W., Ossenbrink H., Helm P. (eds.), WIP-Renewable Energies: 2005, p. 2032-2034.

[741] Ferrazza F., De Lillo A., Farinelli U., "The Italian PV R&D Programme: Status and Perspectives", *in* 29th IEEE Photovoltaic Specialists Conference, 19-24 May 2002, New Orleans, USA, p. 15-20.

[742] The relationship between the Italian actors is analysed in depth below.

domestic landscape, the Italians sought to revive interest in PV interest and ‘switched’ to HCPV for this purpose. Concurrently, this meant favouring large-scale PV installations in contrast to the small-scale installations enable by flat-plate PV.

Figure 6.5 (above) shows that Italian actors managed to obtain the largest share of CPV R&D funding during FP7. In particular, Italian actors attained a 32,96% share of the total CPV funding in the second period, representing 51,51% of the total CPV funding under FP7. This led to a changing dynamic between the formerly dominant CPV champions (i.e. the Spanish actors) and the ‘newcomers’ (i.e. the Italian actors).

As illustrated in Figure 6.6 (above), another important network was formed during FP7. This is the Italian network, formed under the coordination of Ricerca sul Sistema Energetico S.p.A. (RSE). The roots of RSE go back to CESI, which was founded in 1952 to create “a unified electrical power grid in Italy by providing research projects and test facilities.”[743] As we mentioned earlier, CESI had extensive expertise in GaAs solar cells and was involved in the development of III-V solar cells for concentration. In 2005, CESI RICERSA SpA was founded, with ENEA taking a majority stake in the company.[744] Five years later, the company became fully owned by Gestore dei Servizi Energetici S.p.A. (GSE) and was subsequently renamed RSE SpA.[745,746] GSE is owned by the Italian Ministry of Economics and Finance and is primarily tasked with promoting the development of renewable energy in the Italian energy system. GSE is the result of the liberalization of the Italian national electricity sector. Apart from the links between RSE and its predecessors and the actors mentioned above, there is another link. CISE was an interdisciplinary research centre of Enel, which has a long tradition in the study of electrical and energy systems. The project led by RSE focused on the development of HCPV with the aim of exceeding the efficiency target set by the SRA. The RSE network involved different (older) actors of the UPM-IES network (e.g. ENE, ECN, Aixtron, University of Ferrara etc.), while establishing new collaborative relationships. Although a newcomer to the CPV networks, RSE gained a strong position in funding and became a central actor for the CPV networks

---

[743] Ricerca Sistema Energetico, RSE, *70 Anni di Tradizione nella Ricerca*, Available online: http://www.rse-web.it/storia.page, (accessed 8 May 2021).

[744] Ricerca Sistema Energetico, RSE, *70 Anni di Tradizione nella Ricerca*, Available online: http://www.rse-web.it/storia.page, (accessed 8 May 2021).

[745] Ricerca Sistema Energetico, RSE, *70 Anni di Tradizione nella Ricerca*, Available online: http://www.rse-web.it/storia.page, (accessed 8 May 2021).

[746] GSE had bought 49% of the company’s share in 2009, whereas at the time the majority capital share still belonged to CESI (Ricerca Sistema Energetico, RSE, *70 Anni di Tradizione nella Ricerca*, Available online: http://www.rse-web.it/storia.page, (accessed 8 May 2021)).

6.3 Concluding remarks: a break with the dominant technological pathway

In the first period, research for CPV had an exploratory character. Actors, mainly from the semiconductor electronics industry, sought to explore the potential applicability of their technology to this alternative design option. Efforts were primarily focused on the dominant c-Si cells for this alternative design option, while a smaller number of projects focused on exploring the potential of other semiconductors for different CPV systems. The lack of continuity in the actors conducting CPV research from the first to the second energy R&D programme indicates the absence of actors with a strong and/or well-established interest in CPV. At the same time, the lack of an adequate supply of cells inevitably led to limitations in the measurements reported by actors in the early years of CPV research. A second obstacle to the development of this technology was simulators, which were designed for the dominant technology and could not measure the efficiency of CPV cells.

As CPV was understood as a technology for the European South, it was excluded from EC's FP1 R&D funding. The EC's DG, Schuster, used geography as an exclusion criterion amid the EEC enlargements to the European South, while the exclusion of this design also meant the exclusion of Spanish R&D teams from EU R&D funding. From FP2 and for the rest of the first period, CPV received modest funding that supported the research on this alternative technology option. However, this re-introduction of CPV into the R&D programmes came at a time when a major industrial actor from the European North (BP Solar) entered the PV business and expressed interest in CPV R&D. During the first period, a variety of solar cell materials were explored for different CPV systems. With c-Si cells coupled to low and medium CPV systems and Si-Ga(Al)As proposed for HCPV systems, the focus was on the former. BP Solar was one of the first actors to envisage LCPV for building facades, paving the way for small-scale PV systems for countries of the Global South. However, this also meant that LCPV with c-Si cells were a direct competitor to the dominant PV technology (i.e. c-Si flat place).

CPV were seen as a technology for large-scale installations. This understanding gradually begun to change towards the end of the first period when BP Solar attempted to place LCPV on rooftops. As we have argued, the actors of the c-Si networks pursued research and actively promoted this technology through an understanding of how this technology could reconfigure the architecture of the energy system. Thus, in the early days of CPV development, the applications of this alternative design were in direct contrast to the applications of the dominant technology. The limited application possibilities of CPV leading to large-scale installations can help us attribute a different meaning to the marginalization of this technology. Essentially, this design was marginalized because it limited installation options while promoting large-scale PV. Being an 'obstacle' to the potential of further energy market liberalization and energy system reconfiguration.

In the second period, the coupling of system and solar cell material 'settled'. The shift from LCPV systems and c-Si cells to HCPV systems and III-V multijunction cells during the second period involved a shift in (i) the uses and applications of the technology, (ii) the energy policy options they offer, (iii) scale of the systems. In an effort to break the dominant technological path of c-Si flat plate PV, favoured by EU funding schemes and the well-vested interests of electronics industry actors, CPV moved away from the use of c-Si solar cells. LCPV was a potential competitor to the dominant c-Si flat-place, which had the potential for similar to flat plate PV (e.g. rooftops and BIPV). Considering the uses and applications of LCPV systems, they simultaneously offered energy policy with the option of small-scale installations.

Using the same material (i.e. c-Si) in a different way and design, CPV struggled to find a place in both R&D programmes and the market. Early efforts to demonstrate the potential of this technology were halted by the private actors in the dominant technology. Especially in the first period, its development was hampered by the limited EC R&D funds, which made CPV a marginalised technology, whereas in FP1 CPV was excluded.[747] It was only when BP Solar, a private sector actor from Northern Europe, joined the CPV activities that this technology managed to get a share of EU R&D funds. The lack of supply of cells supply for CPV systems has also limited standardization efforts.

The shift in R&D away from LCPV systems and c-Si cells towards HCPV systems with III-V multijunction solar cells in the second period can be attributed to two complementary reasons. First, a technological option using different semiconductors and much smaller amounts of raw material for the solar cells provided fertile ground for mitigating or overcoming part of the problems created by the silicon crisis in PV. At the same time, the shift in materials used for the solar cells provided a clear differentiation from the dominant PV technology. By bringing the issues of efficiency and performance to the fore, CPV proponents turned in their favour the arguments that had traditionally been used in favour of c-Si. C-Si traditionally formed the basis for measuring the efficiency and performance of PV. All other new entrants had to compete with these measurements, which had developed for c-Si. The superiority of HCPV III-V

---

[747] This happened in a time when the attention shifted to responding to the Japanese competition with increased funding to thin films and especially a-Si. However, this shift in R&D funding that is well justified in terms of transnational competitions is found short when considering that this was the period of the EU enlargements in the European South. Thereby constituting the exclusion of CPV under FP1, developed by the Spanish, as a Southern marginalisation from accessing the EU R&D funding and from developing an alternative technology.

multijunction cells based on these measurements was a direct scientific response in favour of CPV.

Second, the coupling of III-V multijunction solar cells with HCPV systems has enabled the establishment of this (niche) technology option in the market while delineating its uses and applications (i.e. creating a clearly defined market for it). The move towards III-V multijunction solar cells meant a parallel move towards HCPV systems to underpin the arguments for their efficiency and performance, while defining their respective uses and applications. In addition, the use of these semiconductors enabled CPV actors to gain a greater share of R&D funding – as evidenced by increased EU R&D funding for CPV – while helping to establish a distinct scientific culture and/or research group within the PV sector.

Parallel to the above changes, the character of research – also for CPV – changed in the second period shifted. The SRAs legitimized both the technical changes and the reorientation of research that had already begun with FP5.[748] In the case of CPV, these changes manifested in the following ways: (i) they made direct cost references and/or specific cost targets (i.e. EUR/Wp), (ii) they aimed at stimulating (mass) production by including either a pre-commercial production of CPV cells or pre-commercial production lines. The changing aims of the projects certainly testify to the changing character and use of research policy in the second period. In this way, research moved closer to the market and significantly narrowed the gap between the two. Research that could shorten the value chain was prioritised (i.e. the development of near-market products directly from the research projects). This was expressed mainly through the constant emphasis on innovation and linking research to the market and industrial production. This is also reflected in research policy through the recurrent efforts to facilitate the integration of RES technologies into the electricity grids and the implementation of PV (i.e. increasing cell efficiencies). Apart from the focus placed on delivering near-market products or production lines and the general focus placed on production issues, the projects sought to cover the entire value chain. In the case of CPV, the silicon feedstock was not a problem to be researched. Rather, the shift to III-V semiconductors was the CPV network's response to the Si crisis. Nevertheless, the projects covered a broader spectrum of the value chain, similar to the case of c-Si in the second period.

Efforts were also made to find the possible and perhaps most suitable applications for CPV. In other words, the research projects actively tried to link each CPV system to specific markets by trying to link them to their potential applications. Concerning the latter, applications are

---

[748] For the analysis of the SRAs see chapter 2.

very diverse, ranging from large-scale grid-connected power plants, to (stand-alone) water pumping and irrigation to the use of CPV in industrial and residential areas, to (limited) BIPV-specific references. The efforts to determine the best uses for CPV in terms of the materials used for the cells and the corresponding costs concerned the R&D projects of the second period. The durability of III-V semiconductors at higher temperatures than c-Si, combined with the tracking systems used for maximizing the energy yield of HCPV, have helped reinforce the notion of CPV as a technology of the European South and for the Global South. However, with a twist! Casted as response to the silicon crisis, the actors from CPV contributed to the understanding the system-cell shift as an advantage that allowed them to distance themselves from the dominant PV technology. By establishing HCPV as a technology for the South, they were able to simultaneously establish clear and direct links and delineate the market and deployment options for this technology. As the technological pathway had already been structured/shaped by the EC R&D funding (i.e. c-Si flat-plate) and incorporated the well-vested interests of industrial actors from the electronics industry, CPV actors shifted their research to III-V multijunction cells for HCPV systems. Since the III-V materials are more expensive, the small area of the concentrator cells enabled taking advantage of their properties. This was a way to compete with the dominant c-Si technology and its proponents.

The dominant technological pathway reinforced and/or promoted by the EC R&D, had specific geographical ramifications that led to the marginalisation of the European South. As we have seen, Spain and Italy were the proponents of CPV R&D. These two Southern European countries turned to CPV for different reasons and needs. They essentially arrived at the same point (i.e. priority for CPV) from different starting points. The Spanish R&D priorities were set bottom-up and were integrated into the national energy policy. The priorities aimed at leveraging domestic know-how and expertise on CPV and made concrete links to this selection with the Si crisis. To this end, the focus was placed on the decades-long scientific tradition in CPV, which had developed into an important European centre of competence for CPV. Moreover, this scientific expertise formed the basis for the industrial development of CPV.

In contrast, Italy, a country with a semiconductor electronics industry, had traditionally been involved in c-Si activities and development. The lack of national resources to fund PV R&D funds and the looming silicon crisis, which practically exposed Italian industrial actors to the pressure of rising silicon feedstock prices, as well as ENEA's interest in CPV, formed the basis for promoting CPV. Using domestic know-how and expertise with III-V cells for space applications (through CESI) as a means to diversify the domestic market and scientific landscape. These changes in the Italian framework provided a solid basis for the turn towards CPV that became evident in the second period.

The CPV technoscientific research networks differ strikingly from the c-Si networks. Instead of large research centres, in the case of CPV a university forms the core of the networks. The UPM-IES is a unique case of a university playing a central role in the EU-funded technoscientific networks. This can be attributed to the close relationships UPM had forged with industry and the entrepreneurial spirit of Luque, who sought to commercialize his research early on, leading to the creating of a spin-off. The Spanish-led projects and their prominent role in the overall EU CPV R&D activities demonstrate Spain's central role in setting the research agenda for CPV. Spain became the European knowledge hub for CPV through UPM-IES.

Despite the differences between the two case studies due to the different problems they had to address and resolve, and the different stages of commercialization of the technologies, they share common features in terms of the conclusions we can draw about how the changing political economy for research has affected research and the research networks. In both case studies, research in the second period was widened to include more steps of the value chain. Addressing and solving production issues, which in turn affect 'where' innovations are made. Minimizing the time lag between research and market while encouraging collaborations that can address this. In the c-Si case, we saw that the above changes led to large research centres forming the core of the networks. In the CPV case, a university that had the capacity and the necessary connections to commercialize its research was the core.

References

Azur Space, azurspace, *Welcome*, Available online: http://www.azurspace.com/index.php/en/, (accessed 11 May 2021).

Barciela Fernando, 17 June 2013, El Pais, *Total eclipse of the sun*, Available online: https://english.elpais.com/elpais/2013/06/17/inenglish/1371471362_164500.html, (accessed 13 April 2021).

Belluque J. and Michel J., "Optimisation d'un ensemble concentrateur cellules solaires au silicium", CECA-CEE-CEEA (Brussels, Luxembourg: 1982).

Bloomberg, *Euroinks srl*, Bloomberg. Available online: https://www.bloomberg.com/profile/company/1523Z:IM, (accessed 10 May 2021).

Call for tenders (C50), 28 February 1980, Official Journal of the European Communities.

Castello S., De Lillo A., Li Causi L., De Lia F., Tucci M., Guastella S., Paletta F., "PV Market, Industry and Research in Italy", *in* 24th European Photovoltaic Solar Energy Conference, 21-25 September 2009, Hamburg, Germany, Sinke W., Ossenbrink H., Helm P. (eds.), WIP Renewable Energies: 2009, p. 4427-4430.

Commission of the European Communities, *Assessment Report on the Community Demonstration Projects in the fields of Energy Saving and Alternative Energy Sources*, COM (82) 324 final/3, Brussels, 17 June 1982.

Crespo L., "Spanish National Photovoltaic Program", *in* Seventh EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Sevilla, Spain, 27-31 October 1986, A. Goetzberger, W. Palz, G. Willeke (eds.), Kluwer Academic Publishers, (Dordrecht, Boston, Lancaster, Tokyo: 1987), p. 1177-1184.

De Lillo A., Li Causi S., Castelllo S., Guastella S., "PV activities and future development in Italy", *in* 20th European Photovoltaic Solar Energy Conference, 6-10 June 2005, Barcelona, Spain, Palz W., Ossenbrink H., Helm P. (eds.), WIP-Renewable Energies: 2005, p. 3099-3102.

De Lillo A., Castello S., De Lia F., Guastella S., Paletta F., "Status and Perspectives of PV in Italy", *in* 25th European Photovoltaic Solar Energy Conference and Exhibition/5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Valencia, Spain, De Santi G. F., Ossenbrink H., Helm P. (eds.), WIP Renewable Energies: 2010, p. 5344-5347.

Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market, Official Journal of the European Communities, 27.10.2001.

Duvauchelle Christophe, Fraisse Jean-Luc, Barlier Yves, "Photovoltaic Integration in the Distribution Grid French Regulation and Network Requirements", *in* Twenty second European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Milan, Italy, 3-7 September 2007, G. Willeke, H. Ossenbrink, P. Helm (eds.), WIP Renewable Energies: 2007, p. 3505-3511.

Fabre E., Smet De L., Mertens R., "High Intensity Silicon Solar Cells", *in* Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Luxembourg, September 27-30, 1977, D. Reidel Publishing Company (Dordrecht, Holland/Boston, USA: 1978), p. 249-258.

Ferrazza F., De Lillo A., Farinelli U., "The Italian PV R&D Programme: Status and Perspectives", *in* 29th IEEE Photovoltaic Specialists Conference, 19-24 May 2002, New Orleans, USA, p. 15-20.

Fraunhofer ISE Press Release, 30 November 2018, ise.fraunhofer, Professor Adolf Goetzberger turns 90: Pioneer of the Energy Transformation and Founder of Fraunhofer ISE, Available online: https://www.ise.fraunhofer.de/en/press-media/press-releases/2018/professor-adolf-goetzberger-turns-90-pioneer-of-the-energy-transformation-and-founder-of-fraunhofer-ise.html, (accessed 12 May 2021).

Fraunhofer ISE, *Photovoltaics Report*, Freiburg: 16 September 2020.

Gaiddon B., "New legal framework and market perspective for grid connected PV in France", *in* Seventeenth Photovoltaic Solar Energy Conference, Proceeding of the International Conference held in Munich, Germany, 22-26 October 2001, B. McNelis, W. Palz, H. A. Ossenbrink, P. Helm (eds.), Vol I, WIP-Munich and ETA-Florence: 2002, p. 911-913.

Gaiddon B., l'Epine M. de, Jediczka M., "The Photovoltaic Market in France", *in* Twentieth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Barcelona, Spain, 6-10 June 2005, W. Palz, H. Ossenbrink, P. Helm (eds.), Vol II, WIP Renewable Energies (Germany: 2005), p. 3064-3067.

Institute for Concentration Photovoltaics Systems, isfoc, *History*, Available online: http://www.isfoc.net/index.php/en/isfoc-2/global-presentation/history, (accessed 13 April 2021).

Instituto de Energia Solar (Universidad Politecnica de Madrid), ies.upm, *40 years leading PV solar energy: History*, Available online: https://www.ies.upm.es/IES_UPM/History, (accessed 13 May 2021).

Kurtz S., *Opportunities and Challenges for Development of a Mature Concentrating Photovoltaic Power Industry*, Technical Report NREL/TP-520-43208, November 2009.

LaMonica Martin, 21 December 2011, CNET, *Another one bites the dust: BP Solar shuts down*, Available online: https://www.cnet.com/news/another-one-bites-the-dust-bp-solar-shuts-down/, (accessed 7 April 2021).

Luque A., "Photovoltaics and its Research and Development Structure in Spain: the situation in 1988", *Solar Cells*, 1989, p. 107-123.

Ministerio de Industria, Turismo y Comercio - Instituto para la Diverficación y Ahorro de la Energía, Plan de Energías Renovables en España 2005-2010, Agosto de 2005.

Munoz E., Vidal P. G., Nofuentes G., Hontoria L., Perez-Higueras P., Terrados J., Almonacid G., Aguilera J., "CPV standardization: An overview", *Renewable and Sustainable Energy Reviews*, 2010, p. 518-523.

Nakopoulou E. and Arapostathis S., "Reconfiguring technologies by funding transitions: priorities, policies, and the renewable energy sources in the European Community funding schemes", *Journal of Energy History / Revue d' Histoire de l' Énergie* [Online], n°4, published 27 July 2020.

Palz W., "Overview of the European Community's Activities in Photovoltaics", *in* Fourth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Stresa, Italy, 10-14 May 1982, W. H. Bloss and G. Grassi (eds.), D. Reidel Publishing Company (Dordrecht, Holland/Boston, USA/London, England: 1982), p. 3-8.

Pérez-Higueras P.J., Muñoz E., Almonacid G., Vidal P.G., Banda P., Luque-Heredia I., Valera P., Cabrerizo M., "A Spanish CPV Regulatory Framework: Proposal of a Feed-in Tarriff", 25th European Photovoltaic Solar Energy Conference and Exhibition/5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Valencia, Spain, De Santi G. F., Ossenbrink H., Helm P. (eds.), WIP Renewable Energies: 2010, p. 5421-5424.

Pérez-Higueras P.J., Muñoz E., Almonacid G., Vidal P.G., "High Concentrator PhotoVoltaics efficiencies: Present status and forecast", *Renewable and Sustainable Energy Reviews*, 2011, p. 1810-1815.

Pfeifer Sylvia and Clark Pilita, 21 December 2011, Financial Times, *BP to exit solar business after 40 years*, Available online https://www.ft.com/content/80cd4a08-2b42-11e1-9fd0-00144feabdc0, (accessed 7 April 2021).

Philipps Simon P., Bett Andreas W., Horowitz Kelsey, Kurtz Sarah, "Current Status of Concentrator Photovoltaic (CPV) Technology", Fraunhofer ISE and NREL, Version 1.2, February 2016.

Ricerca Sistema Energetico, RSE, *70 Anni di Tradizione nella Ricerca*, Available online: http://www.rse-web.it/storia.page, (accessed 8 May 2021).

Sala G. and Luque A., "Past Experiences and New Challenges of PV Concentrators", *in* Concentrator Photovoltaics, Antonio L. Luque and Viacheslav M. Andreev (eds.), Springer (Verlag, Berlin, Heidelberg: 2007), p. 1-23.

Salas V., Olias E., "Overview of the photovoltaic technology status and perspective in Spain", *Renewable and Sustainable Energy Reviews*, 2009, p. 1049-1057.

Sanchez Fernando, "Spanish National Photovoltaic Program", *in* Ninth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Freiburg, Fed. Rep. of Germany, 25-29 September 1989, W. Palz, G. T. Wrixon, P. Helm (eds.), Kluwer Academic Publishers, (Dordrecht, Boston, London: 1989), p. 1195-1196.

Sarno A., Apicella F., Cancro C., Fucci R., Pascarella F., Pellegrino M., Privato C., Roca F., The PhoCUS Standard Unit: Design, Realization and Preliminary Performance Analysis, *in* 20th European Photovoltaic Solar Energy Conference, 6-10 June 2005, Barcelona, Spain, Palz W., Ossenbrink H., Helm P. (eds.), WIP-Renewable Energies: 2005, p. 2032-2034.

Schuster G., "The Future of Photovoltaics in Europe", *in* Third EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes France, 27-31 October 1980, W. Palz (eds.), D. Reidel Publishing Company, (Dordrecht: Holland/Boston: USA/London: England: 1981), p. 4-9.

Silvestrini G., Gamberale M., Frankl P., "Italian PV Roof Programme: First Results", *in* 17th European Photovoltaic Solar Energy Conference, Munich, Germany, 22-26 October 2001, McNelis B., Palz W., Ossenbrink H. A., Help P. (eds.), Vol. III, WIP Renewable Energies and ETA: 2002, p. 2371-2374.

Swanson Richard M., "Photovoltaic Concentrators", *in* Handbook of Photovoltaic Science and Engineering, Antonio Luque and Steven Hegebus (eds.), John Wiley & Sons (England: 2003), p. 449-503.

Treble F. C., "The future of Photovoltaics: A Report on the Panel Discussions", *in* Fifth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Kavouri (Athens), Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 26-32.

Wiesenfarth Maike, Philipps Simon P., Bett Andreas W., Horowitz Kelsey, and Kurtz Sarah, "Current status of concentrator photovoltaic (CPV) technology", April 2017 (version 1.3), Fraunhofer ISE and NREL.

Wilson H. R. and Wittwer V., "Conversion of Solar Energy Using Fluorescent Collectors: Installation of a Test Collector to Deliver Several Watts Power", *in* Photovoltaic Power Generation, Proceedings of the EC Contractors' Meeting held in Brussels, 16-17 November 1982, R. Van Overstraeten and W. Palz (eds.), Vol III, D. Reidel Publishing Company (Dordrecht, Holland/Boston, USA/ London, England: 1983), p. 267-227.

Wolfe Philip R., "Profiles of Early PV Companies and Organizations", *in* The Solar Generation: Childhood and Adolescence of Terrestrial Photovoltaics, John Wiley & Sons, Inc. (Hoboken, New Jersey: 2018), p. 199-270.

Chapter 7. Material politics and geopolitics in PV: the dependency of the Global North to the Global South in achieving the RES transition

7.1 The material intensive side of the RES transition in PV

Raw materials are a key ingredient of modernization and industrialization.[749] As the EU seeks to foster the transition to RES, the demand for raw material for low-carbon energy technologies is increasing and is be expected to continue to increase. As we have already seen in Chapter 5, the European Commission's inclusion of RES in the energy policy map, which required and/or presupposed the upscaling of the production of PV cells/modules, has led to a raw material crisis (silicon crisis in PV).

> "Materials research and control over materials resources is becoming increasingly important in the current global competition for industrial leadership in low carbon technologies."[750]

Indeed, 'control over material resources' is crucial to achieving the EU's (long-term) zero-carbon emissions energy strategy. Given that RES is at the core of the EU's energy transition, of which solar PV is an important pillar, securing the raw materials is needed for these key energy technologies is of utmost importance. However, as we will analyze in the following sections, securing an adequate supply of raw materials for the core technology of PV (polysilicon feedstock for c-Si cells) has been far from unproblematic.

In 2011, the European Commission's JRC published a report on the critical metals for the (six) energy technologies recognized in the SET-Plan as key to the (low-carbon) energy transition.[751] Although solar PV technologies were studied and included in the report to inform future EU R&D activities and priorities, there was a major gap. Although the geographic concentration of minerals (and thus their supply) was recognized as critical to achieving the goals of the SET-

---

[749] Frank Verrart and Stathis Arapostathis, "Entangling Technological Infrastructures, Material Flows and Environmental Modernities", ToE Conference, 2022.

[750] European Commission, *Materials Roadmap Enabling Low Carbon Energy Technologies*, Brussels, 13.12.2011, SEC(2011) 1609 final, p. 1.

[751] R. L. Moss, E. Tzimas, H. Kara, P. Willis, J. Kooroshy, *Critical Metals in Strategic Energy Technologies: Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies*, Publications Office of the European Union (Luxembourg: 2011).

Plan objectives, silicon, the most important material required for the dominant PV technology – and recognized as such in the report – was not included in the study.[752]

Silicon is the second most abundant element.[753] However, as we will see in the following analysis, the production of silicon (polysilicon feedstock) has led to a material shortage and a material crisis, while the production of PV solar cells using (crystalline) silicon has gradually become geographically concentrated. By examining the entire PV production chain and material flows of silicon (from mining to cell/module production and installation), we aim to trace the geopolitics for PV and how is has impacted EU PV research policy priorities and activities. To this end, we pose the following research questions: How has the entanglement of the global extractive industries with the European energy industry impacted EU R&D priorities and funding? How have material flows for PV been reconfigured as the EU seeks to implement the RES transition? What role has the mineral geopolitics played in shaping EU research policy for solar PV technologies?

Based on our analysis, we find that both production and installation have gradually shifted from regions in the Global North to regions in the Global South.[754] Similarly, the origin of mineral for all other minerals required for other PV solar cells (and different PV technologies) has also shifted. As the production of these important minerals (and their by-products) becomes more geographically concentrated in regions of the so-called Global South, there are geopolitical implications – for meeting the material needs required for the transition to RES. Moreover, this changing geopolitical dynamic challenges the previous division between the Global North and the Global South. As we argue, the gradual transfer of increasingly more of steps of the PV production chain to regions of the Global South has led to material dependencies, while at the same time it has led to a shift in geopolitical dynamics that has implications not only for the successful implementation of the RES transition, but also for EU economies.

---

[752] The rationale behind the selection of the minerals that were examined (and by extension the selection of the minerals not included, even though not stated) was the following: "The study identifies 14 metals for which the deployment of the six technologies will require 1% or more (and in some cases, much more) of current world supply per annum between 2020 and 2030." (R. L. Moss, E. Tzimas, H. Kara, P. Willis, J. Kooroshy, *Critical Metals in Strategic Energy Technologies: Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies*, Publications Office of the European Union (Luxembourg: 2011), p. 5). No justification was provided nor was the criterion employed justified or its significance assessed.

[753] Schnebele Emily, 11 January 2018, Earth magazine, *Mineral Resource of the Month: Silicon*, Available online: https://www.earthmagazine.org/article/mineral-resource-month-silicon/, (accessed 1 March 2021).

[754] When referring to the Global North-South we employ the division by the United Nations. Despite the 'simplicity' of this division, we do not insinuate that there are not inequalities in-between regions within a country, across peripheries etc. (Rory Horner and Padraig Carmody, "Global North/South", *in* International Encyclopedia of Human Geography, (2nd ed.), Volume 6, Audrey Kobayashi (eds.), Elsevier (2019), p. 181-187). Rather, this division enables us to trace the direction of the material flows on a macro scale.

7.2 Following the material flows: material dependencies and changing geopolitical dynamics

In the following sections, we first examine two events related to the supply of silicon feedstock (polysilicon) that affected the PV sector. The first event was a material shortage in the 1980s and the second event was a raw material crisis in the 2000s (sections 7.2.1.1. and 7.2.1.2, respectively). Next, we analyse the geography of the extraction of all materials/minerals needed for PV cells (section 7.2.2). This is followed by the other steps of the PV production chain for silicon, which is the dominant technology (sections 7.2.3-7.2.4).

After examining the PV production steps, we analyse and account for the externalities resulting from all these steps (section 7.2.5), which we complement with a step that comes 'after' the production cycle: recycling. We then examine the responses of the PV research networks to the Si crisis. In particular, the analysis in section 7.2.6 allows us to determine whether PV research networks have included the dimensions of the geopolitics of raw materials and the externalities of the PV production chain in their research. In other words, whether these dimensions are also part of the research priorities and the decisions made by the networks. We then proceed with the placement of RES and PV in the EU's energy vision and long-term strategy (and electricity production mix) (section 7.2.7). The focus is on the PV market and the material possibilities offered by the different PV technologies in combination with the users they construct. The attention is on the engagement of users in the design of energy policy and in setting the respective targets. Before reaching our final conclusions, we provide a brief analysis of the recent geopolitical incidents between the EU and China, for the key PV technology (c-Si flat plate PV) (section 7.2.8).

7.2.1 Pressures along the silicon supply chain: the silicon feedstock shortages of the 1980s and the silicon crisis in PV

In the following sections, we analyse two events that caused pressure along the silicon feedstock supply chain. The first event took place in the 1980s and was the result of the unprecedented growth of the electronics industry, especially through the development of the personal computer. This growth in turn caused pressure on the supply of silicon feedstock. In response to this event, the EU redirected its research policy in favour of a-Si. Both the silicon feedstock shortage and the Japanese developments on the a-Si front played a catalytic role in the EU's decision to shift its R&D (and funding) to a-Si during FP1.

The second event was a direct consequence of the inclusion of RES (and PV in particular) in the EU's energy policy map through the White Paper for RES in 1997. By setting installation targets for PV, the introduction of an energy policy that included RES gave the PV sector the green light to become industrial (in terms of production). In other words, in order to meet the energy policy targets set by the EU, the PV sector had to rapidly increase its production rapidly, which led to a shortage of silicon feedstock. This was reflected in the prices of silicon feedstock, which skyrocketed in the mid 2000s. This time, the PV sector was responsible for the increase in silicon feedstock prices and caused pressure on the silicon feedstock pipeline supply. In the previous chapters, we have analysed in detail how the introduction of an energy policy for RES affected the research priorities for PV and how the actors that formed the technoscientific research networks for c-Si and CPV responded to the pressure of upscaled production (Si crisis). In the following sections, the focus is on the Si crisis along the production chain.

7.2.1.1 The Si feedstock shortage caused by the electronics industry: the EU research response

> "**The 1980s were a time of extraordinary growth as well as some angst in the semiconductor industry**. Chip sales skyrocketed from about $10 billion in 1979 to $100 billion by the early 1990s. **The personal computer**, introduced in 1981, **was a mainstream product by the end of the decade**. **Consequently, demand for microprocessors, logic and DRAM exploded**."[755] (emphasis added)

In the early 1980s, the 'computer boom' had a significant impact on the supply (and demand) of silicon feedstock. The personal computer, introduced in the early 1980s, led to the unprecedented growth in the semiconductor industry. However, to cope with this growth, larger quantities of silicon feedstock were needed. This happened at a time when the PV industry was still in its infancy. As we have seen in Chapters 4 and 5, the EU 'traditionally' prioritized c-Si research, which was supported by actors who had expertise, know-how and interests in silicon. During FP1, the EU made a 'U-turn' in its research policy and for the first time prioritized a

---

[755] Joint Electron Tube Engineering Council, JECED, *JEDEC History – 1980s*, Available online: https://www.jedec.org/about-jedec/jedec-history/1980s, (accessed 10 November 2020).

different: a-Si (thin film). Although it was different technology, the choice of material for the solar cell remained the same – only in a different purity: silicon.

> "The **silicon solar-cell industry depends on the same polycrystalline silicon industry that supplies the silicon integrated-circuit industry** with its raw material. **In the past, and probably in the near future** (through 1988), **the silicon solar-cell industry will use "reject" polycrystalline silicon**. This reject silicon consists of virgin material that does not meet integrated-circuit specifications in some particular area, such as in boron, phosphorus or carbon concentration. This deficiency generally does not degrade solar cell efficiency. As much as 5% of all semiconductor-grade polycrystalline silicon manufactured is rejected because of tight silicon crystal specifications for the integrated-circuit industry; most silicon-crystal growers achieve single-crystal yields of only 60%. Some 20% of crystal yield loss is recoverable and satisfactory for growing crystal for silicon solar cells."[756] (emphasis added)

The feedstock used for the production of c-Si wafers for the semiconductor electronics industry was – and is – exactly the same as that for the PV industry. The PV industry depended on the semiconductor electronics industry to supply its silicon feedstock. More specifically, on their scraps or rejects, which was of lower purity and could not be used by the electronics industry, especially for the production of integrated circuits. Due to the rapid growth of the semiconductor electronics industry in the 1980s, silicon feedstock shortages and a simultaneous price increase were expected. As PV was the new sector, it was not yet firmly established in the supply chain of its main raw material. This dependence was not predicted to change, at least not until the end of the decade. The main consumer of the silicon feedstock was the semiconductor electronics industry.[757] Because of anticipated supply problems and

---

[756] E. N. Costogue, R. R. Ferber, "Polycrystalline Silicon Material Availability and Market Pricing Outlook for 1980 through 1988", *in* Fifth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Kavouri (Athens), Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 1028.

[757] By 1985, the PV industry was supplied with a mere 3% of the total Si produced. This number is indicative of the PV industry's small share in the Si feedstock and thus its less advantageous role in exerting pressures to Si feedstock prices.

price increases, the US DoE commissioned the Jet Propulsion Laboratory to conduct a study, which was published in late 1979.[758] As the authors of the study stated:

> "**Because of the dominance of the silicon material market by the semiconductor device manufacturers who need highly pure and damage free silicon**, it would appear that **little will be done to provide solar-grade material without a substantial impetus from government or the solar cell industry**."[759] (emphasis added)

The semiconductor electronics industry was an older, richer industry. As such, its actors were better able to respond and/or adapt to price increases and in this case they were the ones causing them. More importantly, the semiconductor electronics industry did not require as much active material for a single product as the PV industry did; the solar cell was the most important component of the PV technology. Precisely because of the dominant and powerful role of the semiconductor electronics industry in supplying the silicon feedstock, it had an advantageous position in the supply of this raw material. The increased production of integrated circuits put pressure(s) on the market, which led to price increases. However, as mentioned in the quote above, either governments or the PV industry could have pushed for or supported the/a (possible) solution to the expected silicon feedstock shortage to aid the PV industry. In fact, PV was supported by a handful of PV-advocates from the European Commission, albeit at a limited scale. However, in order for them to take action, they had to ask the PV industry to request help.

The price of silicon feedstock fell from about 500USD/kg in the 1960s to almost 50 USD/kg in 1980 but in April 1980 there was a significant increase in the (spot) price to 140 USD/kg.[760,761] During the same period, production of silicon feedstock increased from 30 tons

---

[758] It is important to note that under the US R&D programme by DoE, the Jet Propulsion Laboratory was managing the Low-cost Solar Array (LSA) project. A crucial objective of this project was to develop new processes for lowering the cost of the feedstock required for the manufacturing of solar cells.

[759] E. Costogue, R. Ferber, W. Hasbach, R. Pellin, and C. Yaws, *Silicon Material Outlook Study for 1980-85 Calendar Years*, Jet Propulsion Laboratory: Report Prepared for the US Department of Energy, (November 1, 1979: JPL Publication 79-110), p. 3-10.

[760] W. Freiesleben, "The solar material market: Projections needs & commitments", *in* Third EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes France, 27-31 October 1980, W. Palz (eds.), D. Reidel Publishing Company, (Dordrecht Holland, Boston USA, London England: 1981), p. 166-170.

[761] E. N. Costogue, R. R. Ferber, "Polycrystalline Silicon Material Availability and Market Pricing Outlook for 1980 through 1988", *in* Fifth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Kavouri (Athens), Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 1027-1031.

in the 1960s to 3000 tons in 1980, while a doubling was forecast for 1983.[762,763,764] These figures, undoubtably evidence of the rapid growth experienced by the semiconductor and electronics industries during these decades. Moreover, they demonstrate the close link between Si feedstock manufacturers and semiconductor electronics and how the two grew together during this period. Not surprisingly, the feedstock used for the semiconductor electronics industry (Si-grade feedstock) was called ‘semiconductor electronics feedstock’.

The silicon feedstock shortage was expected to in 1982-3 when the demand of the non-solar sector was predicted to exceed the available feedstock. If we take into account the increasing production of the PV industry, we can understand how dire the situation was. The shortage forecasts were based on the expected growing demand of the semiconductor electronics industry, which did not match the expected production capacity of silicon feedstock manufacturers. This projected – and expected – shortage, which was a direct result of the expanding semiconductor electronics industry (especially integrated circuits), affected the development of PV. It led to two unintended consequences that changed both the production and the market for PV. First, a response to this pressure came from Japan. As we analysed in Chapter 4, the Japanese directed their R&D towards a-Si. We understand the Japanese response in two interrelated ways. First, a response aimed at solving the feedstock problems in the electronics industry, which also resulted in changes in PV. Second, Japanese success in mass production and commercialization of a-Si cells provided a good justification for expanding the PV programme in Japan, while opening a new market for PV by redirecting it to small electronic devices.[765] At the same time, Japanese competition in Europe attracted attention and prompted the EU to focus its R&D programme on the development of a-Si cells. Essentially, the EU shifted R&D funding to a-Si to respond to Japanese competition while countering projected shortages of silicon feedstock supply. FP1 a-Si activities were intended to translate

---

[762] Overall, in most analyses of the time, the Soviet Union was not included. The data offered here include the Soviet Union.

[763] W. Freiesleben, “The solar material market: Projections needs & commitments”, *in* Third EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes France, 27-31 October 1980, W. Palz (eds.), D. Reidel Publishing Company, (Dordrecht Holland, Boston USA, London England: 1981), p. 166-170.

[764] E. N. Costogue, R. R. Ferber, “Polycrystalline Silicon Material Availability and Market Pricing Outlook for 1980 through 1988”, *in* Fifth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Kavouri (Athens), Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 1027-1031.

[765] When the first Japanese energy R&D programme launched, in response to the 1973 oil crisis, the priority was not solar photovoltaics. Instead, solar thermal energy was prioritised. However, as we argue the fast commercialisation of the a-Si cells provided a ‘good justification’ for increasing both the R&D funding for PV and the further enlargement of the PV research activities.

research directly into production, enabling European companies to compete in the market with their Japanese rivals.

In the 1980s, the silicon feedstock issue gradually gained attention in the international PV community. At the Photovoltaic Solar Energy Conferences of EC (see analysis below) it was recognized as a bottleneck for the future development of PV. These conferences were and still are of particular importance, especially considering that key global representatives of the entire PV community participate and/or attend (i.e. scientists/researchers and industrial scientists) as well as politicians and policy makers. These conferences provided the international PV community with a European-based communication platform and also served as feedback 'tool' for the EC to inform its PV research policy.

During the 3rd EC Photovoltaic Solar Energy Conference, held in France in 1980, silicon feedstock was recognized as a potential bottleneck for the development of PV. Industry representatives and silicon feedstock manufacturers expressed their concerns about silicon feedstock supply. Dr Freiesleben from Wacker represented the viewpoint of the European silicon feedstock industry.[766] The way Dr Freiesleben framed the issue is quite indicative of the way the situation was contextualized:

> "**The most vital problem in further development of photovoltaic markets and applications is the availability of low-cost polycrystalline silicon**. Wacker-Chemitronic is willing **to supply beyond the fall-out from electronics larger quantities of polysilicon for the photovoltaic development at lower prices**."[767,768] (emphasis added)

Wacker one of **the** world's largest producers and suppliers of silicon feedstock in the 1980s, placed the issue of silicon feedstock supply at the heart of the future development of PV. Furthermore, this important global supplier of silicon feedstock explicitly expressed positive support for the future silicon feedstock supply of PV. Wacker's commitment to supporting the PV industry was underpinned or accompanied by the announcement of the expansion of silicon

---

[766] See below analysis on Wacker-Chemitronic & AEG-Telefunken partnership/collaboration, as well as the importance of Wacker as the major European Si feedstock manufacturer.

[767] W. Freiesleben, "The Solar Material Market Projections Needs & Commitments", *in* Third EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes France, 27-31 October 1980, W. Palz (eds.), D. Reidel Publishing Company, (Dordrecht Holland, Boston USA, London England: 1981), p. 166.

[768] Within this context, Wacker through its subsidiary Chemitronic, manufactured and promoted its polycrystalline Silicon feedstock 'SILCO'.

feedstock production in Burghausen and the opening a new plant in Oregon. Despite these measures by Wacker, however, it was acknowledged that the PV industry would suffer from the silicon feedstock shortage.

> “Clearly - the expected fall-out from the material suppliers of the electronics industry did not show up except some - what I would call - "political" actions just to keep photovoltaic research going. **The main problem**, of course, **being that photovoltaics must compete against the higher bidder - which is electronics** - and is running into the dilemma: paying higher prices for getting the material obstructs the goal of expanding (or even developing) the market. In slide No. 5 I am showing an estimated percentage for the "solar share" of electronic grade hyper-pure polycrystalline silicon: at least during the coming decade well below 5 %. **The quantities shown** (up to ~ 300 tons in 1990) **will certainly not allow production of "solar power" in the order of the Mega-watts expected**.”[769] (emphasis added)

The pressure coming from the semiconductor electronics industry not only led to changes in the prices of silicon feedstock, but at the same time limited the future expansion and enlargement of the PV industry. This also affected the potential applications, uses and markets for PV. If the PV industry wanted to overcome the silicon feedstock shortage, even partially, it had to find solutions to other problems. One solution that received a lot of attention in the EU research programmes was to increase the efficiency of the solar cells. Essentially – and perhaps ironically – our PV stakeholders followed the tradition of miniaturization in semiconductor electronics and tried to do the same with PV cells/modules to overcome a problem imposed by semiconductor electronics field.

As F. C. Treble, a PV consultant of EC, remarked regarding Wacker’s solution presented by W. Freiesleben:

> “Dr.W. Freiesleben of Wacker Chemitronic, Burghausen, Germany disclosed in a talk on the silicon market that, **to avoid a bottleneck in supplies for solar**

---

[769] W. Freiesleben, “The Solar Material Market Projections Needs & Commitments”, *in* Third EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes France, 27-31 October 1980, W. Palz (eds.), D. Reidel Publishing Company, (Dordrecht Holland, Boston USA, London England: 1981), p. 167.

> **cells, his company had decided to invest in Silso, their cast polycrystalline silicon.** Expansion had started and capacity next year would be 1800 tonnes/year. For orders of several thousand tonnes, they would offer a price of \$25/kg."[770] (emphasis added)

With this, one of the largest – both on global and European level – producers of silicon feedstock has proposed a concrete strategy to deal with the upcoming impact of the expected silicon feedstock shortages. Concern about the silicon feedstock situation continued until the mid-1980s. During the Sixth EC Photovoltaic Solar Energy Conference in 1985, an entire session was devoted to the silicon feedstock situation.

> "…**silicon feedstock was the essential bottleneck**. The feedstock market was still very much linked to the electronics industry, where prices had been affected by the computer boom. This situation might change but, at the moment, since the silicon suppliers were making most of their money from electronics, there was not much hope for improved supplies for pv. **Investors were reluctant to invest in large scale cost effective production using new cheaper techniques because of the possibility of a change to amorphous silicon**. It was a depressing situation but the risk in manufacturing new types of solar grade feedstock might be kept low by building small plants and this might prove to be a solution to the problem. **If a group of European companies approached the European Commission with a proposal for the production of new material at acceptable cost, the Commission would give it favourable consideration**."[771,772] (emphasis added)

The rapid introduction and commercialization of a-Si by the Japanese, which took on a dimension of international competition, had a second dimension. It is not just that these

---

[770] F. C. Treble, "Summary Report: 1980 Photovoltaic Solar Energy Conference", *in* Third EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes France, 27-31 October 1980, W. Palz (eds.), D. Reidel Publishing Company, (Dordrecht Holland, Boston USA, London England: 1981), p. xxxiii.

[771] F. C. Treble, "Material Problems of the Photovoltaics Industry: A report on panel discussion B", *in* Sixth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in London, UK, 15-19 April 1985, W. Palz and F.C. Treble (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1985), p. 35.

[772] The quote presented is a summary of the main points from the Panel Discussion regarding the material problems, which took place during the Sixth EC Photovoltaic Solar Energy Conference. F. C. Treble summarised the main points of all those who participated in the panel discussion, this is why he uses a past tense.

developments in a-Si challenged the dominance of c-Si in the market. Faced with uncertainty about the potential 'achievements' of a-Si, silicon feedstock producres were reluctant to invest in further silicon feedstock development and capacity expansion. Essentially, a-Si developments – led by the Japanese – have further deepened uncertainties about silicon feedstock shortage. Given the potentially expanding development of a-Si, investors were neither eager to look for nor willing to invest in other alternatives. The development of the first standards for PV, as analysed in Chapter 4, seemed to have played a role overcoming hesitation. When the first standards for PV were published in the mid-1980s, they provided the legitimacy for flat-plate c-Si to be the technology on which the PV sector would be built.

7.2.1.2 The silicon crisis in PV: the first tremors in the raw material supply & the PV sector on the path to industrialization

The temporary silicon feedstock shortage in the 1980s was caused by the pressure imposed by the rapid expansion of the electronics industry, especially the development of the personal computer. In contrast to the temporary feedstock shortage in the 1980s, in this section we deal with the Si crisis in PV. In the years of the Si crisis (2004-2008), demand for silicon feedstock exceeded the supply due to the growing (production) needs of the PV industry. This in turn resulted in an unprecedented increase in the prices of silicon feedstock.

The introduction of an EU energy policy for RES and the targets for PV installations gave the Pv sector the green light to upscale production, which in turn led to the PV industry – this time – being able to 'affect' the prices of silicon feedstock. The German and Spanish programmes and financial incentives contributed significantly to the growth of the European PV market. Additionally, China's dynamic entry into the PV sector played a crucial role in the increasing demand for silicon feedstock and added a new dimension to the international competition.

Foreshadowing the Si crisis in PV: Glimmers of the impeding silicon crisis were foreshadowed in the early 2000s. The European Solar PV Conferences are central to the European and global PV community, attracting politicians, policy makers and the scientific and industrial PV community. During the 2001 European Photovoltaic Solar Energy Conference, an important conference for the European and global PV community that also attracts politicians and policy-makers, industry stakeholders raised issues related to the supply of silicon feedstock.[773] For

---

[773] Aulich H., Schulze F., "Silicon feedstock for the photovoltaic industry", *in* Seventeenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Munich, Germany, 22-26 October 2001, B. McNelis, W. Palz, H. A. Ossenbrink, P. Helm (eds.), Vol. I., WIP-Munich & ETA-Florence, 2002, p. 65-68.

example, two Bayer executives pointed directly to the looming silicon crisis while emphasizing the need for new silicon feedstock.[774] In the same year, the European Photovoltaic Industry Association (EPIA), during a Workshop discussing their forthcoming Roadmap, made direct reference to the impeding silicon feedstock and the need to find solutions.[775] In addition, a 2002 article in one of the most important journals for solar photovoltaics, Solar Energy Materials & Solar Cells, states:

> "[...] the **feedstock used to date** [...] **is already limiting the PV market expansion even if a true shortage is not expected before 2004-2005** according to a 'low growing PV market scenario'. This conclusion implies that **a new silicon feedstock not depending on electronic grade silicon production chain must be available on the market from the years 2004 to 2005**."[776] (emphasis added)

The dire need for an silicon feedstock independent of the electronics industry for the ever-growing needs of the PV industry is evident from the above quote. In addition to all these platforms, and in recognition of the same problem, the European Commission played a catalytic role, especially in mobilising all relevant actors to find solutions. In this context, the PVNET was established with the task of setting an (EU) R&D roadmap. PVNET consisted of actors from the European PV community (i.e. industry, research centres and universities) who could communicate with each another through a single platform. In the workshops and meetings held to cerate the EU PV R&D roadmap, the issue of securing silicon feedstock was given the highest priority.[777]

To monitor the international PV research, production and market situation, the EC's Joint Research Centre (JRC) started publishing annual PV status reports in the early 2000s. The

---

[774] Koch W., Woditsch P., "Solar grade silicon feedstock supply for PV industry", *in* Seventeenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Munich, Germany, 22-26 October 2001, B. McNelis, W. Palz, H. A. Ossenbrink, P. Helm (eds.), Vol. I., WIP-Munich & ETA-Florence, 2002, p. 73-76.

[775] EPIA was renamed into SolarPower Europe in 2015; upon celebrating the Association's 30th birthday. Unfortunately, when EPIA was renamed the initial website of the Association changed. As such, the files provided by the EPIA website are not easily obtainable. The information about EPIA's Workshop and its content (i.e. the need for finding solutions to the impeding Si feedstock crisis) was obtained by the FP5 PV R&D project NESSI.

[776] Woditsch P., Koch W., "Solar grade silicon feedstock supply for PV industry", *Solar Energy Materials & Solar Cells*, 2002, p. 11.

[777] Regarding the main conclusions and/or findings from these meetings see: European Commission – DG JRC, *PVNET Workshop Proceedings: 'RTD Strategies for PV'*, held at JRC Ispra, 30-31 May 2002.; Arnulf Jager Waldau, "R&D roadmap for PV", *Thin Solid Films*, 2004, p. 448-454.

publication of such reports is at the same time a clear indicator and recognition from EC that the PV sector is becoming industrial.

The silicon crisis was also highlighted in the research proposals submitted in the (already from the) FP5. In these projects, the imminent shortage of silicon feedstock was directly linked to the energy policy goals of the EC. As we analysed in Chapter 5, a number of projects made direct reference to the impeding silicon crisis and explored various ways to overcoming it (e.g. new production methods and processes, techniques to reduce silicon consumption etc.).[778] Concerns about the shortage of silicon feedstock were reflected in the themes and topics of the projects funded. Concerns arising from the silicon crisis shifted research priorities for both thin-film and c-Si cells. Ultimately, this silicon crisis shifted research priorities in favour of thin film cells in funding, as well as in higher research funding for CPV.[779] While funding for thin-film cell research became a priority, research for c-Si still garnered significant amounts of funding. However, the silicon crisis had a major impact on c-Si research. C-Si research shifted to alternative techniques for processing the feedstock and reducing silicon consumption for cell production. Additionally, c-Si research included the use of different substrate materials, reducing the thickness of the wafers and developing cells with a larger surface area. Lastly, the divide between RD&D began to blur during this period, mainly due to the convergence of energy and research policies. Furthermore, the potential of large-scale production became a central evaluation criterion for the selection of projects. In the context of the silicon crisis in PV, the research agenda for c-Si thin films was relaunched.[780] As the authors who proposed the agenda stated:

> "In 2004, […] about 40% of the production capacity for EG-Si goes to the PV-sector (9000 tons out of 26000 tons) and **from 2005 one is facing the risk of a shortage**."[781] (emphasis added)

---

[778] For example, see the following FP5 PV projects: SOLSILC, SPURT and NESSI on https://cordis.europa.eu and https://publications.europa.eu/en/home. We have thoroughly analysed how the EU's initiation of an energy policy including RES impacted the research priorities for PV, as well as how in direct response to the energy policy targets set by the EU the Si crisis in PV was addresses by the EU-funded PV projects.

[779] We are referring to the c-Si thin films agenda.

[780] We have analysed the c-Si thin films agenda in Chapter 5. It was developed as a direct response to the Si crisis in PV, and concurrently as a means of the c-Si actors to steer the research priorities both for c-Si and for thin films.

[781] Poortmans J., Reber S., Gall S., Zahedi C., Alonso J., "European Cluster on High- and Intermediate Temperature Thin-Film Crystalline Si Solar Cells R&D: Overview of Running Projects and Underlying Roadmap", *in* Nineteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Paris, France, 7-11 June 2004, W. Hoffmann, J. L. Bal, H. Ossenbrink, W. Palz, P. Helm (eds.), WIP-Munich & ETA-Florence: 2004, p. 397.

As already analysed in Chapter 5, the c-Si thin film agenda gained prominence in EU-funded research programmes and led to a reconfiguration of the a-Si geographical funding distribution and networks. The actors proposing this agenda placed silicon feedstock shortage at the heart of their research agenda, providing a direct response to the raw materials crisis.

All these predictions became reality in the mid-2000s. The silicon crisis in photovoltaics lasted from 2004 to 2008 and involved the shortage of purified silicon feedstock, which made it difficult for the photovoltaic industry to meet its rapid demand needs for feedstock and caused silicon prices to skyrocket from about USD 24 per kilo in 2003 to USD 500 per kilo in 2008.[782] Soon after, prices began to fall, dropping to USD 50-55 per kilo in 2009 and reaching USD 50-55 per kilo in 2014.[783] At the same time, global production of photovoltaic cells/modules increased significantly, from 744,1 MW in 2003 to 1.195 MW in 2004, all the way up to 7.350 MW in 2008 and 23.500 MW in 2010, with a continuous increase thereafter.[784] Additionally, the consumption of silicon feedstock in the PV industry grew from 4.000 metric tons in 2000 to 17.000 tons in 2007 to about 40.000 tons in 2008.[785] Within eight years, the feedstock consumption of the PV industry increased tenfold. The production of PV cells/modules increased thirtyfold. The silicon crisis arose from the PV industry's increasing demand for silicon feedstock that the silicon manufacturers were unable (or unwilling) to satisfy. This increase in demand was caused by the continuous growth of the photovoltaic industry, both in terms of production capacity and the number of companies.

The Asian tiger is born: the entrance of Taiwan and China into the photovoltaic market was decisive. Their production of PV cell/module was 124 MW in 2004, 1.070 MW in 2007, and about 5,6 GW in 2009.[786,787]

Since 1999, Japan had the leading role in production of PV cell/module until China took the first place in 2006.[788] China has been leading in PV cell/module production at an unprecedented pace, creating a large gap between the first actor – meaning China – and the others. It is worth noting here that the total world PV cell/module production in 2009 was about 11,5 GW, of

---

[782] The 2008 USD price corresponds to 260 EUR and the 2014 USD price corresponds to 12-14 EUR.

[783] Jäger-Waldau A., *PV Status Report 2016*, Publications Office of the European Union (Luxembourg: 2016).

[784] Data drawn from: Jäger-Waldau A., PV Status Reports, issued by the JRC (2003-2017).

[785] Bruno Ceccaroli and Otto Lohne, "Solar Grade Silicon Feedstock", *in* Handbook of Photovoltaic Science and Engineering, Antonio Luque and Steven Hegebus (eds.), Wiley & Sons (Second Edition, UK: 2011), p. 192.

[786] Data drawn from: Jäger-Waldau Arnulf, *PV Status Report 2008*, Publications Office of the European Union (Luxembourg: 2008).; Jäger-Waldau Arnulf, *PV Status Report 2010*, Publications Office of the European Union (Luxembourg: 2010).

[787] A detailed analysis of the market production, regional market shares etc. are analysed in a forthcoming section.

[788] Jäger-Waldau A., *PV Status Report 2008*, Publications Office of the European Union (Luxembourg: 2008).

which 50% was produced in China and Taiwan.[789] An indicator of this large gap between China and the rest are also the corresponding figures for 2016: total world production was 81,9 GW, of which about 60 GW was produced in China and 11 GW in Taiwan.[790]

When we spoke to a Fraunhofer ISE Head of Department about the silicon crisis in PV and how it affected, if at all, the research topics and priorities in Fraunhofer ISE, the interviewee said:

> "More or less, it stayed the same. Firstly, because you have to see that **it was really dramatic because it was a consequence of a success story**, you know?! Si cells because they got cheaper and cheaper as you produce more, the market was growing and therefore there was this shortage in Si. Because **to build an industry for producing raw silicon is even more capital intensive and so they waited some years** – maybe too much time – **in order to scale that up.** But **it was clear that Si cells would not end now, there would be further development and the market would grow further**. So, there was no reason to step out of this topic and the state would also like to know that by that time. There was a kind of coincidence. The second thing is that you have to consider, especially a large institute is a bit like a big ship. You can't change its direction very quickly. […] **But knowing that this shortage would be over sometime and that it still makes total sense to keep on working on (this) topic, there was no reason to change fundamentally**."[791] (emphasis added)

The silicon crisis in PV was *a* or *the* consequence of a success story. The successful industrial upscaling of PV actors and production, to be precise. At the end of the silicon crisis, the PV actors that had survived were truly industrial. The silicon crisis resulted from the PV industry's increasing demand for silicon feedstock, which the silicon manufacturers could not meet. This increase in demand was caused by the continuous growth of the PV industry, both in terms of production capacity and the number of companies.

---

[789] Jäger-Waldau A., *PV Status Report 2010*, Publications Office of the European Union (Luxembourg: 2010).
[790] Jäger-Waldau A., *PV Status Report 2017*, Publications Office of the European Union (Luxembourg: 2017).
[791] Interview with Fraunhofer ISE Head of Department (via Skype), 13 December 2019, London, UK.

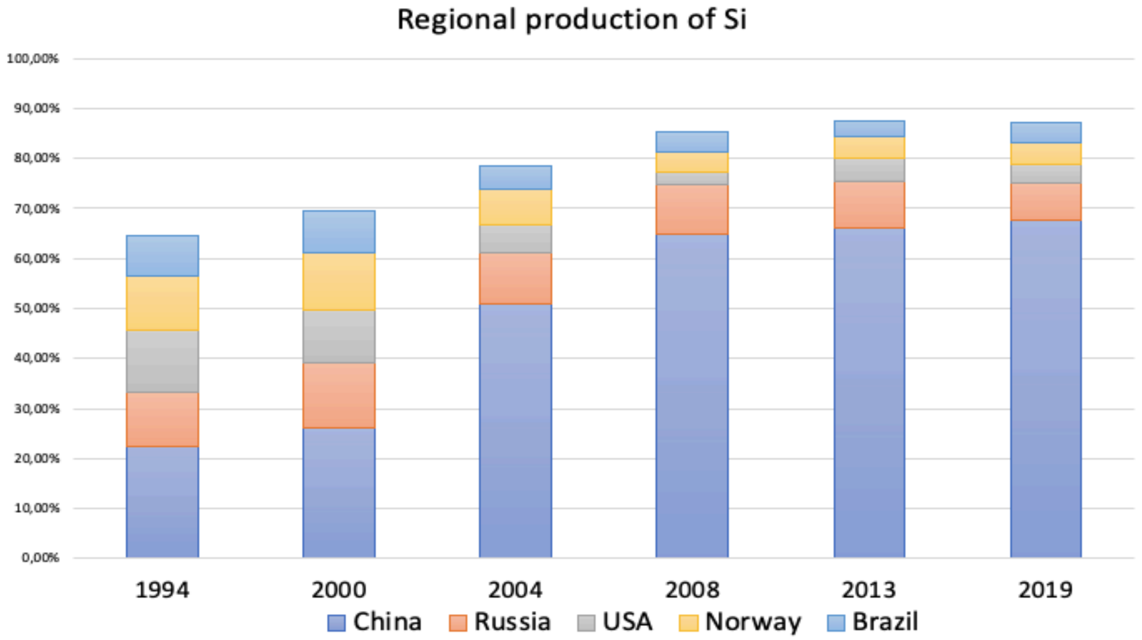


Figure 7.1 Regional production of Si, (1994-2019).[792,793]

However, during the same period (during the silicon crisis years), China increased domestic production of silicon. As shown in Figure 7.1 (above), China's share of silicon increased from 26% in 2000 to 50,81% in 2004, to 64,93% in 2008, to 65,98% in 2013, and finally 67,77% in 2019.[794] Within eight years, China accounted for nearly two-thirds of total global silicon production, becoming the world leader in silicon production.

At the end of the silicon crisis, in 2008, the Commission launched the European Raw Materials Initiative to address the challenges related to non-energy and non-agricultural raw materials.[795] Shortly afterwards, in 2011, the first list of Critical Raw Materials was published.[796,797] What

---

[792] The production share percentages are calculated based on the data from the following USGS Mineral Commodity Summaries: US Geological Survey, "Mineral Commodity Summaries 1996", (Washington DC: US Geological Survey, 1996; US Geological Survey, "Mineral Commodity Summaries 2002", (Washington DC: US Geological Survey, 2002); US Geological Survey, "Mineral Commodity Summaries 2006", (Washington DC: US Geological Survey, 2006); US Geological Survey, "Mineral Commodity Summaries 2010", (Washington DC: US Geological Survey, 2010); US Geological Survey, "2012 Minerals Yearbook: Rare Earths", (Washington DC: US Geological Survey, 2012); US Geological Survey, "Mineral Commodity Summaries 2015", (Washington DC: US Geological Survey, 2015).; US Geological Survey, "Mineral Commodity Summaries 2021", (Washington DC: US Geological Survey, 2021).

[793] Minerals production for selected-top producing regions.

[794] The production share percentages are calculated based on the data from the USGS Mineral Commodity Summaries (USGS, 2002; USGS, 2006; USGS, 2010; USGS, 2015; USGS, 2021).

[795] European Commission, *The raw materials initiative — meeting our critical needs for growth and jobs in Europe*, COM(2008) 699 final, Brussels, 4.11.2008.

[796] European Commission, *Tackling the Challenges in Commodity Markets and on Raw Materials*, COM(2011) 25 final, Brussels, 2.2.2011.

[797] The list has been since revised three times, each time including more raw materials: European Commission, *On the review of the list of critical raw materials for the Eu and the implementation of the Raw Materials Initiative*,

sparked the need for this list was the sharp increase in demand for minerals in the late 2000s and the recognition that raw materials are "crucial" to several sectors and to the future economic growth of the EU. Raw materials were defined as "critical" based on the following criteria: (i) geographical concentration of production, (ii) high risk of supply shortage, (iii) low substitution and recycling rates, and (iv) political and economic instability in the regions supplying the raw materials.[798] Silicon was included in the Commission's second list (2014) and has not been removed since.[799] It is possible that the rare earth incident reinforced the need for these lists and prompted the inclusion of silicon.

The economic importance of silicon has been recognized for a range of uses (e.g. semiconductors, photovoltaics, electronic components etc.) and for various sectors such as textiles, electronics, renewable energy, health, construction and more. These lists enabled the Commission to monitor the supply of raw materials. For this reason, information was provided on the largest producers, the main EU import sources, substitutability, import dependence etc. Based on this data, China was recognized as the largest silicon producer, but not as the main EU importer. In contrast, Norway was listed as the largest EU importer, followed by other regions (e.g. Brazil, France, China, etc.).[800] However, the import shares of silicon refer to production and not extraction, as is the case for other raw materials in the list. Therefore, the data on silicon (and other raw materials) do not match the shares of production and extraction that are combined. As we will see in the following sections, China has become geopolitically empowered throughout the entire PV production chain. Even if Norway processes the imported silicon, Chinas' increasing power in silicon extraction can put further geopolitical and economic pressure on the EU.

7.2.2 Tracing the geopolitics of the PV raw materials: a mining production transfer from the Global North to the Global South

---

COM(2014) 297 final, Brussels, 26.5.2014.; European Commission, *On the 2017 list of Critical Raw Materials for the EU*, COM(2017) 490 final, Brussels, 13.9.2017.; European Commission, *Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability*, COM(2020) 474 final, Brussels, 3.9.2020.

[798] See: European Commission, *Tackling the Challenges in Commodity Markets and on Raw Materials*, COM(2011) 25 final, Brussels, 2.2.2011, p. 12.

[799] This inclusion of silicon as a critical raw materials is a striking difference from the JRC report published in 2011, which concerned the identification of the critical minerals for (SET-Plan) energy technologies and towards the low-carbon transition.

[800] The (average) import shares have changed from one list to the next, but Norway has maintained the leading position steadily since 2012.

Although there is a rich and fruitful body of work on the geopolitics of energy resources, especially oil and gas, and on the implications of the international and transnational dynamics arising from the supply of these critical (energy) resources, there is little work on the geopolitics of minerals required for the transition to RES.[801]

One branch of the literature has examined the general importance of metals and rare earths in the context of geopolitical relations.[802] Another branch has focused on the rare earths needed for specific technologies to implement the RES transition (e.g. wind turbines and batteries) and how they influence and/or reconfigure the global geopolitical relations.[803,804] Lastly, a recent and growing literature has focused on the geopolitics of RES. The focus of this literature is on the reconfiguration of power dynamics between the countries that dominated the scene with formerly dominant energy resources and the ones who will have the 'upper hand' with the transition to RES, and how this shift will affect geopolitical relations in the years to come.[805]

Even though the literature, in one way or the other acknowledges the centrality of the mineral supply to achieving the RES transition, as well as the geopolitical implications associated with their supply, there is a critical gap. They primarily discuss and examine the geopolitical implications of rare earth production and supply, overlooking the importance and geopolitical implications of other minerals critical to the RES transition.[806,807]

---

[801] Regarding the geopolitics of oil and gas, indicatively, see: Correlje Aad and van der Linde Coby, "Energy supply security and geopolitics: A European perspective", *Energy Policy*, 2006, p. 532-43.; Renner Michael, "The New Geopolitics of Oil", *Development*, 2006, p. 59-63.; Kandiyoti Rafael, "What price access to open seas? The geopolitics of oil and gas transmission from the Trans-Caspian republics", *Central Asian Survey*, 2008, p. 75-93.

[802] Looney Robert, "Recent Developments on the Rare Earth Front, Evidence of a new technocratic mercantilism emerging in China?", *World Economics*, Vol. 12, No.1, January-March 2001, p. 47-78.; Habib Komal, Hamelin Lorie, Wenzel Henrik, "A dynamic perspective of the geopolitical supply risk of metals", *Journal of Cleaner Production*, 2016, p. 850-858.

[803] Raman Sujatha, "Fossilizing Renewable Energies", *Science as Culture*, 2013, p. 172-80; Stegen Smith Karen, "Heavy rare earths, permanent magnets, and renewable energies: An imminent crisis", *Energy Policy*, 2015, p. 1-8; Kalantzakos Sofia, China and the Geopolitics of Rare Earths, Oxford University Press (New York: 2018); Manberger Andre and Johansson Bengt, "The geopolitics of metals and metalloids used for the renewable energy transition", *Energy Strategy Reviews*, 2019, p. 1-10.

[804] "The rare earths are a moderately abundant group of 17 elements comprising the 15 lanthanides, scandium, and yttrium." (USGS, 2012, p. 60.1).

[805] Paltsev Sergey, "The complicated geopolitics of renewable energy", *Bulleting of the Atomic Scientists*, 2016, p. 1-6.; Scholten Daniel and Bosman Rick, "The geopolitics of renewables: exploring the political implications of renewable energy systems", *Technological Forecasting & Social Change*, 2016, p. 273-283.; Overland Indra, "The geopolitics of renewable energy: Debunking four emerging myths", *Energy Research and Social Science*, 2019, p. 36-40.; Scholten Daniel, Bazilian Morgan, Overland Indra, Westphal Kirsten, "The geopolitics of renewables: New board, new game", *Energy Policy*, 2020, 111059.

[806] The main trigger behind this literature was the 2009 conflict between China and Japan, which resulted in China to embargo the supply of rare earths, and the concurrent positions of the USA and the EU in the conflict (see Kalantzakos Sofia, China and the Geopolitics of Rare Earths, Oxford University Press (New York: 2018).

[807] Even though we do not examine Silver (Ag) we recognize both its importance in the dominant PV technology. However, Silver and its importance has been examined. For example, see: Andre Manberger and Bengt Johansson, "The geopolitics of metals and metalloids used for the renewable energy transition", *Energy Strategy Reviews*,

The case of PV is an exemplary example of this gap, which has not been empirically analysed and is often mentioned in the literature as a (non-significant) example. PV are the only energy technology for electricity generation that offers another possibility for system integration. They are the only energy technology that can be integrated into the urban environment (e.g. on rooftops), which allows the reconfiguration of the electricity system while constructing different users. In other words, without PV, it would have been impossible to open up energy policy to include smart grids, net metering, etc. Given this unique system integration option PV offers, it is a crucial technology for the implementation of the transition to RES.

The discussions and initiatives that began in the late 1990s to secure the supply of silicon feedstock required for the PV industrial take-off focused on the looming silicon crisis that could jeopardize the development of the PV sector and thus the realization of the energy policy vision for the transition to RES. Even though the silicon crisis resulted in the reorientation of the c-Si research topics and priorities, it also led to the prioritization of thin films in R&D funding as well as concentrating photovoltaics (CPV).[808]

Figure 7.2 (below) shows both the basic minerals and their by-products needed for the various PV solar cell technologies. Our analysis focuses on the materials used for the PV solar cell, not the entire PV system.[809] The reason for this is that firstly, the solar cell is the main PV system component – it can be called the 'heart' of the PV systems. Secondly, but directly related to the former, R&D efforts have focused almost exclusively on the solar cell and its 'improvement'. The rationale was that the solar cell makes for the 'largest contribution to the total cost of a photovoltaic system'.[810] Therefore, research projects rigorously focused on the

---

2019, 100394, p. 1-10.; CRU Consulting, *Market Trend Report: Silver's important role in solar power*, CRU International Limited (UK: June 2020).

[808] CPV are an alternative design option. In contrast to the small flat-plate modules (like c-Si and thin films), CPV concentrate sunlight into a small cell area via lenses. HCPV comprise a complex system configuration, especially because they require tracking systems to 'follow' the sun throughout the day, resulting in large scale installations.

[809] The largest fraction of the PV panels (both c-Si and thin films) comprises of glass. In particular, glass accounts for over 74% and in some cases 95% of the PV panel, whereas for c-Si and CIS/CIGS panels aluminium accounts for an additional 10-12% of the total panel (framing) (European Commission – DG Environment, Study on PV Panels Supplementing the Impact Assessment for a recast of the WEEE Directive, Final Report, 14 April 2011). Glass is made of sand, limestone, and soda ash. Sand (also known as silica sand – SiO_2 – is the same raw material used to produce the c-Si cells, undergoing different processing and refinement methods and different purity requirements) is the main material for the manufacturing of glass. Thus, the above analysis despite focusing on the solar cell, accounts for the largest single fraction (cell, glass and aluminium) of the total PV panel composition as the materials used for the panels are the same as some of the materials used for the solar cell (see Figure 7.2). For an in-depth analysis of the materials used for the manufacturing of glass in the glass industry see: D. A. C. Manning, Raw materials for the glass industry, *in* Introduction to Industrial Minerals, Springer (Dordrecht: 1995), p. 120-140.

[810] Farinelli Ugo, Gelus M., Muus L. T., Rorsch A., Stocker H. J., *The evaluation of the Communities' energy conservation and solar energy R&D sub-programmes*, Office for Official Publications of the European Communities (Luxembourg: 1980), p. 40.

relationship between the solar cell efficiency and the corresponding costs. We must not forget the (main) aim of the EU R&D programmes, which was 'to strengthen the scientific and technological basis of the European industry and to encourage it to become more competitive at international level'.[811] The EU R&D programmes sought to foster synergies at a pan-European (and later international) level to support the European industry. Not surprisingly, the focus of research activities was on solar cells and modules, as Europe had a strong industry.[812] Moreover, the relationship between solar cell efficiency-cost was the starting point for these synergies to make the European industry more competitive.

As indicated in the graphs in Figures 7.3-7.7 (below), the production share from the Global North regions which have traditionally been involved in the mining (extraction) of the minerals required for solar cells, has been steadily declining. In particular, we note that the production share of the Global North regions has steadily declined while at the same time the production share of the Global South regions has steadily increased. As we progress from the 1990s to the 2000s and 2010s, we observe that even those regions of the Global North (e.g. USA, Canada) that continued to produce some of these minerals struggled to keep up with the rising production rate of Southern regions. This is mainly due to the pace that at which the regions of the Global South are expanding their production capacities.

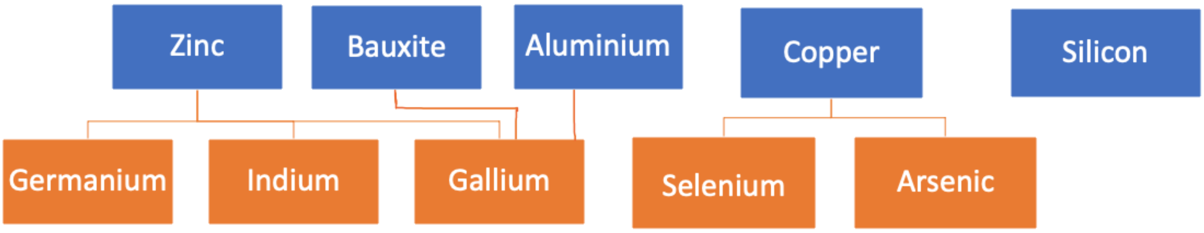


Figure 7.2 Minerals (in blue) and their by-products (in orange) for the PV cells.[813,814]

---

[811] Commission of the European Communities, *Single European Act*, Office for Official Publications of the European Communities (Luxembourg: 1986), p. 10.

[812] That is not to say that other activities were not supported by the programmes – a notable example are the research efforts for a PV sector specific silicon feedstock. However, the majority of the funding has been traditionally dedicated on research for the solar cell and modules.

[813] About 90% of the market accounts for c-Si cells that utilize Silicon. The remaining 10% of the market comprise of other materials for the solar cell (e.g. CIGS, CdTe). LCPV utilizes Silicon for the solar cells, whereas HCPV, which is the dominant CPC technology, utilize a variety of III-V semiconductors for the solar cell.

[814] In our analysis we have not included Cadmium-Telluride (CdTe cells) since their production is primarily located in the US (First Solar), whereas projects on these types of cells have been absent in the EU R&D programmes since the mid 2000s. A catalytic factor for this was that the 'man' behind the EU CdTe research networks, Dieter Bonnet, left the European scenery to help the largest US company (First Solar) in the mass production of the technology. Alongside Bonnet, an important part of the European expertise and know-how on CdTe – as developed via the EU R&D funding schemes – was transferred to the US. At the same time, it was during this period that the environmental health and safety issues surrounding the toxicity of Cd gained attention (early 2000s) (Fthenakis V. M., and Moskowitz P. D., "Photovoltaics: Environmental, Health and Safety Issues and Perspectives", *Progress in Photovoltaics: Research and Applications*, 2000, 27-38.; Fthenakis V., and

Production of all main minerals has become increasingly concentrated in Asia and other regions of the Global South. As depicted in Figure 7.3, Canada was the leading producer of Zinc (Zi) in 1994 (15,92%) followed by Australia (14,61%). By 2019, China was the leading producer of Zi (33,15%), followed by Peru (11%). Even though Canada maintained a 10,47% share, Australian production shrank to a mere 2,65%. Similar is the situation for Copper (Cu) production. Even though Chile has traditionally been the leading producer of Cu (accounting for 23,54% of global production in 1994 and 28,38% in 2019), the regions of the Global North that had a significant production share (US – 13,57% and Canada – 6,6%, in 1994) are gradually declining and losing their market share (US – 6,17% and Canada – 2,8%, in 2019). Concurrently, China increased its Cu production (from 3,71% in 1994 to 8,24% in 2019), while both Peru (4,23% in 1994) and Congo (0% in 1994) also increased their production and their respective shares (12,05% and 6,32%, respectively) by the end of the 2010s. This 'trend' is also prominent in the production of the other main minerals (i.e. bauxite and aluminum). As indicated in Figure 7.4, the production of aluminum has traditionally been concentrated in the USA and in Canada, 17,27% and 11,78% respectively in 1994. Russia also had a significant production share (13,97% in 1994). However, the production share of these regions had been steadily declining. The USA had a mere share of 1,73% in 2019, while Canada accounted for 4,5% of aluminum production and Russia's share was 5,75%. In contrast, China gradually grew to hold the largest share of aluminum production (55,27%) by the end of the 2010s. Bauxite production has always been – mainly – concentrated in Australia. By the end of the 2010s, bauxite production is increasing in regions such as Guinea (13,45% share in 1994 and 18,72% in 2019) and China (6,66% in 2000 and 19,55% in 2019).

As shown in Figures 7.5-7.7, the situation with these minerals by-products is very similar to the production of the main minerals. Arsenic (As) production has traditionally been concentrated in Chile and China. However, production of this minerals has also steadily increased in China, from 30,23% in 1994 to 60,60% in 2004 to 65,41% in 2019. Similarly, production of selenium (Se) has steadily concentrated in Japan, from 31,64% in 1994 to 49,93% in 2013. In Se, production China has become the global production leader in 2019, with a share of 38,19%. For Germanium (Ge), the US was the 'traditional' producer with a share of up to 32,39% of its global production in 2000. Since 2008 however, China has had a

---

Zweibel K., *CdTe PV: Real and Perceived EHS Risks*, Presented at the National Center for Photovoltaics and Solar Program Review Meeting, Denver, Colorado (US), March 24-26, 2003, (NREL/CP-520-33561), p. 1-3), possibly affecting the European CdTe production.

near monopoly on the production of Ge with shares ranging from 73,33% to 65,41%. Indium (In) production is no exception. Gradually, In production had transferred from Canada, Japan and European countries (Belgium and France), which together accounted for 83,9% of global

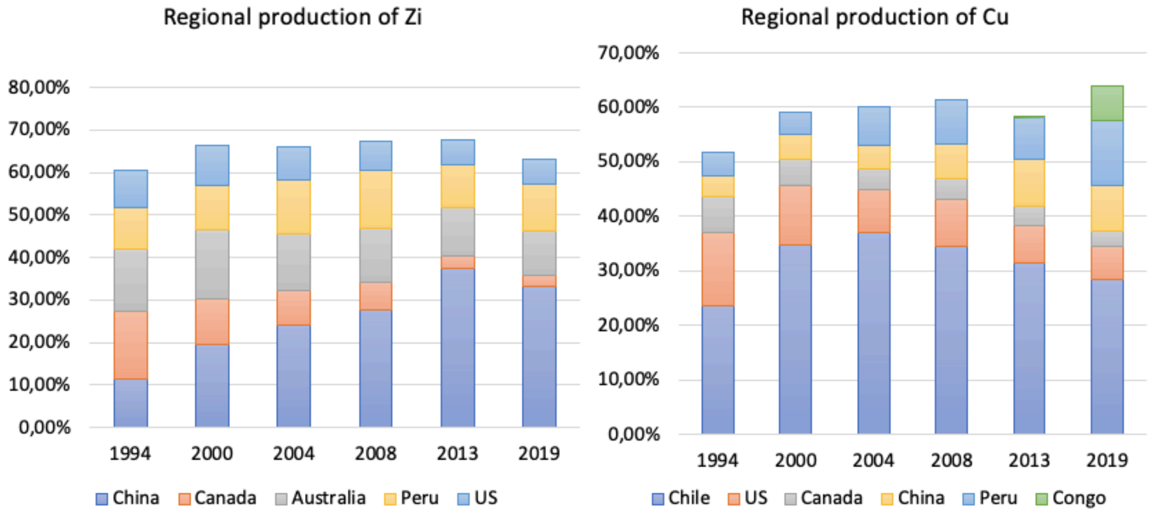


Figure 7.3 Regional production of Zinc and Copper (1994-2019).[815]

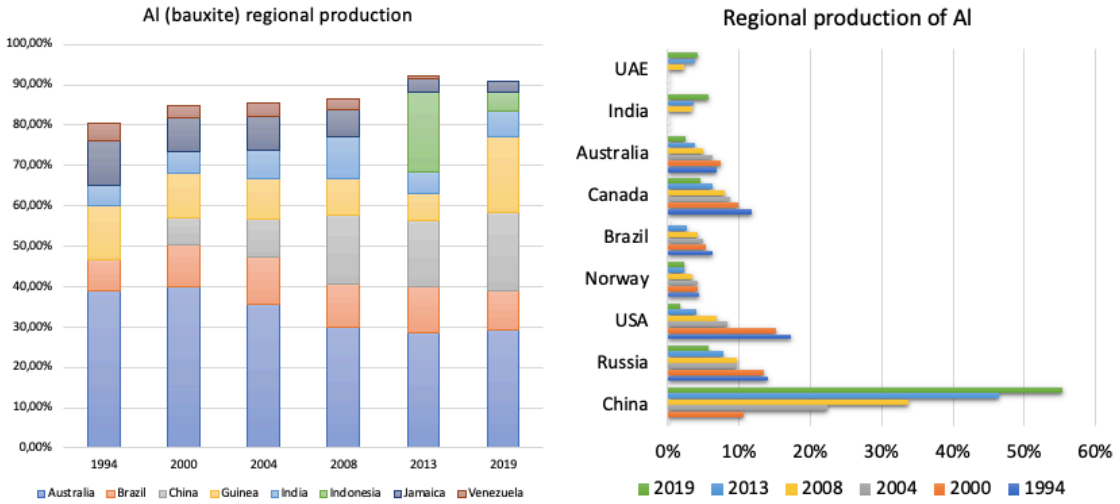


Figure 7.4 Regional production of Bauxite and Aluminum (1994-2019).[816]

---

[815] The production share percentages are calculated based on the data from the following USGS Mineral Commodity Summaries: US Geological Survey, “Mineral Commodity Summaries 1996”, (Washington DC: US Geological Survey, 1996; US Geological Survey, “Mineral Commodity Summaries 2002”, (Washington DC: US Geological Survey, 2002); US Geological Survey, “Mineral Commodity Summaries 2006”, (Washington DC: US Geological Survey, 2006); US Geological Survey, “Mineral Commodity Summaries 2010”, (Washington DC: US Geological Survey, 2010); US Geological Survey, “2012 Minerals Yearbook: Rare Earths”, (Washington DC: US Geological Survey, 2012); US Geological Survey, “Mineral Commodity Summaries 2015”, (Washington DC: US Geological Survey, 2015).; US Geological Survey, “Mineral Commodity Summaries 2021”, (Washington DC: US Geological Survey, 2021). Minerals production for selected, top producing regions.

[816] *Ibid*.

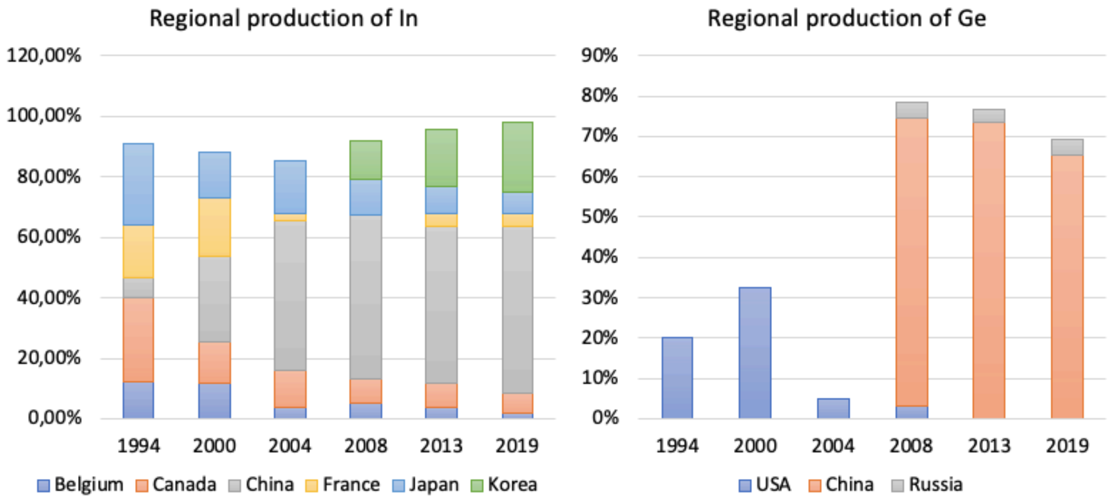


Figure 7.5 Regional production of Indium and Germanium – Zinc by-products (1994-2019).[817]

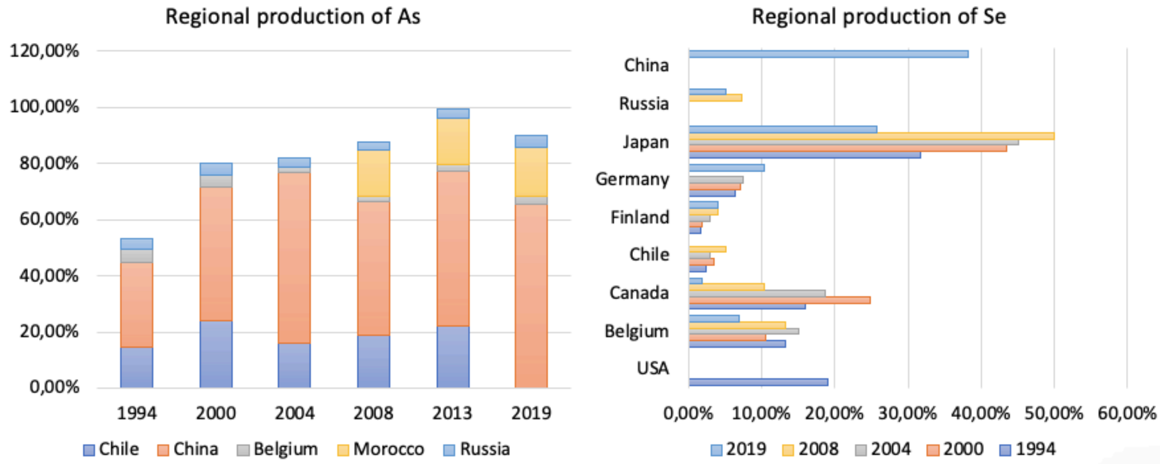


Figure 7.6 Regional production of Arsenic and Selenium – Copper by-products (1994-2019).[818]

---

[817] *Ibid*.

[818] *Ibid*.

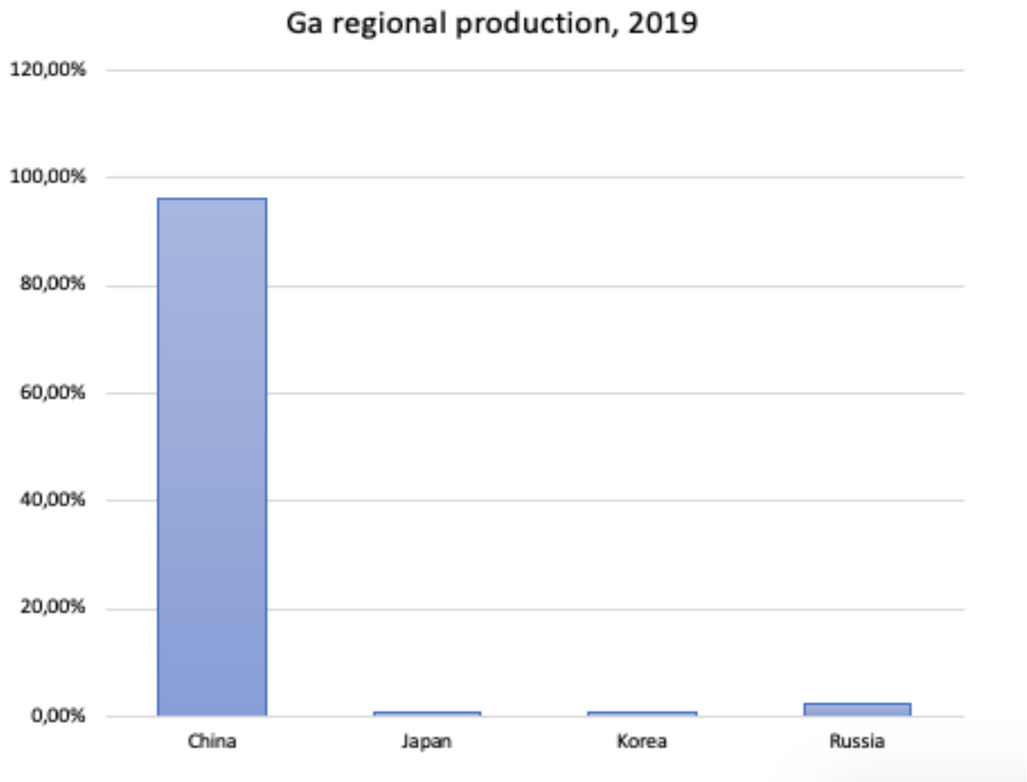


Figure 7.7 Regional production of Gallium – Zinc, Aluminum and Bauxite by-product (2019).[819]

In production in 1994, to China and Korea, which accounted for 78,46% of In production in 2019. Although data for global production of Gallium (Ga) is only available for 2019, it shows that China also holds a monopoly in this mineral, accounting for 96,29% of global production. Apart from the use of these materials for solar cells, they have a variety of other uses in many different areas. Se, for example is used in fertilizers, additives, glass etc. Ga is used in optoelectronic devices, defence applications etc., whereas In is used for LCDs, TVs, glass etc. Ge is used for satellite applications, wireless telecommunication devices, chips, LEDs, fiber optics etc.

As we progress from the 1990s to the 2000s and the 2010s, we observe a gradual shift of mining from the Global North to the Global South. Regions of the Global North (e.g. USA, Canada) that continued to produce the minerals required to manufacture PV technologies struggled to keep up with the rate of production in the Global South in the 2010s. The concentration of

---

[819] The production share percentages are calculated based on the data from: US Geological Survey, “Mineral Commodity Summaries 2021”, (Washington DC: US Geological Survey, 2021). Minerals production for selected, top producing regions.

silicon mining, the mineral required for the dominant PV technology on which the EU has based its policies, has steadily increased in China. In 2004, China accounted for more than half (about 66%) of the global silicon production and a few years later the country entered the PV cell/module business. So, for both the main minerals and the(ir) by-products required to produce the solar cells, we observe a general and steadily increasing concentration of production in regions of the Global South, especially China. We can therefore speak of a (mine-mining) production-transfer from the Global North to the Global South.

7.2.3 From mining to refining: tracing the mineral flows

Insofar, we have seen that production of the key minerals required for solar cells, and thus for the transition to RES, is increasingly taking place in the Global South, and in China in particular. However, since c-Si PV is the dominant PV technology, the question is where does the silicon mined in the Global South go? In other words: What are the mineral flows from mining to refining of this critical mineral used for the dominant PV technology? And what insights can the refinement of silicon (into polysilicon feedstock) offer with regard to the Si crisis in PV? As Johannes Bernreuter, one of the most well-known PV journalists, wrote in 2021:

> "Once upon a time, there were seven sisters who lived in four countries … You think this is a fairy tale? No – for two decades, the polysilicon industry consisted of just seven manufacturers, who bore the nickname "Seven Sisters." In 2005, however, this oligopoly began to crumble."[820,821]

The "Seven Sisters" that monopolized the production of the silicon feedstock required for both the electronics and PV industries were the following: Hemlock Semiconductors Corporation (USA), ASiMI (USA), MEMC Electronic Materials Inc. (USA and Italy), Wacker Polysilicon (Germany), Tokuyama Corporation (Japan), Mitsubishi Materials Corporation (MMC) (Japan), and Sumitomo Titanium Corporation (Japan).

---

[820] Johannes Bernreuter, 29 June 2020, bernreuter, *Silicon Manufacturers: How the ranking of the top ten producers has been whirled around since 2004*, Available online: https://www.bernreuter.com/polysilicon/manufacturers/, (accessed 3 November 2021).

[821] Bernreuter was associate editor in one of the largest and most known PV magazines, Photon-The Photovoltaic Magazine, for five years. He has been writing extensively about the PV sector, specializing in issues regarding the polysilicon market, for over two decades.

Hemlock Semiconductors was one of the largest polysilicon manufacturers of the first period. The company consisted of a joint venture between Dow Corning (major shareholder), Shin Etsu Hondotai and MMC.[822] The three companies that formed the joint venture produced polysilicon in the first period. They merged into a single company to maintain their polysilicon production. The only exception was MMC, which held the minority stake in Hemlock but also retained its own independent polysilicon production. Another major polysilicon producer from the first period was (and is) the German company Wacker. Sumitomo Titanium Corporation founded in 1965, was renamed Osaka Titanium Technologies and is a producer of titanium and silicon.

Two years before the start of the silicon crisis, the Norwegian REC set up a joint venture with ASiMI, a subsidiary of Komatsu Ltd. in the USA. In 2005, REC began acquiring ASiMI, which resulted in REC becoming one of the largest polysilicon producers in the world.[823,824] Unlike the other polysilicon manufacturers, REC entered the polysilicon business by acquiring one of the "Seven Sisters" to secure polysilicon supply for the PV industry. As PV is central to REC's vision and business, this acquisition was critical. It signalled a realignment in the polysilicon market, by putting the PV sector at the centre of attention, while recognising the PV sector – from the polysilicon manufacturers' point of view – as a critical market.

As Bernreuter noted, the monopoly of the "Seven Sisters" indeed began to crumble, but it was not until the 2010s (i.e. shortly after the end of the Si crisis) that the effects of the raw material crisis began to show. In 2009, the "Seven Sisters" accounted for more than 90% of the total silicon feedstock produced worldwide (88.000 metric tons).[825] The silicon crisis in PV paved the way and/or was the main motivation for other companies to enter polysilicon production. By 2009, a total of about seventy companies were present in the market, even if they only accounted for a small share.[826] During the silicon crisis, more companies, especially from Asia, entered the silicon feedstock business. Essentially, during this period, many companies were either established or integrated silicon production in their production chain by making announcements for future silicon production. Moreover, some of these new companies were founded or entered the polysilicon business with the sole purpose of supplying the PV market

---

[822] In 2013 Dow Corning bought-out MMC's share.

[823] Information on the data drawn from: Jäger-Waldau Arnulf, *PV Status Report 2005*, Publications Office of the European Union (Luxembourg: 2005).

[824] The Norwegian Elkem, part of the Orkla group, bought a 23% of REC in 2004. Five years later, Elkem also entered the polysilicon business by opening the first plant.

[825] Information on the data drawn from: Jäger-Waldau Arnulf, *PV Status Report 2010*, Publications Office of the European Union (Luxembourg: 2010).

[826] Information on the data drawn from: Jäger-Waldau Arnulf, *PV Status Report 2010,* Publications Office of the European Union (Luxembourg: 2010).

(e.g. AE Polysilicon – USA, REC – Norway) or expanded their business to include other PV activities (GLC-Poly – South Korea).

By the end of the second period, the landscape of polysilicon manufacturers had changed significantly. In addition to the "Seven Sisters", three other large polysilicon producers had emerged. These are the South Korean OCI Company and the two Chinese companies GCL-Poly Energy Holdings Limited and LDK Solar Co. Ltd.[827] In addition to these large polysilicon producers, a few companies from South Korea and China (e.g. Kumgang Korea Chemical Company and Daqo New Energy Co. Ltd.) as well as from other regions (e.g. AE Polysilicon – USA, Elkem A/S – Norway) started producing polysilicon feedstock in smaller quantities.

From Table 7.1, we can see two things. First, the dynamic entry of polysilicon producers from South Korea and China in the late 2000s. From 2009 to 2011, GCL-Poly's production quadrupled whereas OCI's production quintupled over the same period. Thus, within a short period of time, these companies have significantly expanded both their polysilicon production and their production capacities.

Polysilicon Manufacturer	**2005-2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2017**
Hemlock Semiconductor		19.000	36.000	32.400	28.000	33.000	15.000
MEMC/SunEdison[828]	5.125	10.000		13.661	12.000	11.000	--
ASiMI/REC	5.250-5.600	8.100	11.460	16.672	21.450	8.100	11.636
Wacker Polysilicon	5.800-6.500	18.100	30.500	33.885		49.000	71.000
Tokuyama Corp.	4.800-5.400	8.200	5.200*	8.800	7.800	6.000	
MMC	1.250-3.300	4.300*	4.300*				
Sumitomo Titanium Corp.	900-1.400*	±1.400*	±1.400*	3.500			
GCL-Poly Energy Holdings		7.450	17.850	29.414	37.055	50.440	74.818
LDK Solar		1.000	5.050	10.455			
Daqo New Energy Company		3.300*	3.300*	4.524	3.585	4.293	20.200
OCI Company		6.500-17.000*	27.000*	34.725	33.000	26.000	60.000
Kumgang Korea Chemical Company			6.000*	5.500	5.400		
Xinte Energy Co.							29.400
Sichuan Yonxiang Co. ltd.							17.000

---

[827] GCL-Poly was founded in 2006, whereas LDK- Solar went public in 2007. Therefore, both companies were established and started production in the midst of the Si crisis in PV.

[828] SunEdison was bought by GLC-Poly in 2016.

China Silicon Corp. ltd							14.000
Xinjiang East Hope New Energy Co. ltd.							10.000

Table 7.1 Polysilicon feedstock production volume (in metric tons) by manufacturer, 2005 - 2013.[829]

Second, some of the traditionally dominant companies (e.g. Tokuyama and REC) were overtaken by the new entrants. Within about five years, the large South Korean and Chinese companies surpassed some of the formerly dominant polysilicon producers (i.e. the "Severn Sisters"), such as Tokuyama and ASiMI/REC. Towards the end of the 2010s, in 2016, MEMC/SunEdison was acquired by GLC-Poly. During the 2010s, only two of the "Seven Sisters" (Wacker and Hemlock) still had a strong position in the polysilicon feedstock business. However, it is worth noting that while Hemlock was included in the top ten manufacturers for 2017, its place has been significantly weakened. Only Wacker has managed to maintain a strong position in the global production of polysilicon so far, from the original 'Seven Sisters'. Therefore, the "Seven Sisters" oligopoly gradually began to dwindle during the silicon crisis and escalated during the 2000s and 2010s, as polysilicon production expanded to China and Korea. Essentially, China entered the production of PV cell/module after gaining a significant place in the mining/extraction and refinement of silicon. Until then, both the production and the refining of silicon were mainly located in the regions of the Global North. Furthermore, given the prominent role that Korean and Chinese gained in polysilicon production, they challenged the earlier power dynamics. Resulting in an increasing concentration of polysilicon production in South Korea and China and challenged the dominance of the remaining "Sisters". While the mining of the minerals required for PV cells is increasingly concentrated in the Global South – and the associated material flows from the Global South to the Global North is intensifying – the refining of these minerals is still largely concentrated in the Global North (the remaining "Sisters"). An exemplary exception is China – although not for all materials required for PV but primarily for materials required for industries that are emerging in China and that are becoming very profitable (e.g. GaAs for wireless infrastructures and smartphones in the 2010s).

---

[829] All the data with an asterisk correspond to the manufacturers production capacity based on expansion announcements and estimates. The data have been collected by: Jäger-Waldau Arnulf, *PV Status Report 2007*, Publications Office of the European Union (Luxembourg: 2007).; Jäger-Waldau Arnulf, *PV Status Report 2011,* Publications Office of the European Union (Luxembourg: 2011).; Jäger-Waldau Arnulf, *PV Status Report 2018,* Publications Office of the European Union (Luxembourg: 2018).

7.2.4 From production to installation: the geographical concentration in the Global South continues

The share of European PV cell/module production grew gradually from about 21% in 2000 to about 26% in 2004.[830] Since 2006 – in the midst of the Si crisis – China has been steadily leading in PV cell/module production at an unprecedented pace, creating a large gap/divide between the first – i.e. China – and the rest.[831] It is worth noting here that the total world production of PV cell/module in 2009 was about 11,5 GW, of which 50% was produced in China and Taiwan.[832] At the end of the Si crisis, the corresponding share for Europe had dropped to about 17%.[833] Another indicator of this large gap between China and the rest are the corresponding 2016 figures: total global production was about 81,9 GW, of which about 60 GW was produced in China and 11 GW in Taiwan.[834] As the annual production of PV cell/module continues to increase, the divide between China and the rest is also growing.[835]

From humble beginnings, the global PV market has grown significantly over the past two decades. Indicative of this growth is the increase in cumulative PV power capacity from 22 GW in 2009 to 773,2 GW in 2020.[836] The EU had consistently led the PV market. In particular, the EU market has grown from 1,9 GW of cumulative PV power capacity in 2005 to 16 GW in 2009, to 80,7 GW in 2013, and finally to 139 GW in 2020.[837] In 2018, the EU was 'dethroned' when China became the largest PV market, with a cumulative PV power capacity of 175GW.[838,839]

---

[830] Shares calculated based on the data presented in: Arnulf Jäger-Waldau, *PV Status Report 2003*, Office for Official Publications Office of the European Communities (Luxembourg: 2003).; Arnulf Jäger-Waldau, *PV Status Report 2006*, Office for Official Publications Office of the European Communities (Luxembourg: 2006).

[831] Regarding the annual global PV cell/module production see data presented also in section 4.

[832] Arnulf Jäger-Waldau, *PV Status Report 2010*, Office for Official Publications of the European Union (Luxembourg: 2010).

[833] Arnulf Jäger-Waldau, *PV Status Report 2010*, Office for Official Publications of the European Union (Luxembourg: 2010).

[834] Arnulf Jäger-Waldau, *PV Status Report 2017*, Publications Office of the European Union (Luxembourg: 2017).

[835] As indicated by the most recently published PV Status Report the Chinese steadily lead the PV cell/module production, accounting for about 70% of the total global production in 2018 (Arnulf Jäger-Waldau, *PV Status Report 2019*, Publications Office of the European Union (Luxembourg: 2019)).

[836] Arnulf Jäger-Waldau, *PV Status Report 2010,* Office for Official Publications of the European Union (Luxembourg: 2010).; SolarPower Europe, *Global Market Outlook for Solar Power 2021-2015*, 2021.

[837] Data drawn from: Arnulf Jäger-Waldau, *PV Status Report 2010*, Office for Official Publications of the European Union (Luxembourg: 2010).; Arnulf Jäger-Waldau, *PV Status Report 2014,* Publications Office of the European Union (Luxembourg: 2014).; SolarPower Europe, *EU Market Outlook for Solar Power 2021-2015*, 2021.

[838] In 2018, the total (worldwide) cumulative PV power capacity was 518 GW - the EU accounted for about 23% of the cumulative PV power capacity. (Arnulf Jäger-Waldau, *PV Status Report 2019*, Publications Office of the European Union (Luxembourg: 2019).)

[839] Arnulf Jäger-Waldau, *PV Status Report 2019*, Publications Office of the European Union (Luxembourg: 2019).

The annual installed PV capacity in the EU has been steadily increasing. The annual PV capacity installed in the EU (in GWp) has always been steadily the highest and accounted for over 80% of the annual PV capacity installed worldwide in 2010. Not surprisingly, the EU also leads in cumulative installed PV capacity (in GWp), accounting for more than 50% of global cumulative installed PV capacity until 2013.[840] During the silicon crisis, the EU increased PV installations, resulting to overtaking Japan. Germany accounted for the largest share of PV installations both in the EU and globally.[841] In 2001, Germany led in PV installations with an annual installation of 80 MW.[842] In 2001, a total of about 300 MW had been installed in Europe.[843] Additionally, Germany had a total installed capacity of 194.7 MWp in 2001, whereas Japan had a total installed capacity of 452.2 MWp.[844]

In 2008, Spanish PV installations (in MW) even exceeded those of Germany. Within a single year, about 2,6 GW was installed in Spain.[845,846] The majority of the Spanish PV installations were large-scale installations (i.e. large, centralized plants of more than 10 MW each) and included the installation of CPV.[847] From 2009 to 2013, Italy followed Germany in PV installations. Since the early 2010s, the EU's share has steadily declined, as China, Japan and the US have increased their installed PV capacity.

---

[840] The percentages have been estimated based on the data provided by the following sources: Arnulf Jäger-Waldau, *PV Status Report 2009,* Office for Official Publications of the European Union (Luxembourg: 2009).; Arnulf Jäger-Waldau, *PV Status Report 2014,* Publications Office of the European Union (Luxembourg: 2014).; Arnulf Jäger-Waldau, *PV Status Report 2016*, Publications Office of the European Union (Luxembourg: 2016).

[841] European Photovoltaics Industry Association, *Global Market Outlook: For Photovoltaics 2014-2018*, 2014.; Arnulf Jäger-Waldau, *PV Status Report 2016,* Publications Office of the European Union (Luxembourg: 2016), p. 11.

[842] Wolfgang Palz, "Keynote Speech: Photovoltaics in Europe and the World", *in* PV in Europe - From PV Technology to Energy Solutions, Proceedings of the International Conference held in Rome, Italy, 7-11 October 2002, J. L. Bal, G. Silvestrini, A. Grassi, W. Palz, R. Vigotti, M. Gamberale, P. Hem (eds.), WIP-Munich & ETA-Florence, 2002, p. xxxix.

[843] Wolfgang Palz, "Keynote Speech: Photovoltaics in Europe and the World", *in* PV in Europe - From PV Technology to Energy Solutions, Proceedings of the International Conference held in Rome, Italy, 7-11 October 2002, J. L. Bal, G. Silvestrini, A. Grassi, W. Palz, R. Vigotti, M. Gamberale, P. Hem (eds.), WIP-Munich & ETA-Florence, 2002, p. xxxix.

[844] Thomas Nordmann, "Subsidies Versus Rate based Incentives; For Technology – Economical – and Market-Development of PV. The European Experience", *in* Proceedings of Third World Conference on Photovoltaic Solar Energy Conversion, Joint Conference of Thirteenth PV Science and Engineering Conference, Thirtieth IEEE PV Specialists Conference, Eighteenth European PV Solar Energy Conference, Osaka, Japan, 11-18 May 2003, Kosuke Kurokawa, Lawrence L. Kazmerski, Bernard McNelis, Masafumi Yamaguchi, Christopher Wronski, Wim C. Sinke (eds.), IEEE: 2003, [CD ROM file number: 8OD1102], (pdf) p. 2.

[845] Arnulf Jäger-Waldau, *PV Status Report 2009,* Office for Official Publications of the European Union (Luxembourg: 2009).

[846] This corresponds to fifteen times more PV than the Spanish produced. (Steven Hegedus and Antonio Luque, "Achievements and Challenges of Solar Electricity from Photovoltaics", *in* Handbook of Photovoltaic Science and Engineering, Antonio Luque and Steven Hegebus (eds.), Wiley & Sons (Second Edition, UK: 2011), p. 1-38)

[847] Steven Hegedus and Antonio Luque, "Achievements and Challenges of Solar Electricity from Photovoltaics", *in* Handbook of Photovoltaic Science and Engineering, Antonio Luque and Steven Hegebus (eds.), Wiley & Sons (Second Edition, UK: 2011), p. 1-38.

The EU played a catalytic role in stimulating global PV production and in constructing and fostering a (stable) market for PV. Policy goals and commitments, both at EU and member states level, played a crucial role in these developments. The majority of installations on EU PV were for grid-connected applications.[848]

7.2.5 Externalities accounted for: the impact of extractive industries and the production steps for PV

Extractive industries (i.e. oil, gas, mining) are associated with a plethora of health and environmental problems. It has been noted that: "[m]ining operations typically leave behind a trail of devastation".[849] Mining has been directly linked to a range of health and environmental problems.[850] Regarding the latter, mining activities are known to "… jeopardize farming, fisheries and forestry…".[851] As for mining, it was stated:

> "… has had a deplorable occupational health record due to miners' ongoing exposure to carcinogens, lung-disease inducing dust, toxic mercury vapour, and high rates of injury and death from underground explosions, equipment failure, and mining collapse."[852]

A World Bank report from 2020 noted the following:

---

[848] European Photovoltaics Industry Association, *Global Market Outlook: For Photovoltaics 2014-2018*, 2014.

[849] Ted Schrecker, Anne-Emanuelle Birn, Mariajose Aguilera, "How extractive industries affect health: Political economy underpinnings and pathways", *Health & Place*, 2018, p. 140.

[850] References regarding the health problems associated with mining: (K. Elgstrand, D. L. Sherson, E. Jørs, C. Nogueira, J. F. Thomsen, M. Fingerhut, L. Burström, H. Rintamäki, E. Apud, E. Oñate, N. Coulson, L. McMaster, E. E. Clarke, "Safety and Health in Mining: Part 1*", Occupational Health Southern Africa*, 2017, p. 10-20.; E. Cartwright, "Mining and its health consequences", *in* A Companion to the Anthropology of Environmental Health, M. Singer (eds.), John Wiley (Chichester, UK: 2016), p. 417–434.; Leslie London and Sophia Kisting, "The Extractive Industries: Can We Find New Solutions to Seemingly Interactable Problems?", *A Journal of Environmental and Occupational Health Policy*, 2016, p. 421-430.). References regarding the environmental problems associated with mining: (Ted Schrecker, Anne-Emanuelle Birn, Mariajose Aguilera, "How extractive industries affect health: Political economy underpinnings and pathways", *Health & Place*, 2018, p. 135-147.; B. Prieto, B. Silva, N. Aira, "Methodological aspects of the induction of biofuels for remediation of the visual impact generated by quartz mining", *Science of the Total Environment*, 2006, p. 254-261.; W. Salomons, "Environmental impact of metals derived from mining activities: Processes, predictions, prevention", *Journal of Geochemical Exploration*, 1995, p. 5-23.)

[851] Ted Schrecker, Anne-Emanuelle Birn, Mariajose Aguilera, "How extractive industries affect health: Political economy underpinnings and pathways", *Health & Place*, 2018, p. 142.

[852] Ted Schrecker, Anne-Emanuelle Birn, Mariajose Aguilera, "How extractive industries affect health: Political economy underpinnings and pathways", *Health & Place*, 2018, p. 140.

> “A **low-carbon future will be very mineral intensive** because **clean energy technologies need more materials than fossil-fuel-based electricity generation technologies**. Greater ambition on climate change goals (1.5^0 C–2^0C or below), as outlined by the Paris Agreement, requires installing more of these technologies **and will therefore lead to a larger material footprint**.”[853,854] (emphasis added)

As the urgency to become carbon-neutral increases, the EU energy strategy essentially calls for a disentanglement from oil. Indirectly, however, this strategy also calls for an intensification of mining. Hence, decreasing dependence on oil means increasing dependence on minerals, intensifying mining and increasing environmental and health impacts deriving from these activities.

As indicated by Figure 7.2 (above), PV cells require various minerals. For three of these minerals (i.e. silver, copper, zinc) comments similar to those above were made. Specifically:

> “Mining of **silver, copper** (Latin America is the leading producer of both of these), gold, **zinc**, tin, and other naturally abundant minerals both **consume**s **enormous quantities of water and heavily contaminate**s **watersheds and agricultural land**.”[855,856] (emphasis added)

However, these are examples of minerals that correspond to technologies that account for about 5% of PV production in 2020.[857] What about the most important mineral responsible for the remaining 95% of PV production? A number of diseases have been linked to the quartz mining (crystalline silica). Health problems include silicosis, lung cancer, kidney disease, chronic bronchitis, and several autoimmune diseases (e.g. rheumatoid arthritis, systemic sclerosis, and

---

[853] Kirsten Hund, Daniele La Porta, Thao P. Fabregas, Tim Laing, John Drexhage, *Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition*, International Bank for Reconstruction and Development/The World Bank (Washington: 2020), p. 11.

[854] Similar remarks by Jane H. Hodgkinson and Michael H. Smith, Climate change and sustainability as drivers for the next mining and metals boom: The need for climate-smart mining and recycling”, *Resources Policy*, 2021, 101205.

[855] Schrecker, Anne-Emanuelle Birn, Mariajose Aguilera, “How extractive industries affect health: Political economy underpinnings and pathways”, *Health & Place*, 2018, p. 141.

[856] Regarding the externalities from mining copper see also: Mudd G. M., Weng Z., Memary R., Northey S. A., Guirco D., Mohr S., Mason L., *Future Greenhouse Gas Emissions from Copper Mining: Assessing Clean Energy Scenarios*, Prepared for CSIRO Minerals Down Under National Research Flagship by Monash University Institute for Sustainable Futures, University of Technology, October 2012.

[857] Fraunhofer ISE, *Photovoltaics Report*, Freiburg: 24 February 2022, p. 5.

systemic lupus erythematosus).[858,859] Open cast mining activities, which is the common practice in quartz mining "[…] produce significant effects on the atmosphere, water, soil, vegetation, fauna and landscape."[860]. However, as shown in Figure 7.8, mining is only the first step on the wat to producing a PV system. It has been noted that "[s]melting of ore concentrates results in the release of metals to the atmosphere and may, in fact, be higher compared with the mining activities themselves."[861]

Figure 7.8 The PV production chain: from mining to recycling.

The next step after mining is the refinement of silicon into metallurgical-grade silicon (MG-Si). According to an estimate for 2017, the production of MG-Si requires about 12TWh/yr of electricity.[862] To refine silicon into MG-Si, carbon is added into submerged arc furnaces, resulting in the release of known GHG emissions. In addition, as it was noted:

> "The ecological impact of silicon is high because the metallurgical process for **silicon purification has a high energy demand** and because of the use of

---

[858] Kenneth Michael Pollard, "Silica, Silicosis, and Autoimmunity", *Frontiers in Immunology*, 2016, p. 1-7.; Elizabeth Cartwright, "Mining and its health consequences", *in* A Companion to the Anthropology of Environmental Health, M. Singer (eds.), John Wiley (Chichester, UK: 2016), p. 417–434.; Kenneth Michael Pollard, "Silica, Silicosis, and Autoimmunity", *Frontiers in Immunology*, 2016, p. 1-7.; Christine G. Parks, Karsten Conrad, Glinda S. Cooper, "Occupational Exposure to Crystalline Silica and Autoimmune Disease", *Environmental Health Perspectives*, 1999, p. 739-802.

[859] At least some of these occupational health risks and/or problems have been recognized by the US Department of Labour, resulting in campaigns for the miners' health (United States Department of Labour - Occupational Safety and Health Administration, OSHA, *Safety and Health Topics/Silica, Crystalline*, Available online: https://www.osha.gov/silica-crystalline/health-effects, (accessed 25 May 2022)). Additionally, the European Association for Industrial Silica Producers recognizes (only) silicosis as a possible occupational health risk (The European Association for Industrial Silica Producers, eurosil, *Silica and Health*, Available online: https://eurosil.eu/silica-and-health/, (accessed 23 May 2022)).

[860] B. Prieto, B. Silva, N. Aira, "Methodological aspects of the induction of biofuels for remediation of the visual impact generated by quartz mining", *Science of the Total Environment*, 2006, p. 254.

[861] W. Salomons, "Environmental impact of metals derived from mining activities: Processes, predictions, prevention", *Journal of Geochemical Exploration*, 1995, p. 6.

[862] Calculated by the data provided from: Fidelis Chigondo, "From Metallurgical-Grade to Solar-Grade Silicon: An Overview", *Silicon*, 2018, p. 789-798.

> submerged arc and induction furnaces. **Some toxic compounds such as chlorine can be emitted in the process**."[863] (emphasis added)

Apart from the energy-intensive side of this silicon purification process and the GHG emissions, there is also the potential risk of toxic compounds being released. This makes the ecological footprint of this process even larger. However, the purity requirements (of MG-Si) are not sufficient for PV applications. Therefore, further refinement is required. The most common refinement method is the Siemens^{TM} process.[864] This includes another energy intensive-step that consumes about 10TWh/yr based on 2017 figures.[865,866] With each additional step in the PV production chain (e.g. ingot, wafer, cell), energy consumption continues to increase, while pollutants and toxic substances are produced. As the geographical origin of more and more of these production steps is in the Global South, especially China, the concentration of the negative impacts of the production steps is also concentrated.

However, it is important to ask at least one more question: What happens to these technologies when they reach their end-of-life cycle? For research this was not a concern – it was never a problem that had to be addressed and consecutively resolved. Even though a small number of projects included life cycle assessment (LCA) analyses in the projects, the whole chain was never examined. Rather, in times of crisis (i.e. Si crisis), such analyses were only included for individual production steps or even (very specific) processes. Recycling was part of a few research projects, but only in the context of addressing the Si crisis, which explains why during FP7 when no projects were selected for SoG both recycling and LCA were completely absent from the projects.

It should be noted that in these projects, waste and its minimization were aligned with economic benefits. Hence, although the 'environment' was mentioned, the underlying motivation was

---

[863] Ewa Klugmann-Radziemska, Anna Kuczyńska-Łażewska, "The use of recycled semiconductor material in crystalline silicon photovoltaic modules production - A life cycle assessment of environmental impacts", *Solar Energy Materials and Solar Cells*, 2020, 110259, p. 2.

[864] Accounting for about 90% of the worldwide high purity Si production (Fidelis Chigondo, "From Metallurgical-Grade to Solar-Grade Silicon: An Overview", *Silicon*, 2018, p. 789-798.) For a detailed descriptions of the Siemens^{TM} process see: Hunt Lee P., "Silicon precursors: Their manufacture and properties", in Handbook of semiconductor silicon technology, William C. O'Mara, Robert B. Herring, Lee P. Hunt (eds.), Noyes Publications (USA: 1990), p. 1-32.; Fidelis Chigondo, "From Metallurgical-Grade to Solar-Grade Silicon: An Overview", *Silicon*, 2018, p. 789-798

[865] The calculation is based on the date provided by Fidelis Chigondo, "From Metallurgical-Grade to Solar-Grade Silicon: An Overview", *Silicon*, 2018, p. 789-798.; Arnulf Jäger-Waldau, *PV Status Report 2019*, Publications Office of the European Union (Luxembourg: 2019).

[866] In 2021, the PV in Germany generated a little over 48TWh of electricity (Fraunhofer-ISE, 17 January 2022, Fraunhofer-ise, "*Public Net Electricity Generation in Germany in 2021: Renewables Weaker Due to Weather*", Available online: https://www.ise.fraunhofer.de/en/press-media/news/2022/public-net-electricity-in-germany-in-2021-renewables-weaker-due-to-weather.html, (accessed 19 November 2020)).

economic.[867] Only one single project in the second period referred to end-of-life cycle and the development of such capacities, but this was justified by an industrial rationale.[868,869]

A possible explanation for the lack of such research is provided by DG Environment. A 2011 report prepared by DG Environment for the assessment of the recast of the waste electrical and electronic equipment (WEEE) Directive, states the following:

> "Photovoltaic panel recycling is currently not economically viable because waste volumes generated are too small; significant volumes of end-of-life PV panels will only begin to appear in 2025 or 2030."[870]

Since the amounts of waste are small, recycling of PV panels was not basically economically viable. This explains why the relevant industry was not interested in embarking on the PV recycling business. As scholars have noted, research has rarely addressed on such issues. Moreover, they note, this is reflected in the:

> "… lack of dedicated solar-panel recycling plants. The **research on solar photovoltaic panels' management at the end of life is just beginning in many countries**, and there is a need for further improvement and expansion of producer responsibility."[871] (emphasis added)

Additionally, as the authors note:

---

[867] There are two projects that concerned recycling for thin film technologies (NEBULES and SENSE). In neither of these two projects, it is not clear if they are referring to recycling of the end product or parts of the product. Recycling is being recognized as a 'widely unsolved issue' in SENSE, whereas NEBULES discusses issues of toxicity of the Cd buffer layer (CIGS, CIS) in terms of being proactive since it poses a problem for reputation.

[868] Based on the projects' website we see the following: "The project structure is well prepared for development of methods for recycling of waste and end of life products. This is a new opportunity to enhance the competitive ability for the industry." (*Stiftelsen for industriell og teknisk forskning*, 25 January 2006, SINTEF, *FOXY project summary*, Available online: https://www.sintef.no/projectweb/foxy/project-summary/, (accessed 15 November 2020)).

[869] Even though we have collected all papers (funded under FoXy) published under the EU PV Conferences, the topic at hand was not analysed in any of these papers.

[870] European Commission – DG Environment, *Study on PV Panels Supplementing the Impact Assessment for a recast of the WEEE Directive*, Final Report, 14 April 2011, p. 6.

[871] Yan Xu, Jinhui Li, Quanyin Tan, Anesia Lauren Peters, Congren Yang, "Global status of recycling waste solar panels: A review", *Waste Management*, 2018, p. 450.

> "There are only a handful of PV panel processing and recycling facilities around the world, and end-of-life solar PV panel management is a newly emerging field that needs further research and development."[872]

The two quotes above are from an article published in Waste Management Journal in 2018. They highlight that such capacities still need to developed and that there is a need for research to develop the necessary capacities.

In 2012, the EU re-casted the Waste Electrical and Electronic Equipment Directive, to include PV panels and specify the share of PV panels that must be recovered and subsequently reused and recycled.[873] However, based on these provisions, the recovery or recycling of semiconductors and other known toxic substances (e.g. lead and silved) is not mandatory.[874]

7.2.6 The EU research networks' response to the Si crisis: geopolitics and externalities accounted for?

In the second period, we have seen in our insofar analysis (Chapters 4-6) that the installation targets set by the 1997 White Paper of EC for RES have re-oriented research. The technological choices offered by the first period networks formed the basis for the formulation of the White Paper's goals for PV. The PV installation targets (or take-off campaign) of the White Paper were roof-top.[875] This technology, which the first period networks selected, opened up the possibility of moving to distributed electricity generation. In the second period, the EU-funded PV technoscientific research networks sought to find solutions for the upscaled production of PV, as necessitated by the energy policy. Moreover, the networks sought to find and provide solutions to the silicon crisis in PV, which was the direct consequence of this upscaled production. Based on the analysis in Chapters 4-6, we have seen that PV technoscientific have proposed different solutions to address the silicon crisis in PV.

---

[872] Yan Xu, Jinhui Li, Quanyin Tan, Anesia Lauren Peters, Congren Yang, "Global status of recycling waste solar panels: A review", *Waste Management*, 2018, p. 451.

[873] Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE), Official Journal of the European Union, 24.7.2012.

[874] See composition of PV panels in European Commission – DG Environment, *Study on PV Panels Supplementing the Impact Assessment for a recast of the WEEE Directive*, Final Report, 14 April 2011.

[875] Christos Papoutsis, [Introductory conference speech], *in* 2nd World Conference on Photovoltaic Solar Energy Conversion/15th European PV Solar Energy Conference/27th US IEEE Photovoltaics Specialists Conference/10th Asia/Pacific PV Science and Engineering Conference, Proceedings of the International Conference held at Vienna, Austria, 6-10 July 1998, J. Schmid, H. A. Ossenbrink, P. Helm, H. Ehmann, E. D. Dunlop (eds.), Vol II, WIP Renewable Energies: 1998, p. xl-xliii.; European Commission – Directorate General for Energy, *THERMIE-ALTENER: Renewable Energy Report*, Office for Official Publications of the European Communities (Luxembourg: 1998).

However, in order to achieve the goals of the White Paper (for PV installations), upscaling production was promoted, albeit indirectly, resulting in a raw materials crisis (silicon crisis in PV). With a clear mission to achieve the goals set by the energy policy, research was redirected towards solving the presupposed problems of upscaled production as well as the silicon crisis, which was the direct result of this upscaled production.

Within this framework, different solutions were proposed by the research networks of this period, mainly concerning developments in different steps of production (see corresponding sections in Chapters 4-6). During this period, the networks included more steps of the 'value chain' in their research projects.[876] The term 'value chain' was employed by actors in the c-Si research networks.[877] The 'value chain', defined by the research actors consists of the following steps: feedstock, wafer, cells, module, 'sustainability', and 'integration'. The last two steps of the value chain merit attention. By 'sustainability', the actors mean module recycling and LCA analyses, whereas integration is economically-geared/oriented (i.e. refers to module costs). Recycling has been included in research (already in FP5), but only as a means to solve the problems of upscaled production. Hence, as a means to support industrial production. It did not comprise an issue with broader global, geopolitical and environmental dimensions and concerns.

During this period, the PV research networks (still) set the research priorities. Moreover, the role of these actors was legitimized by the formation of the European Technology Platforms (ETPs). These decision-making platforms – due to their composition – allowed the promotion of national industrial interests. For example, during this period, the Spanish redirected their research towards large-scale HCPV to help boost their domestic industry. This choice was neither conducive nor purposeful in terms of user empowerment. By establishing the ETPs, the EC legitimized the role of the networks as the ones that set and guide the research agenda and priorities to be funded through the FPs, while enabling further promotion of corporate interests to steer the agenda.

---

[876] In contrast to the value chain, we employ the term 'production chain' to indicate steps that are being 'overlooked' or 'ignored' by the research networks and the agenda, which however denote broader issues and problems that derive from the production of PV. As such, this term allows us to account for the externalities and inequalities that are being generated in steps that remain 'hidden' by the term the historical actors from the research networks employ. The steps that comprise the 'production chain' are depicted in Figure 7.8.

[877] We should note that even though under FP6 this term begun to be adopted, it was not always defined (i.e. the steps comprising the value chain were not always stated). The term was first used and defined in the FP6 CrystalClear and FOXY projects. However, the FOXY projects' definition of the value chain begins with feedstock and ends with modules and is not thus the same as the one employed by the actors of the CrystalClear project.

Within Horizon 2020, Responsible Research and Innovation is indirectly included to the R&D for RES through energy policy. Within this framework, society and/or citizen engagement play a central role and are indeed envisioned to play an active role in the reconfiguration of the energy system. However, in the relevant Horizon 2020 PV projects, even though different users are constructed (e.g. prosumers) they do not play an active role 'in the making' of research.

Based on the analysis in Chapter 5, the c-Si thin films agenda gradually gained prominence in the second period as the 'future' agenda for the dominant technology (c-Si). The combination or 'marriage' of both technologies (i.e. c-Si and thin films – a-Si) would allow the dominant technology to improve its of efficiency while maintaining (or increasing) its market share. Essentially, this agenda sought to find a solution for the survival of the dominant technology, whose efficiency had plateaued at around 20%.

This shift in R&D funding in the second period shows that thin films became the main recipient of funding due to the c-Si thin films agenda. In Chapter 5, we examined how the bulk of the thin films funding went to a-Si, and how the c-Si thin films agenda affected a-Si research activities, networks, and geographical distribution of funding. Non-a-Si research activities in the second period accounted for 18,49% of total R&D funding or 48,47% of total thin film total R&D funding.[878,879] The fact that the majority of the funding went to a-Si research highlights the dominance of the c-Si actors in steering the research agenda (including thin film research). Despite that, nearly half of the R&D budget for thin films was dedicated to a variety of other materials (organic and non-organic). Thus, almost half of the thin films budget was allocated to a diverse group of materials.

As we have already analysed in Chapter 6, the shift in CPV proposed by the dominant network actor had two aspects. First, it entailed a shift in the preferred scale of the technology (from small- to large-scale), which had consequences for the future use(s) and application(s) of this technology. Second, it came with a shift in the minerals used for the solar cells. In a move away from c-Si and the silicon crisis, III-V semiconductors were used instead for the cells. The shift

---

[878] Based on the authors' calculations. The projects that combine more than one material (including a-Si) have been excluded for the calculation of the shares.

[879] An additional 13,36% of the thin films funding was dedicated to projects that undertook research on both a-Si and other materials combined; we have isolated this budget and corresponding share. Given that this budget corresponds both to a-Si and other materials research it is difficult to allocate the budget in one category (i.e. a-Si or thin films – other materials).

from LCPV and c-Si to HCPV and III-V multijunction solar cells, comprised a move to other semiconductors and minerals, refined in different EU member states.[880,881]

However, despite the options and/or solutions offered by the PV research networks (both case-studies – Chapters 4-6), to address the silicon crisis, geopolitics does not seem to have had an impact on the direction of research priorities. Overall, the silicon crisis, as an event with geopolitical dimensions, did impact the research priorities and agenda for PV in the second period. However, the broader geopolitical dimensions of securing the material supply required for PV and mitigating the geographical concentration of different steps in the production chain, did not lead to a reorientation of the research priorities. Moreover, the geopolitical dimension of the silicon crisis did not impact the technical choices of the networks. These geopolitical dimensions were neither integral nor incremental to the network's research agenda. Only in times of crisis (e.g. the silicon crisis) were solutions sought, but these did not take into account the geographical concentration of production or the disentanglement from these types of dependencies. Essentially, despite the geopolitical dimension of the silicon crisis, the networks focused on supporting the industrial production. The broader geopolitical dimensions of the crisis were not of concern for the networks and were therefore not incorporated in the projects. However, based on the material flows, we have shown that their production is increasingly concentration in regions of the Global South and in China in particular. As the EU seeks to become carbon-neutral, dependence of mineral supply from the Global South increases, as the minerals required for both the dominant technology and the other emerging and/or niche markets of PV, are sourced in the Global South.

As we have already analysed in Chapter 2, the ETPs determine the priorities to be incorporated and funded in the EU R&D programmes. Under Horizon, the technological frontrunners determined by the dominant actors of the networks have been included and funded. In particular, we see that the trend towards c-Si thin films and for HCPV continues to receive support.[882]

7.2.6.1 Building a market for PV: what about the users?

---

[880] Indium is produced in Belgium and France, Selenium is produced in Belgium, Germany and in Finland, Germanium is produced in Belgium and Gallium is produced in Germany.

[881] High concentrating PV (HCPV) cells utilise Gallium-Arsenic and have a Germanium substrate. CIGS solar cells utilise Copper, Indium, Gallium and Selenide.

[882] Based on data retrieved by cordis for the Horizon 2020 funded projects by 2019. It is worth noting that only HCPV projects were funded. Similarly, c-Si thin films nearly monopolized the R&D funding for the c-Si research activities.

The EU was continuously the largest PV market in the world until the mid-2010s (2014), with countries such as Germany and Italy having the largest market share, when the cumulative installation of PV in China surpassed that of the EU.[883]

Different EU member-states have employed different policies and incentives for installation of PV and the establishment of the respective national PV markets.[884] Until 2018, both Portugal and Denmark had a marginal share of the PV market, favouring small-scale and BIPV installations.[885] In contrast, Spain, Greece, and the UK had different PV scales, but in these countries the trend was mainly towards large-scale installations. In contrast, the Netherlands, Belgium and Austria primarily favoured small-scale installations (buildings and rooftops), but small-scale PV systems (up to 20kWp) were the reference point for the respective measures.[886] Germany had always favoured roof top installations of small-scale PV, while further incentives enabling users to become producers and consumers continued in the 2010s (see analysis in chapter 3 and chapter 5).

Italy and France followed a different path. Italy started with small-scale rooftop installations in the early 2000s but given the interests of the dominant PV actors (see Chapter 6), the legislative framework started to include large(r)-scale PV installations to foster a domestic market for them. In France (see analysis in Chapter 6), grid-connected PV had one major opponent: EDF. When EDF entered the CIGS business, the legal framework changed (2006) to reflect this by introducing FiTs for BIPV. Until the early 2010s, the largest market share consisted of small-scale PV systems. The scenery changed rapidly when France committed in 2015 to reduce the of nuclear energy in electricity generation. The targets set (also for PV) imposed pressures on implementing the transition at a rapid pace, which resulted in an increased installation of large-scale PV systems.[887]

The Energy Union, as proposed by the European Commission, represents a vision for the future of the European energy system.[888] It proposes an EU-wide energy policy, to avoid fragmentation and suggests an ‘integrated continent-wide energy system’ that moves away

---

[883] Jäger-Waldau Arnulf, *PV Status Report 2018*, Publications Office of the European Union (Luxembourg: 2018).

[884] The analysis that follows seeks to provide an overall – yet not exhaustive – overview of a large share of the EU PV market. As such both large (e.g. Germany and Italy) and smaller markets are included.

[885] For more information see: Jäger-Waldau Arnulf, *PV Status Report 2019*, Publications Office of the European Union (Luxembourg: 2019).

[886] For more information see: Jäger-Waldau Arnulf, *PV Status Report 2018*, Publications Office of the European Union (Luxembourg: 2018).

[887] A year later, “the mandatory introduction of smart meters started”, resulting in the inclusion of small-scale PV. (Jäger-Waldau A., *PV Status Report 2017*, Publications Office of the European Union (Luxembourg: 2017), p. 14).

[888] European Commission, *A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy*, Brussels, 25.2.2015, COM(2015) 80 final.

from ‘an economy where energy is based on a centralized, supply-side approach’.[889] To respond to the challenges of climate change, the European Commission establishes a direct link between the transformation of the energy system and consumers. To ‘empower’ consumers, smart technologies are proposed, that:

> “… **will help consumers and energy service companies working for them to reap the opportunities available on the energy market by taking control of their energy consumption (and possible self-production)**. This will deliver more flexibility in the market and potentially reduce consumer bills. The **Commission will continue to** push for standardisation and to **support the national roll-out of smart meters and to promote the further development of smart appliances and smart grids**, so that flexible energy use is rewarded. It will develop synergies between the Energy Union and the Digital Single Market agenda and take measures to ensure privacy protection and cyber-security.”[890] (emphasis added)

To achieve the transformation of the energy system and to engage consumers in the transformation while making the energy market competitive, the European Commission proposes smart grids, smart technologies and smart appliances. The EU R&D programmes are a core part of achieving the Energy Union goals, especially R&D for RES. As we see in the European Commissions’ communication, this is particularly important:

> “A **new strategy for Research and Innovation** (R&I) **must be at the very heart of the Energy Union**. If Europe’s Energy Union is to be the world number one in renewable energies, it must lead on the next generation of renewable technologies as well as to storage solutions.”[891] (emphasis added)

Emphasizing the central role that research will play in the Energy Union, research has again been given the task of providing the technological means to achieve the energy policy goals

---

[889] European Commission, *A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy*, Brussels, 25.2.2015, COM(2015) 80 final, p. 2.

[890] European Commission, *A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy*, Brussels, 25.2.2015, COM(2015) 80 final, p. 11.

[891] European Commission, *A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy*, Brussels, 25.2.2015, COM(2015) 80 final, p. 16.

and targets. This represents a continuation of the second period, during which energy policy directly directed and defined the research policy priorities for energy technologies. In Horizon 2020, we observe the first projects for PV directly targeting consumers. These projects focused on "prosumers" by seeking their active engagement in the transformation of the energy system.[892]

7.2.7 Escalating the tensions between the EU and China

Silicon is an abundant material, but as both its production and refinement (for the PV sector) gradually concentrate in certain regions, this can act as a leverage. As we have seen, not only is production and refining of silicon becoming increasingly geographically concentrated, but the production of c-Si cells and modules is following a similar path, which recent developments in PV installation are also following.

As the EU's dependency on regions in the Global South for critical resources to meet ambitious energy policy goals increases, geopolitical tensions will intensify. The first alarm along the supply pipeline sounded in 2008 when the Chinese government imposed export tariffs on silicon.[893] In response, the USA and EU filed complaints with WTO and the issue was soon resolved.[894]

China has gradually increased its power at both ends of the production chain (i.e. mining and end product) for the key PV technology on which the European PV industry and (EU) vision was built, while showing the first signs of how it could exert geopolitical pressure not only on the realization of the energy transition, but also on the EU economies.

Following the rare earths incident, which was much discussed by scholars, tensions between the EU and China escalated further when the European Commission issued a press release imposing provisional anti-dumping tariffs on Chinese solar panels on 4 June 2013.[895,896] While tensions between the EU and China continue, we observe that the EU has further increased its funding under Horizon 2020 for c-Si thin films developed by the research networks in response

---

[892] See for example (in cordis) the Horizon 2020-funded 'iDistributedPV' project.

[893] Including metal silicon, ferrosilicon, and metallurgical grade silicon (the latter is the base feedstock upon which the Si feedstock is produced).

[894] Regarding the complaint and the surrounding events see: Office of the United States Trade representative, *WTO Case Challenging China's Export Restraints on Raw Material Inputs*, USTR, Available online: https://ustr.gov/about-us/policy-offices/press-office/fact-sheets/2009/june/wto-case-challenging-chinas-export-restraints-raw-materi, (accessed 15 May 2020).

[895] See for example: Kalantzakos Sofia, *China and the Geopolitics of Rare Earths*, Oxford University Press (New York: 2018).

[896] To read the full press release issues by the EC, as well as the events that preceded it see: European Commission, *EU imposes provisional anti-dumping tariffs on Chinese solar panels*, Europa, 4 June 2013, Brussels, Available online: https://ec.europa.eu/commission/presscorner/detail/en/IP_13_501, (accessed 15 May 2020).

to the silicon crisis in PV. Given the knowledge-intensive character of the EU's R&D programmes, these 'hybrid' cells can be seen as a possible response to Chinese pressure to find a technical competitive advantage (in relation to competition). However, the uncertainty about the geopolitical ramifications of securing the supply of all these materials remains unanswered. In neither period was the entire production chain examined nor was geopolitics a dimension included in the PV research agenda, nor was geopolitics a concern that reoriented or redefined the technical choices and/or selections. We argue that the term used by the networks in defining the 'steps' of research interest (i.e. the value chain) points to the lack of a more holistic view – like the problems we identified. At the same time, one possible explanation is that it is taken 'for granted' that certain regions of the Global South are (and will remain) the 'extractive pool' for the raw materials that the Global North needs.

7.3 Concluding remarks

As the urgency to become carbon-neutral intensifies, EU energy policy calls for a simultaneous disentanglement from oil (and its extraction) and an entanglement from minerals, as well as an intensification of mining and the externalities deriving from mining activities. Essentially, the EU's long-term energy strategy is material-intensive and increasingly dependent on the supply of a range of minerals that enable the successful implementation of the RES transition (including PV), making the EU potentially vulnerable to pressure from 'overseas'.

As material flows are continuously diverted from the Global South to both the Global North and Global South, China plays a critical role in the transition to RES, as does South Korea (polysilicon) and Taiwan (PV cell/module) to a lesser extent. There has thus been a restructuring of material flows – and their geographical distribution – throughout the entire PV production chain for the key technology (c-Si flat plate PV) based on which the EU energy targets have been set for PV. Given the current and ongoing war between Russia and Ukraine, the EU's response to the energy crisis enhances further the urgency of a faster transition to RES. In this context of urgency, PV is envisioned to play a central role.

As material flows have been restructured, they challenge the power dynamics between the formerly dominant regions of the Global North and the new dominant regions of the Global South, along the production chain. Concurrently, this signals a shift and/or a transfer of power to the regions of the Global South, not only to achieve the RES transition but also to further strengthen the EU economies.

Even though silicon is an abundant mineral, is has been at the heart of two material crises. In a coherent fashion to the EU energy and research policies' relationship in the second period, the EU R&D programmes sought to ease the material supply situation. This is reflected in the fact that the EU increased its R&D funding for other PV technologies. In the case of CPV, this was achieved by a 'switch' from low to high CPV, essentially a shift from c-Si to III-V semiconductor materials. In the case of CPV, this shift was a direct means and necessity to disentangling from silicon. Similarly, the research agenda of the c-Si research networks shifted to pursuing the c-Si thin films agenda. This affected not only the allocation of R&D funds, but also the research priorities, geography and structure for a-Si networks. Essentially, the networks in both cases sought to respond to the silicon crisis, not the geopolitical dimension from the supply of raw materials.

Based on our analysis, we have shown that the silicon crisis redirected research agenda for PV. However, geopolitics was not included in the research projects either as a dimension or as a concern. Essentially, geopolitics was not included an integral part of the formulation of the EU research agenda for PV. Rather, the networks were responding to the needs of upscaled production and trying to find solutions to the silicon crisis. The actors who formed the networks never addressed the geopolitical dimensions of the crisis (e.g. geographic concentration or geographic transfer of production), showcasing that the geopolitical aspects related to the materials required for the technologies they were developing – and to which they directed the research agenda – did not play a role in the selection of the relevant choices. Essentially, there was no dialogue between energy policy, research policy and geopolitics. Geopolitics remained a separate sphere that was not taken into account in the decision-making processes for formulating the research agenda, nor was it part of the energy policy that redirected research policy in the second period. The 'narrow' definition of the 'value chain' does not allow (or perhaps intentionally hides) a more holistic view and/or assessment of the problems we have identified. In an effort to address this 'gap' and begin accounting for the externalities deriving from PV, we have employed the term 'production chain', which starts with mining and ends with the end-of-life cycle. One possible explanation for this 'gap', is that it is taken 'for granted' that certain regions of the Global South are (and will continue to be) the 'extractive pool' for the raw materials that the Global North needs.

Based on the above, the Global North-South divide is confirmed (and reproduced) for certain regions (e.g. Chile, Peru, etc.). As mining activities are transferred to certain regions of the Global South, they divide is reinstated and reinforced as these regions become the extractive pool supplying the Global North for the benefit of the latter. Although China is part of the

Global South, it does not fall into this category. As the concentration and control of gradually more of the production chain steps is transferred to China, it serves as a means of geopolitical empowerment. As Kalantzakos notes "[t]he PRC has continued to portray itself as a developing nation working with others in the developing world on a common agenda".[897] In other words, China reproduces this 'self-positioning' as a region of the Global South. At the same time, China is gradually gaining more power in the geopolitical setting through the transfer of production. As evident the two 'tensions' events show, China is exerting geopolitical pressure because of its power in the supply of materials required for PV.

By analysing concerning the externalities deriving from the entire production chain, we trace two major gaps in research and its assessment. First, the externalities deriving from mining, second, the externalities resulting from the recycling of end-of-life products. These externalities have never been part of research and have been consistently ignored or overlooked, leading to recognition injustices. The global dimensions of externalities deriving from the entire production chain have never been examined. Ignoring the injustices that emerge from these global chains leads to the reproduction of injustices that are not taken into account or evaluated, as their occurrence is consistently overlooked. Ignoring these dimensions thus promoted the further deepening and enhancement of injustices between the Global North and the Global South. This is especially true for the distribution injustices (environment, health, land degradation, labour risks etc.).

This partial 'outlook' of research leads to issues related to the social, political, and geopolitical dimensions of these technologies being 'lost', as they are consistently not included in the research agendas and priorities. One possible remedy would be to increase the involvement of decision-making platforms (e.g. NGOs, civil society). This can enable the inclusion of different 'voices' in defining the problems (different vulnerabilities, challenges etc.) and their solutions throughout the entire production chain (strengthening the anticipatory capacities of the decision-making system). At the same time, this involvement can also create barriers to the promotion of corporate interests. It is important to include the values, priorities, and meanings of these technologies in response to energy challenges, rather than in response to industrial competitions.

Even though the networks were always mission-oriented, targeting and sought solutions to the crisis at hand, not all externalities were being considered. By following the externalities

---

[897] Kalantzakos Sofia, "Introduction – Rare Earths: A Crisis in the Making", *in* China and the Geopolitics of Rare Earths, (New York: Oxford University Press, 2018), p. 4.

resulting from the different steps of the production chain the divide between the Global North-South is further deepened/enhanced. China in particular, is burdened by the externalities (health, environment, labour etc.). This can also help to understand how 'development' is contextualized in the Chinese context and these externalities are
neglected or not considered.

However, when we combine these two dimensions (i.e. externalities and geopolitics), we face a unique situation. Most notably, it leads to a particular understanding of how the Global North-South divide works. Based on the analysis of the externalities deriving from the different steps of the production chain, the Global South is the extractive pool of the Global North, from which the latter benefits. This includes China and other regions of the Global South (e.g. Chile, Peru etc.). On the other hand, if we look at how China has used the two events (tensions) regarding the supply of PV materials and how China has exerted pressure, we see that China is geopolitically strengthened. This is not the case in other regions of the Global South, resulting in complex geopolitical dynamics that pose a challenge to the perception and analysis of the Global North-South divide in the unique case of China.

The European Commission has directly stated that R&D (Horizon 2020) should address the critical issue of securing the material supply of the energy technologies required to achieve the EU's energy policy vision. This was materialized by 'trends' in research we observed in Horizon 2020, which followed the same path as analysed in Chapters 4-6. Concurrently, engaging consumers, who the European Commission envisages to play an active role in the transformation of the new energy system, and the construction of new consumers (especially prosumers) were also among the PV projects funded by pertained Horizon 2020. However, as the European Commission seeks to engage consumers in the transformation of the new energy system, some member states have either not engaged the users in the design of their energy policies and targets or have 'rushed' the transition, indirectly marginalizing them.

Given the material possibilities offered by flat-plate PV offer, they enable a unique system integration option that was realised early on by the European Commission and some member states (notably Germany). The lack of consistent policy measures, that can foster the RES transition, limits the multiple applications and uses this unique technology offers. This has implications for the energy system transformation, as the transition to smart grids, smart meters etc. is largely dependent on the integration of PV into the urban environment. Furthermore, amid (yet) an(other) energy crisis, more research is needed on the key minerals and/or energy resources required for a successful implementation of the transition to RES – not only on RES technologies, but also on energy storage and smart grids. At EU level, better synergies between and across sectoral policies should be promoted, which can provide insights for policy makers. These proposals can help predict – in advance – potential obstacles to achieving the EU energy vision, while avoiding or minimizing tensions.

References

Agora Energiewende and Ember, *The European Power Sector in 2020: Up-to-Date Analysis on the Electricity Transition*, 2021.

Aulich H., Schulze F., “Silicon feedstock for the photovoltaic industry”, *in* Seventeenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Munich, Germany, 22-26 October 2001, B. McNelis, W. Palz, H. A. Ossenbrink, P. Helm (eds.), Vol. I, WIP-Munich & ETA-Florence: 2002, p. 65-68.

Bernreuter Johannes, 29 June 2020 [last updated 27 April 2022], berneuter, *Silicon Manufacturers: How the ranking of the top ten producers has been whirled around since 2004*, Available online: https://www.bernreuter.com/polysilicon/manufacturers/, (accessed 3 November 2021).

Cartwright E., “Mining and its health consequences”, *in* A Companion to the Anthropology of Environmental Health, M. Singer (ed.), John Wiley (Chichester, UK: 2016), p. 417–434.

Ceccaroli Bruno and Lohne Otto, “Solar Grade Silicon Feedstock”, *in* Handbook of Photovoltaic Science and Engineering, Antonio Luque and Steven Hegebus (eds.), Wiley & Sons (Second Edition, UK: 2011), p. 153-204.

Chigondo Fidelis, “From Metallurgical-Grade to Solar-Grade Silicon: An Overview”, *Silicon*, 2018, p. 789-798.

Commission of the European Communities, *Single European Act*, Office for Official Publications of the European Communities (Luxembourg: 1986).

Correlje Aad and van der Linde Coby, “Energy supply security and geopolitics: A European perspective”, *Energy Policy*, 2006, p. 532-43.; Renner Michael, “The New Geopolitics of Oil”, *Development*, 2006, p. 59-63.

Costogue E., Ferber R., Hasbach W., Pellin R., and Yaws C., *Silicon Material Outlook Study for 1980-85 Calendar Years*, Jet Propulsion Laboratory: Report Prepared for the US Department of Energy, (November 1, 1979: JPL Publication 79-110).

Costogue E. N. and Ferber R. R., “Polycrystalline Silicon Material Availability and Market Pricing Outlook for 1980 through 1988”, *in* Fifth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Kavouri (Athens), Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 1027-1031.

CRU Consulting, *Market Trend Report: Silver’s important role in solar power*, CRU International Limited (UK: June 2020).

Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE), Official Journal of the European Union, 24.7.2012.

EcoGreen Energy, Solar Energy Deployment in EU 2030, Available online: https://www.eco-greenenergy.com/solar-energy-deployment-in-eu-2030-global-energy-crisis/, (accessed 1 June 2022).

Elgstrand K., Sherson D. L., Jørs E., Nogueira C., Thomsen J. F., Fingerhut M., Burström L., Rintamäki H., Apud E., Oñate E., Coulson N., McMaster L., Clarke E. E., "Safety and Health in Mining: Part 1*", Occupational Health Southern Africa*, 2017, p. 10-20.

European Commission – Directorate General for Energy, *THERMIE-ALTENER: Renewable Energy Report*, Office for Official Publications of the European Communities (Luxembourg: 1998).

European Commission – DG JRC, *PVNET Workshop Proceedings: 'RTD Strategies for PV'*, held at JRC Ispra, 30-31 May 2002.

European Commission, *The raw materials initiative — meeting our critical needs for growth and jobs in Europe*, COM(2008) 699 final, Brussels, 4.11.2008.

European Commission, *Tackling the Challenges in Commodity Markets and on Raw Materials*, COM(2011) 25 final, Brussels, 2.2.2011.

European Commission, *A Roadmap for moving to a competitive low carbon economy in 2050*, COM (2011) 112 final, Brussels, 8.3.2011.

European Commission – DG Environment, *Study on PV Panels Supplementing the Impact Assessment for a recast of the WEEE Directive*, Final Report, 14 April 2011.

European Commission, *Materials Roadmap Enabling Low Carbon Energy Technologies*, SEC(2011) 1609 final, Brussels, 13.12.2011.

European Commission, *On the review of the list of critical raw materials for the Eu and the implementation of the Raw Materials Initiative*, COM(2014) 297 final, Brussels, 26.5.2014.

European Commission, *On the 2017 list of Critical Raw Materials for the EU*, COM(2017) 490 final, Brussels, 13.9.2017.

European Commission, *EU imposes provisional anti-dumping tariffs on Chinese solar panels*, Europa, 4 June 2013, Brussels, Available online: https://ec.europa.eu/commission/presscorner/detail/en/IP_13_501, (accessed 15 May 2020).

European Commission, *A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy*, COM(2015) 80 final, Brussels, 25.2.2015.

European Commission, *A Clean Planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*, COM (2018) 773 final, Brussels, 28.11.2018.

European Commission, *The European Green Deal*, COM (2019) 640 final, Brussels, 11.12.2019.

European Commission, Directorate-General for Climate Action, *Going climate-neutral by 2050: a strategic long-term vision for a prosperous, modern, competitive and climate-neutral EU economy*, Publications Office, 2019.

European Commission, *Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability*, COM(2020) 474 final, Brussels, 3.9.2020.

European Commission, *Strategic Energy Technology Plan*, Europa, Available online: https://energy.ec.europa.eu/topics/research-technology-and-innovation/strategic-energy-technology-plan_en#european-technology-and-innovation-platforms, (accessed 14 March 2022).

European Photovoltaics Industry Association, *Global Market Outlook: For Photovoltaics 2014-2018*, 2014.

Eurostat, (January 2022), Europa, *Renewable energy statistics*, Europa. Available online: (https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics) (accessed 18 March 2022).

Farinelli Ugo, Gelus M., Muus L. T., Rorsch A., Stocker H. J., *The evaluation of the Communities' energy conservation and solar energy R&D sub-programmes*, Office for Official Publications of the European Communities (Luxembourg: 1980).

Fraunhofer-ISE, 17 January 2022, Fraunhofer-ise, "*Public Net Electricity Generation in Germany in 2021: Renewables Weaker Due to Weather*", Available online: https://www.ise.fraunhofer.de/en/press-media/news/2022/public-net-electricity-in-germany-in-2021-renewables-weaker-due-to-weather.html, (accessed 19 November 2020).

Fraunhofer ISE, *Photovoltaics Report*, Freiburg: 24 February 2022.

Freiesleben W., "The solar material market: Projections needs & commitments", *in* Third EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes France, 27-31 October 1980, W. Palz (eds.), D. Reidel Publishing Company, (Dordrecht Holland, Boston USA, London England: 1981), p. 166-170.

Fthenakis V. M., and Moskowitz P. D., "Photovoltaics: Environmental, Health and Safety Issues and Perspectives", *Progress in Photovoltaics: Research and Applications*, 2000, 27-38.

Fthenakis V., and Zweibel K., *CdTe PV: Real and Perceived EHS Risks*, Presented at the

National Center for Photovoltaics and Solar Program Review Meeting, Denver, Colorado (US), March 24-26, 2003, (NREL/CP-520-33561), p. 1-3.

Habib Komal, Hamelin Lorie, Wenzel Henrik, “A dynamic perspective of the geopolitical supply risk of metals”, *Journal of Cleaner Production*, 2016, p. 850-858.

Hegedus Steven and Luque Antonio, “Achievements and Challenges of Solar Electricity from Photovoltaics”, *in* Handbook of Photovoltaic Science and Engineering, Antonio Luque and Steven Hegebus (eds.), Wiley & Sons (Second Edition, UK: 2011), p. 1-38.

Hodgkinson Jane H. and Smith Michael H., “Climate change and sustainability as drivers for the next mining and metals boom: The need for climate-smart mining and recycling”, *Resources Policy*, 2021, 101205.

Horner Rory and Carmody Padraig, “Global North/South”, *in* International Encyclopedia of Human Geography, (2nd ed.), Volume 6, Audrey Kobayashi (eds.), Elsevier (2019), p. 181-187.

Hund Kirsten, La Porta Daniele, Fabregas Thao P., Laing Tim, Drexhage John, *Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition*, International Bank for Reconstruction and Development/The World Bank (Washington: 2020).

Hunt Lee P., “Silicon precursors: Their manufacture and properties”, in Handbook of semiconductor silicon technology, William C. O’Mara, Robert B. Herring, Lee P. Hunt (eds.), Noyes Publications (USA: 1990).

Jäger-Waldau Arnulf, *PV Status Report 2003*, Office for Official Publications Office of the European Communities (Luxembourg: 2003).

Jäger-Waldau Arnulf, *PV Status Report 2005*, Office for Official Publications Office of the European Communities (Luxembourg: 2005).

Jäger-Waldau Arnulf, *PV Status Report 2006*, Office for Official Publications Office of the European Communities (Luxembourg: 2006).

Jäger-Waldau Arnulf, *PV Status Report 2007*, Office for Official Publications Office of the European Communities (Luxembourg: 2007).

Jäger-Waldau Arnulf, *PV Status Report 2008*, Office for Official Publications Office of the European Communities (Luxembourg: 2008).

Jäger-Waldau Arnulf, *PV Status Report 2009,* Publications Office of the European Union (Luxembourg: 2009).

Jäger-Waldau Arnulf, *PV Status Report 2010,* Publications Office of the European Union (Luxembourg: 2010).

Jäger-Waldau Arnulf, *PV Status Report 2011,* Publications Office of the European Union (Luxembourg: 2011).

Jäger-Waldau Arnulf, *PV Status Report 2014,* Publications Office of the European Union (Luxembourg: 2014).

Jäger-Waldau Arnulf, *PV Status Report 2016*, Publications Office of the European Union (Luxembourg: 2016).

Jäger-Waldau Arnulf, *PV Status Report 2017*, Publications Office of the European Union (Luxembourg: 2017).

Jäger-Waldau Arnulf, *PV Status Report 2018*, Publications Office of the European Union (Luxembourg: 2018).

Jäger-Waldau Arnulf, *PV Status Report 2019*, Publications Office of the European Union (Luxembourg: 2019).

Jäger-Waldau Arnulf, *PV Status Report 2021,* Publications Office of the European Union (Luxembourg: 2021).

Jäger-Waldau Arnulf, "R&D roadmap for PV", *Thin Solid Films*, 2004, p. 448-454.

Joint Electron Tube Engineering Council, JEDEC, *JEDEC History – 1980s*, Available online: https://www.jedec.org/about-jedec/jedec-history/1980s, (accessed 10 November 2020).

Kalantzakos Sofia, *China and the Geopolitics of Rare Earths*, Oxford University Press (New York: 2018).

Kandiyoti Rafael, "What price access to open seas? The geopolitics of oil and gas transmission from the Trans-Caspian republics", *Central Asian Survey*, 2008, p. 75-93.

Klugmann-Radziemska Ewa and Kuczyńska-Łażewska Anna, "The use of recycled semiconductor material in crystalline silicon photovoltaic modules production - A life cycle assessment of environmental impacts", *Solar Energy Materials and Solar Cells*, 2020, 110259.

Koch W., Woditsch P., "Solar grade silicon feedstock supply for PV industry", *in* Seventeenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Munich, Germany, 22-26 October 2001, B. McNelis, W. Palz, H. A. Ossenbrink, P. Helm (eds.), Vol. I, WIP-Munich & ETA-Florence: 2002, p. 73-76.

London Leslie and Kisting Sophia, "The Extractive Industries: Can We Find New Solutions to Seemingly Interactable Problems?", *A Journal of Environmental and Occupational Health Policy*, 2016, p. 421-430.

Looney Robert, "Recent Developments on the Rare Earth Front, Evidence of a new technocratic mercantilism emerging in China?", *World Economics*, Vol. 12, No.1, January-March 2001, p. 47-78.

Manberger Andre and Johansson Bengt, "The geopolitics of metals and metalloids used for the renewable energy transition", *Energy Strategy Reviews*, 2019, p. 1-10.

Manning D. A. C., Raw materials for the glass industry, *in* Introduction to Industrial Minerals, Springer (Dordrecht: 1995), p. 120-140.

Moss R. L., Tzimas E., Kara H., Willis P., Kooroshy J., *Critical Metals in Strategic Energy Technologies: Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies*, Publications Office of the European Union (Luxembourg: 2011).

Mudd G. M., Weng Z., Memary R., Northey S. A., Guirco D., Mohr S., Mason L., *Future Greenhouse Gas Emissions from Copper Mining: Assessing Clean Energy Scenarios*, Prepared for CSIRO Minerals Down Under National Research Flagship by Monash University Institute for Sustainable Futures, University of Technology, October 2012.

Nakopoulou Efi and Arapostathis Stathis, "Reconfiguring Technologies by Funding Transitions: priorities, policies, and the renewable energy sources in the European Community funding schemes", *Journal of Energy History/Revue d'Histoire de l'Énergie* [Online], n°4, published 27 July 2020.

New York State Department of Health, health.ny.gov, *Silicosis and Crystalline Silica Exposure and Mining: Information for Workers*, Available online: https://www.health.ny.gov/environmental/investigations/silicosis/mineworker.htm, (accessed 20 May 2022).

Nordmann Thomas, "Subsidies Versus Rate based Incentives; For Technology – Economical – and Market-Development of PV. The European Experience", *in* Proceedings of Third World Conference on Photovoltaic Solar Energy Conversion, Joint Conference of Thirteenth PV Science and Engineering Conference, Thirtieth IEEE PV Specialists Conference, Eighteenth European PV Solar Energy Conference, Osaka, Japan, 11-18 May 2003, Kosuke Kurokawa, Lawrence L. Kazmerski, Bernard McNelis, Masafumi Yamaguchi, Christopher Wronski, Wim C. Sinke (eds.), IEEE: 2003, [CD ROM file number: 8OD1102], (pdf) p. 1-4.

Office of the United States Trade representative, USTR, *WTO Case Challenging China's Export Restraints on Raw Material Inputs*, Available online: https://ustr.gov/about-us/policy-offices/press-office/fact-sheets/2009/june/wto-case-challenging-chinas-export-restraints-raw-materi, (accessed 15 May 2020).

Overland Indra, "The geopolitics of renewable energy: Debunking four emerging myths", *Energy Research and Social Science*, 2019, p. 36-40.

Papoutsis Christos, [Introductory conference speech], *in* Second World Conference on Photovoltaic Solar Energy Conversion, Fifteenth European PV Solar Energy Conference, Twenty Seventh US IEEE Photovoltaics Specialists Conference, Tenth Asia/Pacific PV Science and Engineering Conference, Proceedings of the International Conference held at Vienna, Austria, 6-10 July 1998, J. Schmid, H. A. Ossenbrink, P. Helm, H. Ehmann and E. D. Dunlop (eds.), Vol. II, WIP Renewable Energies: 1998, [CD-ROM], p. xl-xliii.

Paltsev Sergey, “The complicated geopolitics of renewable energy”, *Bulleting of the Atomic Scientists*, 2016, p. 1-6.

Palz Wolfgang, “Keynote Speech: Photovoltaics in Europe and the World”, *in* PV in Europe - From PV Technology to Energy Solutions, Proceedings of the International Conference held in Rome, Italy, 7-11 October 2002, J. L. Bal, G. Silvestrini, A. Grassi, W. Palz, R. Vigotti, M. Gamberale, P. Hem (eds.), WIP-Munich & ETA-Florence: 2002, p. xxxix-xl.

Parks Christine G., Conrad Karsten, Cooper Glinda S., “Occupational Exposure to Crystalline Silica and Autoimmune Disease”, *Environmental Health Perspectives*, 1999, p. 739-802.

Pollard Kenneth Michael, “Silica, Silicosis, and Autoimmunity”, *Frontiers in Immunology*, 2016, p. 1-7.

Prieto B., Silva B., Aira N., “Methodological aspects of the induction of biofuels for remediation of the visual impact generated by quartz mining”, *Science of the Total Environment*, 2006, p. 254-261.

Poortmans J., Reber S., Gall S., Zahedi C., Alonso J., “European Cluster on High- and Intermediate Temperature Thin-Film Crystalline Si Solar Cells R&D: Overview of Running Projects and Underlying Roadmap”, *in* Nineteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Paris, France, 7-11 June 2004, W. Hoffmann, J. L. Bal, H. Ossenbrink, W. Palz, P. Helm (eds.), WIP-Munich & ETA-Florence: 2004, p. 397-402.

Raman Sujatha, “Fossilizing Renewable Energies”, *Science as Culture*, 2013, p. 172-80.

Regulation (EU) No 1291/2013 of the European Parliament and the Council of 11 December 2013 establishing Horizon 2020 – the Framework Programme for Research and Innovation (2014-2020) and repealing Decision No 1982/2006/EC, L 347, 20.12.2013, Official Journal of the European Union, p. 104-173.

Salomons W., “Environmental impact of metals derived from mining activities: Processes, predictions, prevention”, *Journal of Geochemical Exploration*, 1995, p. 5-23.

Schnebele Emily, 11 January 2018, Earth magazine, *Mineral Resource of the Month: Silicon*, Available online: https://www.earthmagazine.org/article/mineral-resource-month-silicon/, (accessed 1 March 2021).

Scholten Daniel and Bosman Rick, “The geopolitics of renewables: exploring the political implications of renewable energy systems”, *Technological Forecasting & Social Change*, 2016, p. 273-283.

Scholten Daniel, Bazilian Morgan, Overland Indra, Westphal Kirsten, “The geopolitics of renewables: New board, new game”, *Energy Policy*, 2020, 111059.

Schrecker Ted, Birn Anne-Emanuelle, Aguilera Mariajose, “How extractive industries affect health: Political economy underpinnings and pathways”, *Health & Place*, 2018, p. 135-147.

Stegen Smith Karen, “Heavy rare earths, permanent magnets, and renewable energies: An imminent crisis”, *Energy Policy*, 2015, p. 1-8.

Stiftelsen for industriell og teknisk forskning, 25 January 2006, SINTEF, *FOXY project summary*, Available online: https://www.sintef.no/projectweb/foxy/project-summary/, (accessed 15 November 2020).

SolarPower Europe, *Global Market Outlook for Solar Power 2021-2015*, 2021.

The European Association for Industrial Silica Producers, eurosil, *Silica and Health*, Available online: https://eurosil.eu/silica-and-health/, (accessed 23 May 2022).

Treble F. C., “Summary Report: 1980 Photovoltaic Solar Energy Conference”, *in* Third EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes France, 27-31 October 1980, W. Palz (eds.), D. Reidel Publishing Company, (Dordrecht Holland, Boston USA, London England: 1981), p. xxvii-xliii.

Treble F. C., “Material Problems of the Photovoltaics Industry: A report on panel discussion B”, *in* Sixth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in London, UK, 15-19 April 1985, W. Palz and F.C. Treble (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1985), p. 34-35.

United Nations, “Paris Agreement”, 2015 (https://unfccc.int/sites/default/files/english_paris_agreement.pdf).

United States Department of Labour - Occupational Safety and Health Administration, OSHA, *Safety and Health Topics/Silica, Crystalline*, Available online: https://www.osha.gov/silica-crystalline/health-effects, (accessed 25 May 2022).

US Geological Survey, “Mineral Commodity Summaries 1996”, (Washington DC: US Geological Survey, 1996.

US Geological Survey, “Mineral Commodity Summaries 2002”, (Washington DC: US Geological Survey, 2002).

US Geological Survey, “Mineral Commodity Summaries 2006”, (Washington DC: US Geological Survey, 2006).

US Geological Survey, “Mineral Commodity Summaries 2010”, (Washington DC: US Geological Survey, 2010).

US Geological Survey, “2010 Minerals Yearbook: Rare Earths”, (Washington DC: US Geological Survey, 2012).

US Geological Survey, “Mineral Commodity Summaries 2015”, (Washington DC: US Geological Survey, 2015).

US Geological Survey, “Mineral Commodity Summaries 2021”, (Washington DC: US Geological Survey, 2021).

Veraart Frank and Arapostathis Stathis, “Entangling Technological Infrastructures, Material Flows and Environmental Modernities”, Tensions of Europe Workshop, 2022.

Woditsch P., Koch W., “Solar grade silicon feedstock supply for PV industry”, *Solar Energy Materials & Solar Cells*, 2002, p. 11-26.

Xu Yan, Li Jinhui, Tan Quanyin, Peters Anesia Lauren, Yang Congren, “Global status of recycling waste solar panels: A review”, *Waste Management*, 2018, p. 450-458.

Chapter 8. Conclusions

In this chapter we summarize our main arguments and reach our conclusions. This chapter is divided into five main sections. In section 8.1 we discuss the mineral-intensive side of the RES transition and the accumulation of increasingly more steps in the production chain in certain regions (especially China). We argue that the EC has been actively constructing the market for PV technologies. Through a bottom-up research policy, the technoscientific research networks that formed the 'pool' of national PV interests made the technological choices that shaped and defined the European market for PV technologies (8.1.1). However, the selections made for the transition to RES, as proposed and endorsed by the European Commission, result in a technological lock-in (8.1.2). This, in turn leads to a series of dependencies that call into question the successful implementation of the transition to RES. The geopolitics that are being established, by the RES transition, challenge the insofar notion of Global North-South divide in the case of China, which is becoming geopolitically empowered by this transition while bearing the burden of the production chain externalities (section 8.1.3).

In section 8.2 we examine the political economy of the EU for/or research. We focus on who is funding (section 8.2.1), where this funding goes and what is funded (section 8.2.2). Regarding the former, we examine whether the EU was/is directing the national research or vice versa. We argue that the Commissions' clear prioritization of PV over all other RES in R&D funding has enabled the promotion of certain member states' interests over others. The programme evaluators of the first two energy R&D programmes noted a series of issues regarding the project selection and rejection procedures alongside the direct selection of projects by the Commission and the overlap between individuals advising the Commission and directly benefiting from the programmes, which can be understood as issues of bias and lack of transparency. The non-delineation between the demonstration and pilot programmes is discussed in section 8.2.1.1. We argue that the non-delineation between these two programmes has resulted in a duplication of efforts and funding. By using "risk" as a justification for this continuous financial support to the private sector, the Commission was taking all the "risks" by using public funding. 'Where' the funds go and 'what' is funded are explored in section 8.2.2. We argue that the distribution of R&D funding has never been even or equal and that the EU enlargements had no impact on the redistribution of funds. Rather, the distribution of EU funding for R&D reproduces and reinforces inequalities between the countries of the European North and South. These inequalities have emerged from the technological choices, which further empowered the actors of the European North. The selection of c-Si promoted the interests of the electronics industry that was at large located in the European North. Through this selection allowed the electronics industry to enter a new market (the energy market), whereas the new actors who did not have the corresponding capacities, know-how and expertise were at a disadvantage (i.e. a gap in terms of know-how, knowledge and infrastructures (production) etc.). The choice of c-Si thus constructed and reproduced a division between the old actors and the newcomers. Given the specific geographical dimension(s) of the electronics sector (and industry), this choice formed a social order that further reinforced and solidified the European North-South divide (section 8.2.2). Efforts to develop CPV were halted and stalled by semiconductor electronics actors who actively pursued the development of c-Si flat plate PV. We argue that this alternative technological design was marginalized due to the vested interests of semiconductor electronics sector actors in the context of technological competitions (section 8.2.2.1). The contrasting applications enabled by CPV can help us attribute a complementary understanding regarding CPV's marginalization. We argue that CPV was marginalized because it limited PV applications by promoting large-scale PV installations. It was an 'obstacle' to the potential of the further energy market liberalization and energy system reconfiguration, which was the politics of the c-Si network actors. In section 8.2.3, we use the analytical concept of 'upscaled research' to provide insights into the characteristics of the Knowledge-Based Economy (KBE). We argue that the KBE conditioned the networks' structure, and in turn, the KBE's context was conditioned by the networks. The thrust to narrow the gap between research and the market, and by extension help construct the KBE, further augmented the role of actors who had the capacities and infrastructures to carry out this 'upscaled research'. Moreover, the KBE further empowered the already strong actor networks and reproduced the networks' power, especially those of the dominant technology who gained prominence in defining the research agenda and priorities resulting in the restructuring other technologies' networks and the reorientation of their research agenda and priorities (a-Si case). This empowerment had implications for the technology and energy markets. Although indirectly, the KBE supported and promoted the possibility to shift towards small-scale PV installations and distributed electricity generation and consumption. The actors who had the capacity to conduct the EU-funded 'upscaled research' were limited, while those who did not have the prerequisite knowledge infrastructures were either marginalized or excluded. Even though knowledge creation expanded geographically in the second period, those with the capacity(-ies) to exploit it remained geographically uneven and constrained. Thus, not only did the KBE further empower the already strong actors of the networks, but at the same time the emphasis on knowledge infrastructures led to the marginalization of small research groups, universities and certain geographical areas (see also section 8.2.2).

In section 8.3 we briefly summarize the relationship between EU research and energy policies from 1975 to 2020. We argue that during the first period, the politics of the research networks (bottom-up research policy) promoted small-scale PV through the understanding that this technical option could reconfigure the architecture of the energy system and its infrastructures. Because of the material possibilities offered by this technology, the networks chose the technological frontrunner (i.e. c-Si flat plate). This in turn comprised the basis for the formulation of the Commissions' energy policy. In other words, the Commission adopted the politics of the research networks to set the energy policy goals, actively promoting (i) the reconfiguration of the energy system and (ii) the further liberalization of the energy market. This desire for further liberalization of the energy market led to the promotion of research activities for system integration, coming full circle back to research again. Given the actors in the system integration networks, who are primarily from the energy sector, we argue that this research directed them to accept and materialize the further liberalization of the energy market. However, the design of the artifacts and the network were not a mutual undertaking, nor were the corresponding research endeavours. We argue that this fragmentation of research activities, keeping the artefact separate from the network, enabled the interests of energy sector actors to marginalize and/or hinder the research required for small-scale PV system integration. As member states make energy supply decisions, choices vary as not all member states 'embrace' the unique possibilities offered by small-scale PV. We argue that both the politics of the research networks and the Commission's politics to promote small-scale PV installations have not fully materialized because the electricity supply decisions were/are made at the national/state level.

In section 8.4 we discuss two important dimensions of/for research policy. The first concerns those "moments" that provide an opportune moment for change (i.e. crises), whereas the second concerns what kind of changes are needed in research policy by first identifying the gaps in the insofar definition of the problems the networks were trying to solve. Regarding the former, the prominent role of crises in reorienting research policy and priorities is discussed in section 8.4.1. We argue that crises can be understood as "opportune moments", that pray open the window for new sectors, areas, directions and choices. Moreover, in times of crisis, the relationship between policy areas shifted and the dynamic interplay between the Commission and the member states was reshaped as the Commission sought to gain further powers. This section concludes with insights into current and ongoing crises (i.e. the global pandemic and the energy crisis). In section 8.4.2, we argue that the insofar missions are not holistically defined, leading to gaps in both the research and the 'solutions' proposed by the research. At the same time, we trace the prevalence and prioritization of an 'economic rationale' and argue that this (further) promotes the establishment of problems or challenges that are not holistically defined. Lastly, in section 8.5 we make recommendations for future research.

8.1 RES transition: fostering new dependencies and redefining the Global North – South divide

The EU-supported transition to RES is both mineral-intensive and results in entanglements with another extractive industry (i.e. mining of minerals) and their corresponding geographies. This directly leads to the creation of new dependencies for the successful implementation of the RES transition. As increasingly more of the steps in the 'production chain' are geographically concentrated in regions of the so-called Global South, this leads to two distinct but complementary shifts. First, the choice of minerals on which the EU depends is shifting to other regions. Second, it shifts the geopolitical dynamics that the EU itself indirectly reinforces through the selection of mineral resources, which in turn puts pressure on the previously dominant geopolitical dynamics. This leads to the emergence of new powerful regions that can impose pressure on the successful implementation of the RES transition and problematize the notion of a Global North-South divide. For PV and other key components needed for the transition to RES (e.g. batteries), the EU is increasingly dependent on China.[898]

8.1.1 Constructing the technology market of the EU

Even though we lack information on the actual results (outcomes/deliverables) of the funded research projects and therefore do not have a complete account from the historical actors on the outcome of their research (i.e. research project outcomes: patents, intellectual property rights etc.), we will try to show the links between the research conducted by the EU and its

---

[898] Hatch Gareth P., "Dynamics in the Global Market for Rare Earths", *Elements*, 2012, p. 341-446.; Stegen Smith Karen, "Heavy rare earths, permanent magnets, and renewable energies: An imminent crisis", *Energy Policy*, 2015, p. 1-8.; Kalantzakos Sofia, China and the Geopolitics of Rare Earths, (New York: Oxford University Press, 2018).; Luo Jin and He Hongwei, "Trade Dispute on rare Earths Export from China to the United States, *Advances in Economics, Business, and Management Research*, 2018, p. 391-394.; Manberger Andre and Johansson Bengt, "The geopolitics of metals and metalloids used for the renewable energy transition", *Energy Strategy Reviews*, 2019, p. 1-10.

linkage and/or connected to the technology and the energy market. We argue that the research policy of the EC has been important for the formation of the technology market.[899]

As Laredo has already pointed out, the involvement of both private and public French actors in the Framework Programmes is an indication of the importance of examining EU research policy.[900] He shows that almost all major French public and private sector actors are involved in the EU-funded R&D programmes (i.e. the Framework Programmes). Similarly, we have shown through our analysis that all major European PV actors actively participate and are consistently present in the EU R&D programmes.[901,902] By collaborating with each other, these actors formed the technoscientific PV research networks and actively steered the EU research policy and agenda in both periods. These actors – and their politics – directed both the outcome of research in terms of available technological options and the direction of EU research funding for PV.

The technological choices made by the networks led to technological pluralism, but at the end of the first period to a clear technological frontrunner (c-Si flat plate PV), which became the building block of energy policy for PV (EC White Paper for RES, 1997). These technological choices are reflected in both the EU R&D funding and the (technological) PV market and go hand in hand. The Commission has consistently given priority to c-Si in the R&D programmes, with minor exceptions (FP1 shift to a-Si in response to Japanese competition). In parallel, the European, even the global (technological) PV market has been built on c-Si.[903] Moreover, we must not forget that the EC contributed to constructing the first European PV market in the 1980s through the pilot programmes.

---

[899] It should be noted that 'data problems' have been acknowledged by FP evaluators. There seems to be a chronic and persistent problem in the availability of information regarding both the actual outcome of the EU funded projects and especially the information surrounding patents and intellectual property rights deriving from this publicly funded research. For example, see the remarks made by the FP6-7 Energy programme evaluators: Geert van der Veen, Patrick Eparvier, Matthias Ploeg, Paola Trucco, *Evaluation of the impact of projects funded under the 6th and 7th EU Framework Programmes for RD&D in the area of non-nuclear energy*, Final Report (Version 4, 19 June 2013), Technopolis Group (2014), p. 1-2.

[900] Laredo Philippe, "The networks promoted by the framework programme and the questions they raise about its formulation and implementation", *Research Policy*, 1998, p. 589-598.

[901] All the actors involved in the PV cell/module manufacturing were present in the EU-funded research projects during the first period, whereas all the top PV cell/module manufacturing actors were actively participating in the second period research projects. Moreover, other important private sector actors from other parts of the production chain (e.g. polysilicon feedstock and other system components etc.) were also actively participating to the EU research projects, even though to a lesser extent. At the same time, several important actors from the scientific community of the member states had a strong participation in the projects (during both periods), comprising the core of the technoscientific research networks.

[902] Deriving from the national research landscape information we have collected and analysed in the empirical chapters.

[903] C-Si has almost consistently accounted for over 80% of the PV market, with two exceptions. First, during the 1980s when the share of a-Si peaked (for the first and last time); 32% in 1988. Second, during the Si crisis when thin films managed to attain a larger market share; up to 20% in 2009.

The European Commission R&D funding has increasingly prioritized the market frontrunner over research for market participants and those who create the scientific and technological basis of the European industry.[904] The field of PV is ‘patent – generating’, especially the EU-funded projects.[905] Although we do not have an exact figure or specific information per project, it has found that:

> “Within this context, the FP programme has delivered numerous outputs. Consortia of research institutions and enterprises have generated demonstrable knowledge in the form of patents, peer-reviewed publications and PhD’s. Several projects have established world records for cell efficiency. Some projects led to spin-off activities and while other projects have generated knowledge and practices that have spilled over to other sectors. These results have led to favourable outcomes for the European PV industry.”[906]

Overall, it was found that the EU-funded projects of the second period were directly linked to patent applications and a large number of peer-reviewed publications and have contributed to improving the competitiveness of the participants.[907] From this we can see that the knowledge generated by the EU-funded projects was transferred to spin-offs as well as to European industry. Given the overwhelming presence of European industry in the projects and research networks, and the overlap between the research and the technological frontrunners in the market, it is inevitable that the funded research has impacted and shaped the EU technology market. The EC has actively steered the market for PV technologies. Through a bottom-up research policy, the technoscientific research networks that formed a ‘pool’ of national PV interests made the technological choices that shaped and defined the European PV technology market.

---

[904] Even though we cannot assess if the research funded by the EC was fully or partially transferred to the market, we will employ the evaluations and assessments of the FPs.

[905] Geert van der Veen, Patrick Eparvier, Matthias Ploeg, Paola Trucco, *Evaluation of the impact of projects funded under the 6th and 7th EU Framework Programmes for RD&D in the area of non-nuclear energy*, Final Report (Version 4, 19 June 2013), Technopolis Group (2014).

[906] Geert van der Veen, Patrick Eparvier, Matthias Ploeg, Paola Trucco, *Evaluation of the impact of projects funded under the 6th and 7th EU Framework Programmes for RD&D in the area of non-nuclear energy*, Final Report (Version 4, 19 June 2013), Technopolis Group (2014), p. 110.

[907] Geert van der Veen, Patrick Eparvier, Matthias Ploeg, Paola Trucco, *Evaluation of the impact of projects funded under the 6th and 7th EU Framework Programmes for RD&D in the area of non-nuclear energy*, Final Report (Version 4, 19 June 2013), Technopolis Group (2014), p. 90.

8.1.2 Dependencies and geopolitical dynamics shift fostered and reinforced by the RES transition

With the 1997 White Paper for RES, the European Commission made a clear choice regarding the technology on which PV installations should be based. Similarly, in Germany, the roof-top programmes have helped construct the PV market and foster the industrial take-off of the PV sector.[908] In both cases, the technological choice was the same: c-Si flat-plate PV. The White Paper had a direct impact on the research priorities for PV in the second period, leading to a raw materials crisis (i.e. the Si crisis).[909] In other words, we argue that the choices made by the Commission at the energy policy level had an impact on the EU's (future) geopolitical and technological dependencies.[910] Moreover, both the technology and energy markets for PV were shaped/build on the basis of this selection. In the current EU long-term strategy RES plays a central role, while the choices made in the face of the current energy crisis give a clear priority to PV installations. The above selections (policy initiatives, industry, research, market) led to a technological lock-in: c-Si. This selection fostered certain dependencies that are reproduced. This has implications for the successful implementation of the transition to RES and how it can be implemented.

The entry of new polysilicon producers into the market, especially during the years of the silicon crisis, provided relief in the supply of polysilicon feedstock. However, the rise of China as a superpower along the production chain led to the demise of many European PV companies and eventually to their collapse. The silicon crisis was seen as a 'success story'. It was the events surrounding this crisis that put PV on the energy policy map, and it during this time PV installations increased, while the PV sector became industrial (in terms of production). During the second period, the geopolitical dimension surrounding the supply of polysilicon feedstock was not a concern for EU research policy. One possible explanation for why the geopolitical dimension was not a concern was provided by an interviewee from Fraunhofer-ISE. To paraphrase their words, it was a matter of increasing production capacities and it was only a matter of time before they did so.[911] Thus, a belief that the relevant industries will provide

---

[908] Even though other similar programmes launched by other member states, the German programme was critical.

[909] The energy policy goals redirected research in more ways than the one we mention here (e.g. networks structure, geographical distribution of funding, content of research activities etc.), evident by our empirical analysis. However, for the purposes of this section we limit the impact only to one of its dimensions.

[910] The dimension of the research networks technological selections is accounted for and assessed in a forthcoming section.

[911] The exact quote can be found in Chapter 5. In section 8.4 we provide a comprehensive interpretation regarding the lack of holistically defined challenges (e.g. why geopolitics was not a concern).

sufficient supply. However, apart from relying on the industry to solve the problem this does not fully explain the geopolitical dimension that has inevitably changed the PV scene and increased the EU's dependencies. Another possible explanation stems from the abundance of silicon and its geographically dispersed extraction, processing and production of c-Si cells and modules. The rise of China helped deflate the market at a time of crisis and foster the perception of China as a good supplier.

The rare earths that have been widely discussed by scholars, are in fact not rare.[912] So, their 'rarity' is not a matter of their geological abundance or scarcity. Hanna Vikström noted that despite the importance of metals, no single country has sufficient or adequate domestic production.[913] Thus, (adequate) supply cannot be guaranteed. The increasing demand for minerals and the realization that imports are required is not new. Rather, this has been a common trend and understanding since the Second Revolution.[914] This displaces the importance to global supply chains of minerals. Vikström suggests to move beyond the simple understanding of scarcity in terms of supply and demand. She argues that a metal is defined as scarce based on actors' perceptions and actions – how they attribute (increasing) value to a mineral. Moreover, she argues that scarcity is best described by issues surrounding power. Our work corroborates Vikström's theorization of scarcity. Silicon is one of the most abundant minerals. Therefore, abundancy does not seem to be an issue in the study of silicon. Rather, scarcity concerned issues surrounding who has the know-how and capacity to extract and process it, as well as on this minerals' uses and the economic impact of a supply disruption.[915] Furthermore, the geopolitical dimensions around silicon concern supply disruptions and the regional concentration of the production steps of this mineral. In other words, it is a matter of power. In this sense silicon, however abundant, was made scarce. The implications of coping with scarcity reoriented the research themes, topics and priorities during the second period.

---

[912] Hatch Gareth P., "Dynamics in the Global Market for Rare Earths", *Elements*, 2012, p. 341-446.; Stegen Smith Karen, "Heavy rare earths, permanent magnets, and renewable energies: An imminent crisis", *Energy Policy*, 2015, p. 1-8.; Kalantzakos Sofia, China and the Geopolitics of Rare Earths, (New York: Oxford University Press, 2018).; Luo Jin and He Hongwei, "Trade Dispute on rare Earths Export from China to the United States, *Advances in Economics, Business, and Management Research*, 2018, p. 391-394.; Manberger Andre and Johansson Bengt, "The geopolitics of metals and metalloids used for the renewable energy transition", *Energy Strategy Reviews*, 2019, p. 1-10.

[913] Vikström Hanna, The Specter of Scarcity: Experiencing and Coping with Metal Shortages, 1870–2015, [Doctoral dissertation, KTH Royal Institute of Technology], 2017, p. 3.

[914] Vikström Hanna, The Specter of Scarcity: Experiencing and Coping with Metal Shortages, 1870–2015, [Doctoral dissertation, KTH Royal Institute of Technology], 2017, p. 3.

[915] For more information on this topic see: Overland Indra, "The geopolitics of renewable energy: Debunking four emerging myths", *Energy Research & Social Science*, 2019, p. 36-40.

However, the networks were not concerned with the geopolitical dimensions surrounding the supply of this mineral.

Before the silicon crisis, the “Seven Sisters” had an oligopoly on the production of polysilicon feedstock. During the silicon crisis, the emergence of Chinese and Korean polysilicon producers acted as a relief to the market. Only one of the (original) “Seven Sisters” (i.e. Wacker) maintained a strong position in polysilicon production, while two other “Sisters” (i.e. REC (formerly ASiMI) and Hemlock Semiconductors) continued to produce but lost their previously prominent position, in the 2010s. The “Seven Sisters” oligopoly thus began to weaken during the years of the silicon crisis and escalated during the 2010s, leading to geographical changes among polysilicon producers. In particular, polysilicon production ‘expanded’ from being geographically concentrated in four regions (USA, Japan, Germany, and Italy) to six regions (China, Korea, Germany, USA, Japan, and Norway). Despite this geographical expansion, which is also due to the larger number of companies entering this business, we can speak of a new polysilicon oligopoly concentrated in different geographically expanded locations. Italy has dropped out of polysilicon production, while both Japan and the US have been significantly weakened. In contrast, China and Korea have emerged as **the** geographical locations for polysilicon production, alongside Germany, which has maintained its leading role.

To respond to the silicon crisis, which we can interpret as an ‘esoteric’ crisis of the PV sector, the networks made different choices. In this context, the Spanish chose a pathway away from the material **in** crisis. This decision was based on domestic scientific and industrial capacities, while the shift away from c-Si was justified by the country’s climatic conditions and the argument of resource conservation.[916] This led to prioritizing different semiconductors for the solar cells and a change in the scale of the installations made possible by the chosen system design. The Italians followed this pathway shortly after scientific and industrial interests arose domestically. Although both countries have a c-Si based industry, they did not have the same interests in c-Si as other countries in the European North.[917] For example, the Spanish managed to build a c-Si industry in the 1980s because they did not have deep national and cultural traditions in the c-Si industry like some of the countries in the European North. Nevertheless,

---

[916] HCPV cells could use 250-1000 times less material than c-Si flat plate cells.

[917] We remind the reader about the unique particularities of the Italian semiconductor electronics and Si interests. The Italian semiconductor electronics industry was not ‘fully’ Italian. The selections made domestically were at large influenced by the German interests (Siemens in particular), which via joint ventures, had penetrated the Italian market. The Italian polysilicon feedstock interests diminished during the second period when the Americano-Italian MEMC was acquired by the Chinese GLC-Poly.

c-Si was the entry point into the PV sector, the PV market and R&D activities for the Spanish actors, as the interests of semiconductor electronics actors prevailed in choosing c-Si as the technological frontrunner.

In contrast, the countries of the European North had built their PV industry around c-Si. Their vested interests in c-Si is also reflected in the clear prioritization of c-Si in their respective national R&D programmes, which promoted c-Si as **the** technological frontrunner. As their selections resulted in a technological lock-in, during the silicon crisis the c-Si network actors looked for different pathways to respond to the silicon crisis – all of which were Si-based! These solutions drew on the deep-rooted sectoral traditions and know-how from the semiconductor electronics, which these actors transferred to the PV sector (e.g. recycling, wafer thickness reduction, etc.).[918] At the same time, new solutions to the needs of the PV sector were proposed, leading to different choices (e.g. the c-Si thin film agenda).

However, the interests in c-Si in countries with a long history and tradition in Si led to a technological lock-in. These interests were transferred to the PV field by the actors who formed the networks that made the choices. Moreover, these interests and tradition in working with Si affected the proposed solutions, all of which were Si-based. In contrast, both the Spanish and the Italians – for different reasons in each case – had more flexibility in choosing a different technological pathway to address the silicon crisis. These technological lock-ins and pathways have shaped and configured the research culture and priorities, which can be seen in both the research agenda and the direction of EU research funding.

The silicon crisis influenced the choices of the research networks in terms of the solutions they pursued. However, as the geopolitical dimension did not play a role in setting the agenda, it was not taken into account in the selection of topics. In the 2000s and 2010s, China increased its power along the production chain of the main mineral used for the dominant technology (c-Si). In addition, China accounts for a significant share of the extraction of all minerals needed for all technological options in PV. This increases the EU's dependence on the supply of all minerals needed for PV and other critical sectors, even if other technologies are chosen. By accumulating more power along this chain and expanding its production capacity at an unprecedented pace, this eventually led to China's rise as the leading power in PV. At the same time, this accumulation of power in a single geographical location directly affected whether

---

[918] Vikström expands on the coping mechanisms that have been historically developed to overcome scarcity. Based on our analysis we trace several of these coping mechanisms that have been transferred to research (e.g. recycling, substitution, resource savings etc.). For a detailed analysis of these coping mechanisms see Vikström Hanna, The Specter of Scarcity: Experiencing and Coping with Metal Shortages, 1870–2015, [Doctoral dissertation, KTH Royal Institute of Technology], 2017, p. 40-47.

the PV industry would be stronger in Europe or in China. Resulting in the demise of the European PV industry, which was built on c-Si, as were the policies and the market. Even though the EU relies on the supply of polysilicon feedstock from Wacker and the supply of Si from other regions (except China), the choice of c-Si has created a set of dependencies that are difficult to overcome given China's strong position.

8.1.3 Global North-South divide: the unique case of China

Based on our analysis, the Global North-South divide is confirmed (and reproduced) for certain regions (e.g. Chile, Peru, etc.). As mining activities are being transferred to certain regions of the Global South, the divide is restored and reinforced as these regions become the 'extractive pool' of raw materials supplying the Global North for the benefit of the latter. Although China is part of the Global South, it does not fall into this category. As concentration and control over more and more steps of the production chain are geographically concentrated in China, this acts as a means of geopolitical empowerment. As Kalantzakos notes, "[t]he PRC has continued to portray itself as a developing nation working with others in the developing world on a common agenda".[919] In other words, China reproduces this 'self-positioning' as a region of the Global South. At the same time, China is gradually gaining more power in the geopolitical environment through the transfer of production. The advantage and control over more and more steps of the production chain have enabled China to become the leading PV production region. Furthermore, China has exerted geopolitical pressure due to its power in supplying the materials and components needed for PV, leading to a more complex understanding of where to place China in the discussion of the Global North-South divide.

The externalities resulting from mining and recycling of end-of-life products have never been part of the research and have been consistently ignored or overlooked, leading to recognition injustices. The global dimensions of externalities resulting from the entire production chain have never been studied. The injustices that result from these global chains lead to the reproduction of injustices that are not taken into account or evaluated, as their occurrence is consistently overlooked. Ignoring these dimensions thus promotes the further deepening and enhancement of injustices between the Global North and the Global South. This is especially true when considering distributional injustices (environment, health, land degradation, labour risks, etc.).

---

[919] Kalantzakos Sofia, "Introduction – Rare Earths: A Crisis in the Making", *in* China and the Geopolitics of Rare Earths, (New York: Oxford University Press, 2018), p. 4.

However, when we combine these two dimensions (i.e. externalities and geopolitics), we face a unique situation. Most notably, it leads to a particular understanding of how the Global North-South divide works. Based on the analysis of externalities deriving from the different steps of the production chain, the Global South is the extractive pool of the Global North, from which the latter benefits. This includes China and other regions of the Global South (e.g. Chile, Peru etc.). On the other hand, if we look at how China has used the two events (tensions) regarding the supply of PV materials and exerted geopolitical pressure, we see that China is geopolitically empowered. This results in a complex geopolitical dynamic that challenges the perception and analysis of the Global North-South divide in the unique case of China.

8.2 The political economy of the EU for/of research: insights into the characteristics of the Knowledge-Based Economy

With the 1997 White Paper for RES, the European Commission made two clear choices regarding PV. First, the Commission chose ‘where’ PV should be installed. Placing PV on rooftops also meant a clear choice in terms of both the scale and Commission’s preferences in terms of electricity generation and consumption (i.e. small-scale installations on rooftops).[920] Secondly, and directly related to the first point, the Commission legitimized the selection of research networks for the technological frontrunner. This selection determined which industry and which actors would ‘benefit’ from the industrialization of the sector as a result of this clear technological choice, and at the same time legitimizing the role that these actors would play in directing the research agenda and funding for PV (ETPs).

The EU R&D funding programmes merit special attention since we are discussing the directionality of public funding. As Horizon is a regulation, the EC has the legislative means to set the GDP share that member states must spend on R&D. The direct (GDP share) and indirect (cost-shared contracts) control that the Commission has over the direction and control of public funds in an area (R&I) that is seen as **the** focal point for the economy (and towards a KBE), should not be underestimated. In this section we discuss our main findings from the empirical analysis, which give us insights into the changing political economy for/of research: who is funding, where is this funding going, and what is being funded, in relation to the configuration of energy and technology markets. In the next sections, we discuss the three ‘W’s’ (who, what and where) of R&D funding. Starting with the ‘who’, we discuss the dynamic

---

[920] Regarding how this point impacted the technology and energy markets, see section 8.3.

interplay between the EU and the member states. Did the EU direct national research or vice versa? Next, we examine the two remaining 'W's' together. The focus is on the distribution and accumulation of EU R&D funds in specific technologies and their geography(-ies). To this end, we problematize the European North-South divide while considering the impact of EU enlargements on R&D funding and EU priorities. Lastly, we use the analytical concept of 'upscaled research' to gain insights into the characteristics of KBE (section 8.2.3).

8.2.1 The Commission-member states interplay: the chicken and the egg problem

It is not clear whether the EU guided/directed national research or vice versa, especially considering that 'multiple nationals' was and is always an integral part of what the EU was and is, which is attributing to the complexity of the dynamic interplay between the EU and the member states. Despite this complexity, we address some key points that can help to untangle the complexity – at least in part.

Soon after the 1973 oil crisis, several R&D programmes were launched in many regions that included RES (and PV). This was true for European countries such as Germany and France as well as non-European regions such as the USA and Japan. At the EU level, each member state pursued different research priorities for RES and made different technological choices, drawing on its own (domestic) scientific and industrial expertise. For example, both the German and French programmes prioritized PV R&D and favoured c-Si research. The Danish programme on the other hand, prioritized wind energy R&D, relying on their own interests and know-how. The Dutch programme initially gave priority to thermal solar energy research, while PV briefly enjoyed a more favourable funding position in the 1990s due to Shell's interest in PV. Italian R&D programmes suffered from a lack of continuity and consistency. For both the Dutch and the Italians, these national shortcomings were remedied – at least in part – by EU R&D programmes that provided stable and continuous funding for PV research. In all cases, national research programmes were developed and structured based on relevant national interests, know-how and expertise.

Evident by the above, not all member states had an interest in PV (or c-Si). On the contrary, there were member states that had interests in other RES (e.g. the Netherlands and Denmark) and in other PV technologies (e.g. the UK and Spain in CPV). However, PV enjoyed a favourable funding position in the EU R&D programmes. The allocation of funds was determined by the Commission. Thus, this PV prioritization was a choice made by the Commission, which had an active role in directing research funding. The person responsible for the RES unit in DGXII was Wolfgang Palz. Palz has experience in the field of PV and was involved in the preparation of the French R&D programme that gave priority to PV, which demonstrated his agency in promoting PV over other RES. Palz's key affected the allocation of R&D funds (RES) a point highlighted by a former DGXII (RES Unit) scientific officer. In turn, the preference for PV in the EU research funding enabled the promotion of certain national scientific and industrial interests in shaping EU research policy for PV and the corresponding selection of PV technologies. In addition, during the 1970s (and part of the 1980s), Roger van Overstraeten, who has a long experience in c-Si (and was an active actor in the c-Si research networks), was head of the Photovoltaics Advisory Committee. He represented specific national and technological interests from an influential position. The project selection procedures during the first decade of EU R&D programmes, as noted by the corresponding programme evaluators, raise serious issues regarding both the transparency and bias of the Commission. Nearly half of the PV projects during the first energy R&D programme were selected directly by the Commission, while there is a complete absence of justification on behalf of the Commission for selecting or rejecting projects.[921] The overlap of people in influential positions (funding, priorities) and their involvement in EU-funded research activities (as contractors) further complicates matters.[922]

The selection made by the Commission was aligned with the national interests of a handful of countries that have been heavily involved in PV research activities supported by the EU R&D programmes (e.g. Germany and France). Trying to examine which came first strongly the resembles the "chicken and the egg" problem. However, we can argue that the choices made by the Commission allowed the the interests of certain member states to be promoted over others. After excluding CPV and the corresponding Southern European interests in FP1, the Commission "baptised" PV as a technological solution for climate in Northern European countries. It helps us to understand "whom" this prioritization should benefit given that this exclusion took place amid the completion of the Southern EU enlargements. At the same time, PV R&D can also be understood as a means to strengthen the European semiconductor electronics industry. We should not forget that transnational competitions have always been

---

[921] Regarding these issues see: Farinelli Ugo, Gelus M., Muus L. T., Rorsch A., Stocker H. J., *The evaluation of the Communities' energy conservation and solar energy R&D sub-programmes*, Office for Official Publications of the European Communities (Luxembourg: 1980), p. 49-51.

[922] These issues were raised by the evaluators of the second energy R&D programme of the Commission, see: Boffa C., Chadjivassiliadis J., Chemillie P., Stocker H.J., Weaire D., Wehenkel C., *Evaluation of the Community cost-shared research programme on solar, wind and biomass energy and of the Joint Research Centre's programme on non-nuclear energies (1979-1985)*, Office for Official Publications of the European Communities (Luxembourg: 1987), p. 96-97.

part of the funding decisions of EC. In this context, EC switched funding to a-Si during FP1 to help European industry to compete with their Japanese counterparts, while at the same time safeguarding the interests of the semiconductor electronics industry by consistently promoting Si-based solutions.

In all cases, collaborations formed at national level and their transnational arrangements (e.g. joint ventures) are reflected in the corresponding EU research networks. For example, the “big” Belgian (e.g. KU Leuven and imec), German (e.g. Fraunhofer ISE and University of Konstanz), and French (e.g. CNRS and Photowatt) actors in the field of c-Si were present in the EU R&D networks and in most cases formed the core of the corresponding activities. Accordingly, the joint venture between UPM, Isofoton, and BP Solar was reproduced in the corresponding CPV research networks. It was the actors that emerged as ‘leading’ actors domestically that were present in the corresponding EU research networks, and in many cases formed their core. This also shows that *national interests, strategies and priorities shaped and were reflected in EU R&D programmes*. These interests are reflected in the EU networks, forming a new ‘arena’ for ‘competing while collaborating’. This also means that in this new ‘arena’ national corporate interests can ‘block’ the emergence of various technological options or halt their development (e.g. in the case of CPV). Competitions between the actors forming the EU networks formed the basis for the choices made at the EU level in the area of research and development. With the establishment of the ETP-PV in the second period, the EC legitimized the role of ETP actors not only in setting the research agenda, but also in influencing and directing EU R&D funding. Given the structure of the ETP, this allowed for the promotion of national corporate interests and their strategies to guide EU R&D activities and funding.

Despite the difficulties in tracing whether the EU directed national research or vice versa, we argue that the clear prioritization of PV over all other RES in research funding allowed the interests of certain member states to be promoted and to determine the RES frontrunner and to make the selections for the PV technological frontrunner. These member states had both scientific and industrial interests in PV due to their active role in semiconductor electronics. This shows the Commission’s commitment to helping the European electronics industry to compete internationally, while enabling these actors to enter a new market (i.e. the energy market). By pursuing a bottom-up research policy, the EC delegated power to the networks to make the technological choices. However, the lack of transparency in the procedures for selecting and rejecting projects, as well as the direct selection of projects by the Commission and the overlap between individuals advising the Commission and directly benefiting from the programmes, raise issues of bias and lack of transparency. The Commission’s decision to exclude CPV during FP1 indicates that national corporate interests played a role in the selection of the R&D programmes and that alternative technological pathways were marginalized. We address these technological choices and their corresponding geography in section 8.2.2. In section 8.2.2.1 we discuss the marginalization of other technological pathways due to national competitions. Before turning our attention to these topics, we first turn to the 'risk' overlap in the EC's pilot and demonstration programmes during the first period.

8.2.1.1 Pilot and demonstration: the 'risk' overlap

Based on our analysis, we have found that there is a fragmentation of EU policies and a concurrent fragmentation of efforts undertaken (using public funds) in the EU programmes. DGXII and DGXVII did not have a dialogue when they set up their individual programmes and their priorities. The demonstration programmes implemented by DGXVII were not part of the FPs until the mid-1990s. This only changed towards the end of the first period when the demonstration programmes became part of the FPs. The only starting point for discussions between the two DGs was to avoid a possible 'overlap' between the programmes. The effort to delineate between pilot and demonstration programmes was a recurring problem for DGXVII, which used various criteria to delineate the role of demonstration programmes, such as 'scale' and 'market proximity'.[923] However, our analysis showed that in practice none of these criteria were met. For example, the pilot programme had 'large scale' projects. These projects were indeed larger in scale (in terms of installed capacity) than the corresponding demonstration projects.[924] Moreover, it was the actors who selected and determined whether their project was classified as a pilot or a demonstration project, which contributed to the continuity between the two programmes. Although they are epistemologically distinct, because they are used for different purposes and target different audiences, this distinction is blurred in this case. Therefore, it is possible to speak of a duplication of effort, where 'risk' was used in both programmes as a justification for continued financial support to the private sector. Resulting in the EU to take all the risks with public funding for the benefit of the private sector.[925]

8.2.2 It has never been equal: the politics of the networks

---

[923] For more information on the criteria employed by the DGXVII to delineate the differences between pilot and demonstration, see Appendix A.

[924] See chapter 4 and Appendix A.

[925] See chapter 4, Appendix A and Nakopoulou Efi and Arapostathis Stathis, "Reconfiguring Technologies by Funding Transitions: priorities, policies, and the renewable energy sources in the European Community funding schemes", *Journal of Energy History/Revue d'Histoire de l'Énergie* [Online], n°4, published 27 July 2020.

PV has always been favoured among all other RES in R&D funding by the EC. Through a bottom-up research policy, the technoscientific PV research networks directed research and gave a clear technological frontrunner at the end of the first period: c-Si flat plate PV. It was these networks that determined technological choices and research priorities based on the material possibilities their technical choices offered. In what follows, we examine the politics of the networks and of EC with respect to the selection of this technological frontrunner and the geography in which these technological choices were made.

R&D funding for PV have never been evenly or equally distributed, either geographically or technologically. Even at times when funding was distributed among more countries, there was a consistent accumulation of funding in a handful of countries.[926] These geographies were reiterated and further reinforced when examining the actors that form the networks, as well as the continuities and discontinuities in the networks.[927,928] Even when 'new' actors entered the networks, they managed to attain a continuous presence when coming from the countries that accounted for the majority of the R&D funding. There are two exceptions to this. First, the a-Si case-study, where the structure of the networks, geography, distribution of funding, and research priorities changed during the second period as a result of the dominance of the c-Si thin film agenda. Second, the CPV networks of the second period. During this period, the efforts of UK CPV were discontinued, leading to the departure of a core actor (BP Solar) from the network, while a strong Italian network emerged as a result of national R&D priorities. These changes were in turn reflected in the networks.[929]

The above geographies were determined by and directly related to the respective technological choices. In particular, the research activities for the technological frontrunner (c-Si) were geographically located in countries of the European North, while the research activities for CPV were geographically located in the European South. The actors of the c-Si network had vested interests and background in semiconductor electronics. These actors came from countries that had in industry in semiconductor electronics and brough their expertise and

---

[926] During the second period the funding allocation was geographically enlarged, however the funding continued to be accumulated by a handful of countries. Accordingly, during the first period nearly all member states were the recipients of R&D funding but based on how the funding allocation was located geographically it resulted in an accumulation with specific geographical extensions that remained unchanged in both periods.

[927] Essentially, showcasing the directionality of the knowledge that was being generated (i.e. who is concentrating the knowledge generated and who is participating in this process).

[928] There is a continuity in the actors forming the core of the networks. Even in times when new actors emerged, they did not manage to maintain this place, nor were they the recipients of the bulk of the funding. Additionally, with minor exceptions (e.g. TU Denmark) their geography is the exact same as that of the funding allocation.

[929] Following Isofoton's bankruptcy, we can expect to see further changes in the CPV technoscientific research networks supported under the future EU R&D programmes.

know-how on c-Si. In contrast, Spain did not initially have such an expertise or an industry. Thus, lacking the deep historical traditions and interests that the actors from the European North had developed around c-Si. They developed a c-Si industry while trying to transfer the knowledge attained from c-Si flat plate PV to CPV. Therefore, during the second period the Spanish were able to propose the shift to HCPV, which used different semiconductors. The Italians embarked on HCPV research as soon as their global position in the production of Si feedstock diminished.

The above differences, regarding the technical choices of European countries (i.e. CPV in the European South and c-Si in the European North) can be explained by another complementary reason. We argue that these technical choices were developed through two different and conflicting understandings about the energy system and control over supply, which directed their technical choices. Thus, actors from the European North developed a technology that could reconfigure the architecture of the energy system and had the potential of reconfiguring different relations between producers and consumers, whereas the actors from the European South developed a technology that was closer to the dominant paradigm of electricity generation and consumption. In this context, supply continues to be centrally controlled and regulated rather than diffused across the civil society.

The dominance of the c-Si thin film agenda led to a shift in a-Si funding to the European North, displacing the former prominent role of a Southern European country (Greece). To better explain this European North-South divide, we will go a step further and problematizing the concept. From the European South, only Spain and Italy have been heavily involved in PV research. Other countries of the European South have never played such a prominent role in PV activities and networks. Similarly, the Scandinavians played a central role in the networks (c-Si), but their funding share was low compared to the Belgians, Germans, Dutch etc. Thus, two powerful nuclei/cores formed to guide the research activities for each technology option.

The countries of the European South comprised the periphery for the dominant technology and the core for the marginalized technology.[930] Moreover, as we have examined, the Spanish and the Italians gradually completely dropped out of the c-Si activities in the second period. Concurrently this signified the enhancement of an even more powerful core from the south of Europe in CPV. Although Spain and Italy are, in purely geographical terms, countries of the European South – and of the Mediterranean in particular – they had a major impact on the

---

[930] The actors from these countries did not accumulate the bulk of the c-Si funding nor did the comprise consistent network participants.

research activities and character of CPV. Therefore, it might be more accurate to speak of the emergence of a powerful core, geographically located in Southern Europe, and more akin to the European North in terms of defining research. Similar is the situation for the Scandinavian countries but in reverse. Although they are geographically located in the North of Europe, they did not play a major role in defining the research activities and agenda. In contrast, Germany, Belgium, the Netherlands and France have had a greater influence on the research activities and technical characteristics of the dominant technology. Several countries in the European North, South, and East had little involvement in the PV R&D activities and were marginalized or excluded from the research agenda setting processes. Thus, the EU enlargements have not led to an 'even' distribution of funding, nor have they allowed actors from the new member states to access the relevant networks.[931]

One possible explanation for this comes from the objectives of the EU R&D programmes. EU R&D programmes have been designed to 'serve' a core aim: to strengthen the scientific and technological basis of the European industry and aid its international competitiveness. Industry is a key word when it comes to where knowledge generated by public funds is intended to end-up. In the case of PV, this had a specific and narrow geographical dimension, as not all European countries had a semiconductor electronics industry, nor the capacities and know-how to build one. By favouring PV in funding over all other RES, as well as a single PV technology (c-Si), the EC essentially promoted the dominance of the semiconductor electronics industry to define the priorities for PV. This was accompanied by the promotion – directly or indirectly – of certain geographies as dominant, which we see being replicated in the PV case study.

There is a vast literature on European Union politics in relation to the role and impact of EU enlargements and political and economic integration(s).[932] One branch of the literature has examined how institutional inequalities resulting from enlargements lead to and/or are linked to economic inequalities. Budgetary inequalities between the member states, are thought to stem from inequalities in decision-making, and, in particular, the distribution of voting rights

---

[931] Actors from these countries never attained a steady place in the networks nor did they accumulate large funding shares.

[932] There is another branch of literature that examines the regional and spatial inequalities between different countries and within a given country (indicatively see: Gonzalez Sara, "The North/South divide in Italy and England: Discursive construction of regional inequality", *European Urban and Regional Studies*, 2011, p. 62-76.; Martin Ronald L., "The contemporary debate over the North-South divide: images and realities of regional inequality in late-twentieth-century Britain", *in* Geographies of England. The North-South Divide, Material and Imagined, Alan R. H. Baker and Mark Billinge (eds.), Cambridge Univesity Press (Cambridge, UK: 2004), p. 15-43.). We acknowledge this literature as important for yielding significant insights regarding the inequalities at a different 'scale'. However, given the scope of our research we do not extend our analysis to this scale, since this would have resulted in different aims and research questions, being a different topic.

among member states in the Council of Ministers.[933] Another branch of the literature has defines core/centre-periphery on the basis of socio-economic and political inequalities between EU member states, which EU enlargements have not eliminated but rather exacerbated, and argues that the EU features a dualist economy.[934,935] Some scholars suggest that the core-periphery divide is not sufficient to explain the EU's current situation. Rather, they show that the core has a periphery, and the periphery has a core.[936] This is very similar to, and perhaps even mirrors, the distribution of EU R&D funding in the two PV cases.

We argue that the distribution of R&D funding has never been even or equal and that EU enlargements have had no impact on the redistribution of funds. Rather, the distribution of EU funding for R&D reproduces and reinforces inequalities between the countries of the European North and South. These inequalities emerged from the technological choices, which further empowered the actors of the European North. The selection of c-Si promoted the interests of the electronics industry that was at large located in the European North. Through this selection, the electronics industry was able to enter a new market (the energy market), whereas the new

---

[933] Bindseil Ulrich and Hantke Cordula, "The power distribution in decision-making among EU member states", *European Journal of Political Economy*, 1997, p. 171-185.; Felsenthal Dan S. and Machover Moshe, "The Weighted Voting Rule in the EU's Council of Ministers, 1958-95: Intentions and Outcomes", *Electoral Studies*, 1997, p. 33-47.; Kauppi Heikki and Widgren Mika, "Voting rules and budget allocation in the enlarged EU", *European Journal of Political Economy*, 2007, p. 693-706.; Zaporozhets Vera, Garcia-Valinas Maria, Kurz Sascha, "Key drivers of EU budget allocation: Does power matter?", *European Journal of Political Economy*, 2016, p. 57-70.; Gruisen Philippe van and Crombez Christophe, "The Commission and the Council Presidency in the European Union: Strategic interactions and legislative powers, *European Journal of Political Economy*, 2021, 102040.

[934] The countries forming the core are the following: Germany, France, the United Kingdom, the Netherlands, Belgium, Luxembourg, Denmark, Sweden, Finland and Austria (North-Western Europe), whereas the periphery comprises of Portugal, Spain, Greece, Malta, Cyprus, Hungary, Poland, the Czech Republic, Slovakia, Slovenia, Croatia, Bulgaria, Romania, Estonia, Latvia and Lithuania (Southern-Easter Europe). Italy and Ireland are perceived as the perimeter of the core – forming the in-between 'layer'. Laffan Brigid, "Core-Periphery dynamics in the Euro area: From conflict to cleavage?", *in* Core-Periphery Relations in the European Union: Power and Conflict in a Dualist Political Economy, Jose M. Magone, Bridgit Laffan and Christian Schweiger (eds.), Routledge/UACES contemporary European studies (London and New York: 2016), p. 19-34.

[935] Kuus Merje, "Something old, something new: Eastness in European Union enlargement", *Journal of International Relations and Development*, 2007, p. 150-167.; Magone Jose M., "Centre-Periphery conflict in the European Union? Europe 2020, the Southern European Model and the euro-crisis", *in* European Union at the crossroads: The European perspectives after the global crisis, Attila Agh (ed.), Budapest College of Communication (Budapest: 2011), p. 71-122.; Kukovec Damjan, "Law and the Periphery", *European Law Journal*, 2015, p. 406-428.; Pascariu Gabriel Carmen and Tiganasu Ramona, "Integration, Growth and Core-Periphery Pattern in EU's Economy: Theoretical Framework and Empirical Evidences", *in* Core-Periphery Patterns across the European Union: Case Studies and Lessons from Eastern and Southern Europe, Gabriela Carmen Pascariu and Maria Adelaide Pedrosa da Silva Duarte (eds.), Emerald Publishing Limited (Bingley, UK: 2017), p. 23-85.

[936] Sepos Angelos, "The centre-periphery divide in the Eurocrisis", *in* Core-Periphery Relations in the European Union: Power and Conflict in a Dualist Political Economy, Jose M. Magone, Bridgit Laffan and Christian Schweiger (eds.), Routledge/UACES contemporary European studies (London and New York: 2016), p. 35-56.; Agh Attila, "The increasing core-periphery divide and new member states: Diverging from the European Union's mainstream developments", *in* Core-Periphery Relations in the European Union: Power and Conflict in a Dualist Political Economy, Jose M. Magone, Bridgit Laffan and Christian Schweiger (eds.), Routledge/UACES contemporary European studies (London and New York: 2016), p. 117-129.

actors who did not have the corresponding capacities, know-how and expertise were at a disadvantage (i.e. a gap in terms of know-how, knowledge and infrastructures (production) etc.). The choice of c-Si thus constructed and reproduced a division between the old actors and the newcomers. Given the specific geographical dimension(s) of the electronics sector (and industry), this choice formed a social order that further reinforced and solidified the European North-South divide.

8.2.2.1 Technological competitions: marginalizing CPV

The EC clarified that PV was an R&D priority because it was understood as a/the technological solution to the climate in Northern European countries. This was used in conjunction with climate as an exclusion criterion for CPV (FP1) from R&D funding at a time when EU enlargements in the South were to be completed. It was thus a direct exclusion of Southern European interests from EU R&D programmes and their actors (academia and industry) from networks and R&D funding.[937] It was only when an industrial actor from Northern Europe expressed interest in this alternative design that CPV was included in the EU R&D programmes and funding for CPV was increased (which did not match the funding dedicated for c-Si). BP Solar was interested in developing CPV modules (using c-Si) that could be used for building facades. This made BP Solar one of the first actors to 'place' CPV as an integral part of buildings. At the same time, the company was interested in developing a technology for the Mediterranean climate and the so-called 'developing' countries. LCPV, as proposed by BP Solar, offered the same installation options as flat-plate c-Si (i.e. both large- and small-scale).

The early attempts to standardize the (CPV) design and demonstrate its reliability were blocked by actors who had an interest in c-Si flat plate PV (late 1970s). A situation that remained virtually unchanged for about twenty-five years due to the 'shortage' of suitable CPV cells. At the same time, early efforts in CPV R&D were 'judged' on whether this design could work with c-Si flat plate cells (adapted CPV cells were not used). The criterion was thus the adaptability of this design 'around' the dominant technology 'brought' by semiconductor electronics, rather than the 'actual' potential of this design for future applications. LCPV, utilizing c-Si for the cells, was a direct competitor to c-Si flat plate PV.[938] As c-Si flat plate PV

---

[937] The Spanish (UPM-Isofoton) managed to enter the PV market because they established a production of c-Si cells/modules. Accordingly, access to the R&D activities and continuity in funding was ensured via the transferability knowledge (both CPV and flat-plate utilized c-Si cells).

[938] This was the dominant CPV design during the first period, enabling the same unique system integration option as c-Si flat plate PV.

was a technology that represented the interests of the actors from the semiconductor electronics sector it therefore comprised a possible competitor to their interests. As efforts to develop CPV were halted and stalled, we argue that this technological design was marginalized due to the vested interests of the actors of the semiconductor electronics sector in the context of technological competitions.

Furthermore, as CPV was conceived as a technological option enabling large-scale power plants this was in direct contradiction to the dominant technology's network politics. As we analyze further in section 8.3, the actors of the c-Si networks pursued research and actively promoted this technology through an understanding of how it could reconfigure the architecture of the energy system. The contrasting applications enabled by CPV can help us attribute a complementary understanding regarding the marginalization of CPV. We argue that CPV was marginalized because it limited PV applications by promoting large-scale PV installations. Offering a more 'centrally controlled' artifact as opposed to the more 'liberal' c-Si flat plate. An 'obstacle' to the potential of further liberalization of the energy market and reconfiguration of the energy system, which was the politics of the c-Si network actors.

8.2.3 Insights for the Knowledge-Based Economy characteristics: the analytical concept of upscaled research

Despite the fuzziness and vagueness of what the Knowledge-Based Economy (KBE) is, the 'term' was used by evolutionary economists – for the OECD – by observing and describing trends in advanced economies and measuring how to sustain and promote their economic growth/development in global markets.[939] Essentially, the KBE was developed to help

---

[939] The KBE was employed by Lundvall during a mid-1990s OECD conference and was used Foray and other economists hereinafter. The vagueness of the KBE has been acknowledged by many scholars (indicatively see: Godin Benoit, "The Knowledge-Based Economy: Conceptual Framework or Buzzword?", *Journal of Technological Transfer*, 2006, p. 17-30.; Camagni Roberto and Capelo Roberta, "Knowledge-Based Economy and Knowledge Creation: The Role of Space", *in* Growth and Innovation in Competitive Regions: The Role of Internal and External Connections, U. Fratesi and L. Senn (eds.), Springer (Berlin: 2009), p. 145-166.), whereas different scholars have described the KBE as a 'term', 'metaphor' or 'concept' (indicatively see: Camagni Roberto and Capelo Roberta, "Knowledge-Based Economy and Knowledge Creation: The Role of Space", *in* Growth and Innovation in Competitive Regions: The Role of Internal and External Connections, U. Fratesi and L. Senn (eds.), Springer (Berlin: 2009), p. 145-166.; Leydesdorff Loet, "The Knowledge-Based Economy and the Triple Helix Model", *Annual Review of Information Science and Technology*, 2010, p. 367-417.). Moreover, different approaches have been developed in order to define what this concept is (indicatively see: Camagni Roberto and Capelo Roberta, "Knowledge-Based Economy and Knowledge Creation: The Role of Space", *in* Growth and Innovation in Competitive Regions: The Role of Internal and External Connections, U. Fratesi and L. Senn (eds.), Springer (Berlin: 2009), p. 145-166).

advanced economies maintain their advantageous position.[940] An important change recognized by economists – and reflected in the KBE – is that competition in global economies is no longer based upon material resources but on knowledge.[941] Although science and scientific processes are reduced to a 'tradable' outcome, and the role of material resources is downplayed – or attempts are made to hide their importance and the complexity arising from global supply chains the emphasis on knowledge deserves attention as it is recognized as **the key** to future economic growth.[942,943]

With the Lisbon agenda, the EU endorsed KBE as a policy discourse to make Europe "the world's most competitive and dynamic knowledge economy in the world, capable of sustainable economic growth with more and better jobs and greater social cohesion."[944] In this context, research was placed at the heart of the future growth of EU economies, as research was envisioned as the focal point for innovation and knowledge production. Thus, the KBE was advocated as a policy discourse for the direction of EU economic policy. However, as the EU is neither homogeneous nor a single EU economy, there cannot be a single KBE. Likewise,

> "…**there is no single path of economic development and towards a KBE**, derivable in the abstract. Instead, **this process depends on the socio-historically and geographic particular political/cultural/technological conditions**. Hence, explanation of the concrete, historical trajectory of economic change, in particular places is an empirical question and there is no single and ahistorical economics of science."[945] (emphasis added)

---

[940] Organization for Economic Co-operation and Development, 9 September 2005, *OECD*, Knowledge-Based Economy, Available online: https://stats.oecd.org/glossary/detail.asp?ID=6864, accessed 11 September 2022.

[941] Camagni Roberto and Capelo Roberta, "Knowledge-Based Economy and Knowledge Creation: The Role of Space", *in* Growth and Innovation in Competitive Regions: The Role of Internal and External Connections, U. Fratesi and L. Senn (eds.), Springer (Berlin: 2009), p. 145-166.

[942] We must at this point note that scholars have – quite accurately – noted that knowledge was always key for economic growth. While it has been pointed out that Schumpeter was the first to recognize the important role knowledge plays in the economy (Cooke Philip and Leydesdorff Loet, "Regional Development in the Knowledge-Based Economy: The Construction of Advantage", Journal of Technology Transfer, 2006, p. 5-15).

[943] We should note that this term or concept entails a very simplistic or better yet reductionist understanding regarding what science is and about the scientific processes.

[944] Decision No 1513/2002/EC of the European Parliament and of the Council of 27 June 2002 concerning the sixth framework programme of the European Community for research, technological development and demonstration activities, contributing to the creation of the European Research Area and to innovation (2002 to 2006), Official Journal of the European Communities: Luxembourg, 29.08.2002, p. 16.

[945] Tyfield David, "The Knowledge-Based Bio Economy", *in* The economics of science: a critical realist overview. Volume 1. Illustrations and philosophical preliminaries, Routledge (London: 2011), p. 45.

It can be assumed that the KBE has different characteristics in different contexts, while the development towards a KBE is embedded in different contexts that help attribute distinct characteristics to the KBE. Thus, when we study different countries or regions, we can assume that there will be differences in the construction of the KBE. Given the importance KBE has acquired in shaping R&D funding, it deserves special attention in our case, as our starting point is the EU's R&D funding programmes.

Scholars in Innovation studies and STS have studied the relationship between public funding and innovation. In particular, Mazzucato and Semieniuk draw attention to public funding and how it can influence the direction of innovations.[946] To this end, they employ the concept of mission-oriented policy and show how this type of policy, which is linked to public funding, can influence the direction of innovations. Although the above work links R&D funding flows to the direction of innovation, it does not examine research and changes in research (and its political economy). Rather, the focus is on the 'origin' of directionality (i.e. funding) and its 'outcome' (i.e. innovations). The intermediate step (i.e. research) and how it relates to, is influenced by or affects the above changes is not examined by the scholars. Laredo has studied the impact of the EU FPs on French participants.[947] He identifies specific network configurations that he associates with types of research and towards discussing the outcomes of each network configuration in relation to EU research policy objectives. Again, changes in research are not examined, as the focus is on informing and influencing future EU research policy objectives and the FP organization. Tyfield reintroduces political economy into STS and proposes a Cultural Political Economy of Research and Innovation (CPERI), to identify and examine how changes in liberalism have affected and/or impacted research and innovation.[948] Despite the title, the focus is not on research but on science and innovation. Finally, a report prepared for the Commission distinguished three types of innovation based on the type of research from which they resulted.[949] Even though the focus is on the link between research

---

[946] Mazzucato Mariana and Semieniuk Gregor, "Public financing of innovation: new questions", *Oxford Review of Economic Policy*, 2017, p. 24-48.; Mazzucato Mariana and Semieniuk Gregor, "Financing renewable energy: Who is financing what and why it matters", *Technological Forecasting & Social Change*, 2018, p. 8-22.

[947] Laredo Philippe, "The networks promoted by the framework programme and the questions they raise about its formulation and implementation", *Research Policy*, 1998, p. 589-598.

[948] Tyfield David, The economics of science: a critical realist overview. Volume 1. Illustrations and philosophical preliminaries, Routledge (London: 2011).; The economics of science: a critical realist overview. Volume 2. Towards a synthesis of political economy and science and technology studies, Routledge (London: 2011).; Tyfield David, "A Cultural Political Economy of Research and Innovation in an Age of Crisis", *Minerva*, 2016, p. 149-167.

[949] European Commission – DG for Research and Innovation, *The role of Universities and Research Organizations as drivers for Smart Specialization at regional level*, Publications Office of the European Union (Brussels: 23 January 2014).

and innovation, only the latter is emphasized. Even though the changes in the different types of innovation and their characteristics are analysed, a corresponding analysis is not made for research. For example, research and changes in research in tandem to R&D funding flows have not yet been analysed. Nor have changes in the research networks and their structure been analysed in the context of (constructing) the KBE.

The Triple Helix model focuses on examining the relationship between the university, industry and government.[950] However, it is often criticized for not including other actors (e.g. NGOs, civil society) in the model.[951] Overall, the model's triadic focus seems to neglect other actors that comprise the public-private sphere and by extension does not examine their relationships and interactions with the triple helix, while ignoring the role of other actors in innovation. It has been suggested that "the Triple Helix is mainly a model for analysing innovation in a knowledge-based economy".[952] This has partly acted as a response to the critique of why other actors were not included in the analysis. However, the focus on innovation has resulted in changes in research that are not part of the Triple Helix's model inquiry to be completely overlooked. Concurrently, despite the models' focus on innovation in a KBE, the latter is taken as a closed category. Therefore, the historical processes and changes that occur in the context of introducing and constructing a KBE are not examined, while the processes and changes that a KBE reinforces are lost. Accordingly, the role of actors within a KBE is also not examined since the focus is on the university-industry-government relations.

To fill the above gaps, we employ the analytical concept of 'upscaled research' to examine the following questions: Does the increasing importance attached to knowledge for 'sustainable' economic growth (in global markets and competition) also imply a restructuring of the systems that support knowledge? Are there changes in the 'knowledge systems'? Furthermore, are there changes in those who controls knowledge and those who generate it? Is there a shift in those who benefit and those who are marginalized or even excluded from these processes? And more importantly, can everyone benefit or are there systemic differences that lead to a reinforcement of already existing inequalities?

Even though the core objective of the R&D programmes has remained essentially unchanged, the actual implementation (or 'how' to achieve this objective) has changed from the first to the

---

[950] Leydesdorff Loet and Etzkowitz Henry, "The Triple Helix of Innovation: Introduction", *Science and Public Policy*, 1998, p. 358-364.

[951] Cai Yuzhuo and Etzkowitz Henry, "Theorizing the Triple Helix model: Past, present, and future", *Triple Helix*, 2020, p. 189-226.

[952] Leydesdorff Loet and Etzkowitz Henry, "The Triple Helix as a model for innovation studies", *Science and Public Policy*, 1998, p. 198.

second period. This change, which was a change in the character of research, in turn directly affected 'who' could carry out that research. The KBE resulted in changes in the technoscientific research networks and in the relationship between the actors forming the networks, during the second period. We argue that the thrust to narrow the gap between research and the market, and thus contribute to the construction of a KBE, further strengthened the role of actors who had the capacities and infrastructures to carry out this 'upscaled research'. Even though knowledge creation expanded geographically in the second period, those with the capacity(-ies) to exploit it remained geographically uneven and constrained. Thus, not only did the KBE further empower the already strong actors of the networks, but at the same time the emphasis on knowledge infrastructures led to the marginalization of small research groups, universities and certain geographical areas.

Levidow, Birch and Papaioannou have argued that KBE, acting as the master narrative in the FPs, enables different visions (divergent paradigms) to co-exist but primarily promotes the dominant vision.[953] In a similar way of reasoning, we argue that the KBE further empowered the already strong actors of the networks, especially those of the dominant technology who gained prominence in defining the research agenda and priorities. In this context, dominant technology actors attained the power to restructure the networks of a-Si, reorient the corresponding research priorities and agenda. Furthermore, we argue that the entrepreneurial university as proposed in the Triple Helix model is not sufficient or adequate to explain the role of universities in a KBE, especially since the role of universities is not the same in all cases. In the case of c-Si, we have seen that the research centres have always played a prominent role in the networks. During the first period, the universities had a stronger role, but in the second period they did not manage to establish a closer relationship with industry and the market, or they did so through the research centres they had (already) established (e.g. KU Leuven and imec, University of Konstanz and ISC Konstanz). During the second period, the role of the universities was limited to very specialized topics that could serve the general objective of the research project. In contrast, the research centres played an important role in both periods. During the second period, the research centres emergence as 'hubs' of knowledge exploitation. Moreover, during the second period we see a further restructuring, with the research centres establishing spin-offs in an attempt to get closer to the market and establish closer relations with industrial actors (e.g. PSE, NexWafe etc.). Essentially, they developed

---

[953] Levidow Les, Birch Kean, Papaioannou Theo, "Divergent Paradigms of European Agro-Food Innovation: The Knowledge-Based Bio-Economy (KBBE) as an R&D agenda", *Science, Technology, & Human Values*, 2013, p. 94-125.

spin-offs in an effort to transfer research and translate it into profitable outcomes. This resulted in the construction of a new market: the research market.[954] The pre-competitive character of the EU R&D programmes alongside the endorsement of the KBE manifested during the second period in the construction of the research market, which was nurtured by research centres and spin-offs.

In the case of CPV, a university (the UPM) formed the core of the network. As unique as this case is, it underlines the thesis that KBE cannot have a single application in all regions and the importance of paying attention to the discrete cultural, political and technological contexts and conditions. In the Spanish case, and for a marginalized technology, UPM became the core of the networks because UPM was linked to a spin-off (Isofoton) and had established close collaboration ties with another major Northern European industrial actor (BP Solar). Essentially, UPM had developed the capacities and know-how for transferring and translating knowledge to the market. During the first period, the UPM was the core of the CPV networks, whereas its role was further enhanced in the second period. UPM played a prominent role at the national level, both in setting research priorities for PV and in influencing energy policy. In contrast, the Italian CPV network, which emerged in the mid-2000s, was created by a company (RSE). RSE had established its research interests and activities through Enel and ENEA, which played a prominent role in steering the energy policy and research activities domestically.

Even as knowledge creation expanded geographically in the second period, those with the capacity(-ies) to exploit it remained geographically uneven and geographically constrained. This not only limited who conducted this ‘upscaled research’, but also reinforced inequalities in the use of the results and reproduced pre-existing inequalities in economic growth. At the same time, the need to resolve production issues, in line with energy policy goals, required that research ‘serve’ already established industrial actors by offering insights and proposing solutions with developments for already established production lines. This is an indication of the orientation of the knowledge generated to increase the benefits for the industrial actors.

The scope of the projects was broadened in the second period to include more or all steps of the ‘value chain’. This is in direct contrast to the first period, where research continued to focus mainly on the solar cell or individual system components. During the second period, by actively directing the scope and priorities of research, exclusions or marginalization were not only about

---

[954] Research market is employed to refer both to the research system and the competitions in research (i.e. to attain funding and maintain a place in the research programmes and networks).

‘who can innovate’. The last point essentially links the question of who generates and forges the EU’s knowledge and technical capacities with the constraints imposed on the scope and breadth of research in terms of ‘where’ innovation(s) can emerge. In the case of PV, this also relates to the question of who forges the EU’s knowledge bases and capacity, and who directs the technical decisions for the transition to RES.

The reorientation of research in the second period described above is also reflected in what Dosi, Llerena and Labini note about the ‘usefulness’ of research:

> “The belief in a purported paradox, together with an emphasis on the ‘usefulness’ of research, has led to a package of policies whereby the EU support for basic research is largely non-existent.”[955]

Basic research and the role of universities were largely downgraded in the second period, as their presence in the research networks and activities was limited.[956] The establishment of the European Research Council in 2007 indicated the gap and the need for funding basic research. According to Europe 2020, one of the proposed flagships to implement the vision of the strategy for smart, sustainable and inclusive growth was the Innovation Union flagship. The Innovation Union aimed to strengthen the innovation chain to address and resolve grand societal challenges, covering all types of research (i.e. from blue skies research to commercialization).[957] Regarding higher education, it was stated that “reform is (equally) urgent”.[958] Towards this end, closer links with the private sector and the market were proposed.[959] Higher education institutions and research organizations attained a central role in regional development in the context of smart specialization.[960] A reconceptualization of how

---

[955] Dosi Giovanni, Llerena Pratrick, Labini Mauro Sylos, “The relationships between science, technologies and their industrial exploitation: An illustration through the myths and realities of the so-called ‘European Paradox’”, *Research Policy*, 2006, p. 1461.

[956] The European paradox is based on the premise that even though the EU is ‘excellent’ scientifically, in comparison to its main competitors, there is a lag or weakness in the translation of scientific research and outcomes to competitive advantage. The authors examine the ‘European paradox’ and find it wanting.

[957] European Commission, *Europe 2020: A European strategy for smart, sustainable and inclusive growth*, COM(2010), Brussels, 3.3.2010, p. 10.

[958] European Commission, *Europe 2020 Flagship Initiative Innovation Union*, COM(2010), Brussels, 6.10.2010, p. 9.

[959] Regarding the role of the universities towards achieving the 2020 goals and corresponding assessments see: European Commission – DG for Research and Innovation, *State of the Innovation Union 2020: Accelerating change*, COM(2013) 149 final, Brussels, 21.3.2013.; European Commission – DG for Research and Innovation, *Assessing Europe’s University-Based Research – Expert Group on Assessment of University-Based Research*, Publications of the European Union (Luxembourg: 2010).

[960] European Commission – DG for Research and Innovation, *The role of Universities and Research Organizations as drivers for Smart Specialization at regional level*, Publications Office of the European Union (Brussels: 23 January 2014).

economic growth can be achieved in a decentralized way (i.e. through the peripheries and their growth), which could simultaneously enrich the role of higher education and research institutions.

We argue that the KBE conditioned the structure of the networks and the context of the KBE was in turn conditioned by the networks. As illustrated in Figure 8.1 (below), the endorsement of a KBE was translated into the R&D programmes by narrowing the gap between research and the market, which resulted in changes in the technoscientific research networks. This change had implications for (i) the role of actors in the networks and in the generation of knowledge, (ii) the relationships between actors, and (iii) the relationship of actors to the market. These changes, in turn, helped to construct and attribute meaning to the KBE.

We argue that the changes in research and technoscientific research networks in the second period indicate that the advocacy of KBE (in an effort to construct it) reinforced already powerful actors and reproduced the power of the networks. This empowerment had implications for the technology and energy markets. Although indirectly, the KBE supported and promoted the possibility to shift towards small-scale PV installations and distributed electricity generation and consumption. Actors with the capacity to carry out the EU-funded 'upscaled research' were limited, while those without the prerequisite knowledge infrastructures were either marginalized or excluded.

Figure 8.1 The relation between the KBE and the technoscientific research networks.

Some of the KBE characteristics we can trace, which essentially correspond to the creation and maintenance of a competitive market in the context of global competitions are the following: (i) intensification of innovation production: increasing participation of spin-offs in R&D programmes and networks, (ii) increased risk-taking with public funding: the private sector participates but is not eager to coordinate projects, (iii) establishing a market for "innovations" in which research centres play a core role: constructing new actors for this new research market, and (iv) emphasis on the "value chain": indicates that research is shifting towards the production of innovations that are profitable for the market (and for maintaining a competitive market).

8.3 The co-production of the EU research and energy policies: constructing a new social order in the energy market

In Figure 8.2 we have schematized the relationship between EU research and energy policies in the two periods. We must emphasize that Horizon 2020 represents a continuity of the second period based on the character of research, its relationship with energy policy and the directionality of research funding by technology.[961] As shown in Figure 8.2, the 1973 oil crisis (an energy crisis) was the main trigger for the launch of the first EC energy R&D programme, which included research for RES. However, energy policy did not influence the definition and orientation of research policy and priorities. In fact, the Commission did not have the legislative power to design energy policy in the first period, this policy area remained a national matter. What existed was an energy strategy by the Commission that provided some general objectives that aimed at reducing oil imports and ensuring energy security. Each member state designed its own energy policy and as they had conflicting interests their path to oil substitution differed. Towards this end, each member state responded differently to the oil crises, depending on the respective geographical and cultural specificities.[962]

Given that no common energy policy existed, research in the first period was steered by industrial policy. During this period, the actors that formed the technoscientific PV research networks explored the potential applications of different PV technologies and designs, leading to technological pluralism. It was the actors in these networks who determined the technological choices and set the research priorities. In other words, a bottom-up research policy. Moreover, we argue that their selections were based on the actors' understanding of how the material possibilities of their technological choices could reconfigure the architecture of the energy system. The networks played a crucial role in developing new technologies that

---

[961] The c-Si thin films agenda continues to receive the bulk of the c-Si activities' funding, whereas CPV research is pursued for HCPV systems. For more information see chapter 7.

[962] For more details see: Nakopoulou Efi and Arapostathis Stathis, "Reconfiguring Technologies by Funding Transitions: priorities, policies, and the renewable energy sources in the European Community funding schemes", *Journal of Energy History/Revue d'Histoire de l'Énergie* [Online], n°4, published 27 July 2020.

promoted industrial competitiveness (semiconductor electronics). On this basis, research focused on the development of a single system component: the solar cell.

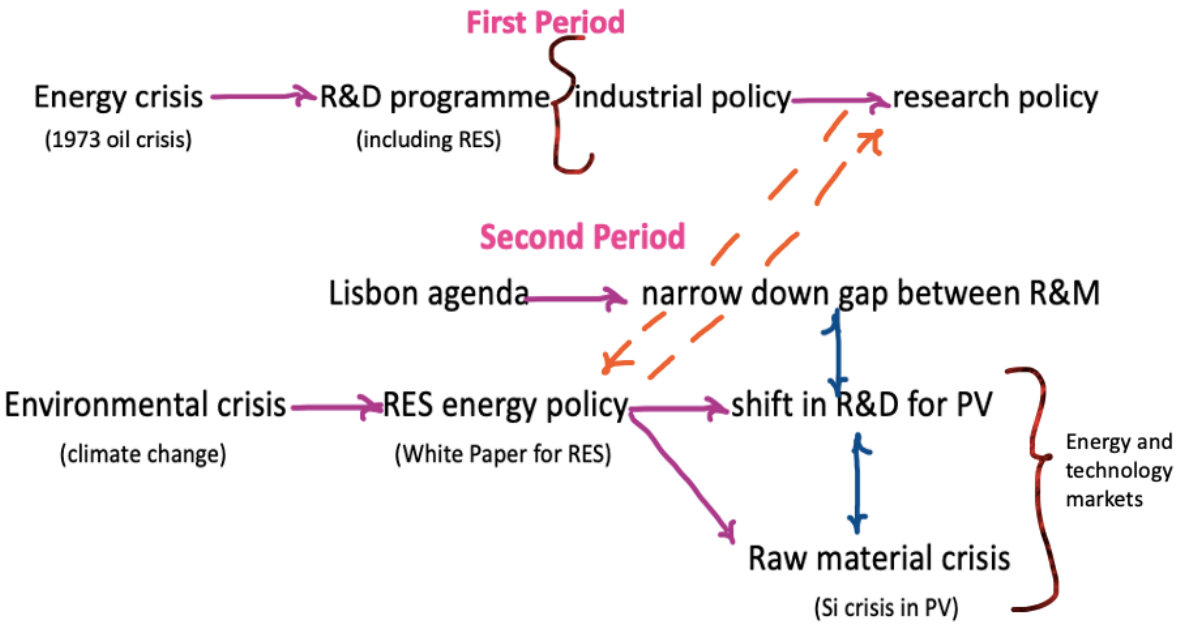


Figure 8.2 A schematic representation of the relationship between EU research and energy policies, 1975-2020.

During the second period, the relationship between the EU energy and research policies changed. In a context of urgency to respond to climate change and reduce CO_2 emissions, the European Commission (EC) published the White Paper for RES in 1997.[963] With this White Paper, the Commission placed RES on the energy policy map and gave the PV sector the green light for to become industrial (in terms of production).[964] The technological frontrunner selected by the first period research networks formed the basis for the PV installation targets of the Commission. In essence, the Commission wrote the PV installation targets based on the technological choices made by the research networks. PV is the only energy technology that can be integrated into the urban environment (e.g. on rooftops), allowing the reconfiguration of the electricity system while constructing different users (e.g. prosumers). We argue that it was through this understanding that the Commission set the targets for PV. By recognizing the unique system integration opportunity that small-scale PV offers, the Commission placed PV

---

[963] European Commission, *Energy for the Future: Renewable Sources of Energy White Paper for a Community Strategy and Action Plan*, COM (97)599 final, 1997.
[964] We have already analysed how the installation goals set by the White Paper led to a raw materials crisis (silicon crisis in PV) and how in turn the research networks sought to respond to the crisis.

directly on rooftops. The material possibilities offered by PV not only have the power to reconfigure the energy system and its infrastructures but can also further liberalize the energy market. Thus, small-scale PV installations can not only change how the electricity market works, but also the role that the different users of this technology can play in this market.[965] In other words, the Commission has adopted the politics of the research networks to set energy policy goals, actively promoting (i) the reconfiguration of the energy system and (ii) the further liberalization the energy market.

The EU's current long-term energy strategy is in line with this 1997 vision, calling not only for a transition to the energy sources we use (including RES), but at the same time calling for a transition to a different way of generating and consuming electricity. This transition is enabled by RES technologies that offer the possibility to transform the entire energy system. All RES can support this transition, while small-scale PV systems offer the unique opportunity to further liberalize the energy market.[966] *RES technologies form the building block for transforming the entire energy system, which is the focus of the EU's long-term energy strategy*. This carbon-neutral strategy, which includes RES, forms the basis for the energy policies of the member states. We argue, that on this basis, the EC, as a consistent advocate of this shift, has successfully defined the EU energy market.

The Commission has succeeded in 'placing' RES on the energy policy map and setting installation targets. The member states have retained their sovereignty in designing their energy policies. As a result, member states have made different decisions regarding PV.[967] Germany, Belgium and the Netherlands, for example, have continuously promoted the installation of small-scale PV systems. In contrast, Greece, Spain and the UK have favoured large-scale PV installations. Italy and France have promoted both small and large-scale PV installations at different times. Thus, we argue that although the EC does not have the legislative powers to define the conditions for the transition to RES, it has been successful in setting the targets (e.g.

---

[965] Recently, scholars have started to discuss and examine the inequalities that derive from such a transition. Indicatively see: Florian Hanke, Rachel Guyet, Marielle Feenstra, "Do renewable energy communities deliver energy justice? Exploring insights from 71 European cases", *Energy Research & Social Sciences*, 2021, 102244.; Jesse Hoffman, Megan Davies, Thomas Bauwens, Philipp Spath, Maarten A. Hajer, Bleta Arifi, Amir Bazaz, Mark Swilling, "Working to align energy transitions and social equity: An integrative framework linking institutional work, imaginaries and energy justice", *Energy Research & Social Sciences*, 2021, 102317.; Stephen Knox, Matthew Hannon, Fraser Stewart, Rebecca Ford, "The (in)justices of smart local energy systems: A system review, integrated framework, and future research agenda", *Energy Research & Social Sciences*, 2022, 102333.

[966] During the first period, research funds were allocated to c-Si flat plate PV that enable both small and large-scale installations. Similarly, during the second period, funding was mainly allocated to c-Si thin film agenda, that enables both small and large-scale installations, while HCPV can only offer large-scale installations.

[967] For a detailed analysis see Chapter 7. To clarify, this point should not be taken as a critique on the member states sovereignty for setting up their energy policies.

RES share) and providing a variety of ways (through research) to achieve them.[968] Although not all member states have promoted and/or favoured the installation of small-scale PV, the transition to RES represents a reconfiguration of the energy system and a further liberalization of the energy market. At the same time, the EC has provided (through research) another option for reconfiguring the energy system and expanding the energy market (small-scale PV systems). It is therefore a paradigm shift in energy policy and in the way(s) electricity is generated and consumed. We argue that both the politics of the research networks and of the Commission to promote small-scale PV installations did not fully materialize because decisions concerning the electricity supply are made at the national/state level.

For the realization of transitioning to RES, the Commission has supported research for "large-scale integration of distributed energy sources" in the second period.[969] This shows that the Commission's energy policy goals for RES also became commitments for research policy, coming full circle back to research. We argue that in the second period, the two sets of EU policies were aligned and jointly co-produced the energy market, in the Commission's effort to further liberalize the energy market, the energy system and its infrastructures. This was enabled by the material possibilities offered by the technological choices of the networks, which made their selections through this exact realization. The actors of the networks made their selections through the understanding of how these technologies could reconfigure the architecture of the energy system and further liberalize the energy market. This reasoning was adopted by the Commission upon setting the energy policy goals for PV, placing them on the rooftops. The desire to further liberalize the energy market led to the promotion research activities on/for system integration. Given the actors in the system integration networks are primarily from the energy sector, we argue that this research directed them to accept and materialize the further liberalization of the energy market. However, the design of the artifacts and the network were not a mutual undertaking, nor were the corresponding research endeavours. We argue that this fragmentation of research activities, keeping the artefact separate from the network, enabled the interests of actors from the energy sector to marginalize and/or hinder the research required for small-scale PV system integration.

8.3.1 A new social order: constructing and liberalizing the EU energy market

---

[968] The political will of several other historical actors (e.g. Scheer) has been instrumental towards enacting the goals set by the Commission and fostering PV installations.

[969] See chapter 5 analysis.

The transition to RES means reconfiguring the energy system and its infrastructures. All RES 'move' the location of electricity generation closer to where it is consumed. By shifting the location of generation away from the insofar centralized power plants and closer to the place of consumption, RES minimize transmission losses.

Small-scale PV can further minimize the distance between generation and consumption, as they are the only RES technology (for electricity) that can be integrated into the urban environment. This offers proximity to the point of consumption. PV In particular offer another way of system integration option and construct new users (prosumers). Basically, it is a further liberalization of the energy market. These users/consumers have control over the production/generation of electricity and are actively involved in this process. Instead of this step being centrally controlled by the electric utilities the users/consumers play a more active role in the electricity market since they can sell the remaining electricity to the grid. This type of electricity generation enables the creation of smaller grids (microgrids). These changes also foster a new relationship between the (new) producers and the traditional electricity suppliers. For PV to be used, new policies are needed to incentivize prosumers to participate in the market. New schemes are also needed to calculate the electricity fed into the network by prosumers and to provide them with more 'real-time' estimates of the electricity they generate. This not only changes the way electricity is generated, but also requires new policy incentives to ensure that this technology is used.

8.4. Moments of 'intervention' and 'opportunity' and the necessity in defining holistically the problems

Before concluding this chapter with suggestions for future research (section 8.5), we turn our attention to two dimensions that are important for research and research policy. First, to those moments in time (i.e. crises) when shifts usually occur and the path for new selections becomes 'open' (8.4.1). Second, the insofar gaps in research policy during times of crises (section 8.4.2). We not only attempt to highlight these gaps, but also offer useful insights into how they can be overcome.

8.4.1 Crises as 'opportune moments'

In our analysis we have examined four different crises. In particular, the two oil crises (1970s), the environmental crisis (1990s) and the raw materials crisis (2000s, Si crisis). We claim that each of these crises was an 'opportune moment' in the sense that it opened the window for new sectors, areas, directions and choices. In times of crises, relationships between different policy areas (i.e. energy and research policy) shifted and the dynamic interplay between the Commission and member states was reshaped. Crises were 'opportune moments' for further accumulation of power by the Commission, which had a legitimizing effect due to their urgency. Given the current and ongoing crises (e.g. COVID-19 and energy crisis) and the choices made, crises deserve special attention.

The 1973 oil crisis was the main trigger for the launch of the first EC R&D programme, which also included RES.[970] It opened a new research area and sector (i.e. RES) and new technological options (e.g. for PV c-Si flat plate, CPV, etc.) for the future EU energy system. The EC has tried to gain more powers beyond what is officially laid down in the Treaties, and to some extent it has succeeded. These (energy) crises have been an 'opportune moment' for the Commission to further expand its powers in energy policy and (energy) research policy.

In an effort to respond to the urgent need of the environmental crisis, the EC placed RES on the energy policy map. The installation targets set by EC in response to this crisis in turn led to a raw materials crisis. This directly affected the dynamics between EU energy and research policies and led to a reorientation of research priorities for PV. Furthermore, by linking climate change and RES, the EC also managed to expand its institutional powers to energy policy. Moreover, by using its market and research powers, the Commission has successfully directed part of the member states' energy policy. Essentially, despite not possessing the official legislative powers the Commission is *doing* energy policy through the successful construction of the energy market.

Against the backdrop of the current and ongoing energy crisis, RES and in particular PV are envisioned to play an important role in the EU's energy future and drive the faster implementation of the transition to RES. However, as EU member-states try to manage the energy crisis, ensure energy security and ease the burden on their economies, the reality diverges from the vision. To meet their immediate energy needs – even in the middle of a very hot summer – many member states are going 'back to the basics' (i.e. fossil fuels and possibly nuclear energy).[971] It remains to be seen what the future holds, both for the energy crisis and for the RES transition.

---

[970] As we have analysed, the 1973 oil crises resulted in the launch of similar R&D programmes for RES in other regions both in Europe and globally.

[971] Igor Todorović, 11 March 2022, *Balkan Green Energy News*, Europe switching on coal plants amid energy crisis, Available online: https://balkangreenenergynews.com/europe-switching-on-coal-plants-amid-energy-crisis/, (accessed 30 June 2022).; Angeliki Koutantou and Vassilis Triandafyllou, 16 June 2022, *Reuters*, In a Greek coal mine, stocks build up ahead of peak summer demand, Available online: https://www.reuters.com/business/energy/greek-coal-mine-stocks-build-up-ahead-peak-summer-demand-2022-

The 'vaccine deal' to combat the global pandemic was not handled at the member state level, but at the EU level, where the Commission was tasked with ensuring access to vaccines. With the current energy crisis, the Commission is calling for 'emergency' powers.[972] Essentially, this time – in the midst of an energy crisis – the Commission is seeking further powers in energy policy by using its market powers. As the discussions on this issue have not yet taken place, it remains to be seen whether the Commission will be successful or not. However, the examination of EU unanimity seems to indicate that a more centrally controlled 'solution' should be sought.[973] The recent discussions on EU unanimity raise important questions about the democratic future of the EU and make contemporary the 'old' disputes about federalist EU. This has direct ramifications for the power interplay between EU-member states. Given the importance of crises for reorientating research and its activities, as well as the relationship between policy areas, it remains to be seen how these two crises will affect the direction of Horizon Europe and whether this programme will comprise a continuity of the second period or mark the beginning of a new, third period.

8.4.2 The need for holistically defined problems: depending on how the problem is defined will determine the solutions we will provide

In the words of one of my professors, it matters how we define a/the question.[974] The definition of a question or a problem affects not only 'where' we start looking for solutions, but also what remains out of our reach (i.e. what is 'left out'). The same applies to the missions and challenges and their definition. They form the framework based on which the solutions are

---

06-16/, (accessed 30 June 2022).; Noah Browning and Nora Buli, 22 June 2022, *Reuters*, EU signals shift to coal, accuses Russia of 'rogue moves' on gas', Available online: https://www.reuters.com/business/energy/russian-gas-flows-europe-via-nord-stream-ukraine-unchanged-2022-06-22/, (accessed 30 June 2022).; Elisabeth Schumacher, 23 June 2022, *Deutsche Welle*, Available online: https://www.dw.com/en/will-germany-return-to-nuclear-power/a-62223935, (accessed 30 June 2022).; Reuters, 27 June 2022, *Reuters*, G7 leaders debate fossil fuel investments amid energy crisis, Available online: https://www.reuters.com/world/g7-leaders-debate-fossil-fuel-investments-amid-energy-crisis-sources-2022-06-26/, (accessed 30 June 2022).

[972] Chee Foo Yun and Murray Miranda, 2 September 2022, *Reuters*, EU Commission seeks emergency powers on supply crisis with threats of fines, Available online: https://www.reuters.com/markets/europe/eu-commission-plans-emergency-powers-avoid-crisis-bottlenecks-faz-2022-09-02/, (accessed 3 September 2022).

[973] Bosoni Adriano, 31 August 2022, *World View*, Can the EU Avoid the Unanimity Trap?, Available online: https://worldview.stratfor.com/article/can-eu-avoid-unanimity-trap, (accessed 2 September 2022).; Tidey Alice, 11 May 2022, *Euronews*, Explained: Why EU countries are at odds over treaty changes, Available online: https://www.euronews.com/my-europe/2022/05/11/explained-why-eu-countries-are-at-odds-over-treaty-changes, (accessed 2 September 2022).

[974] It was one those magical occasions that someone's words both resonate and 'stick' with you. This was the case with this paraphrased phrase that Professor Arabatzis said during a bachelor course I attended all the way back to the early 2010s. It has stayed with me throughout my insofar scholarly (and non-scholarly) life.

found, and actions are taken. Therefore, how we define the missions is important and deserves attention.

The research networks always had the task of finding technological solutions to the challenges the defined by the EU.[975] The challenges have always been the result of crises – be they energy, environmental or raw material crises. They were tasked with finding solutions and/or responding to the problem or crisis at hand, and these networks offered the technological options based on the choices they made. However, our analysis has shown that the research and research responses have not taken into account concerns about the supply of resources that are critical to the technologies selected. As a result, the geopolitical dimension is 'missing' from the research. This 'gap' is particularly critical as research networks play an important role in selecting the technologies (and/or technological options) based on which the RES transition will take place. Moreover, the externalities resulting from these technological selections (by following their production chain steps) have never been included in the research and thus never considered or evaluated. Considering that the networks provide the technological solutions to these problems or challenges, this partial view of the research leads to the social, political, cultural, and geopolitical dimensions of the technologies being 'lost'.

One explanation for this partial view lies in the terms the networks used to delineate the beginning and end of their research: the 'value chain' (***from*** feedstock ***to*** module). Even when recycling was included in the research, it was only as a means to solve the problems of upscaled production (i.e. as a means to support industrial production). A more 'holistic' view of research with a broader global, geopolitical, and environmental dimension was not considered. At the same time, we should not forget that the actors who shaped the research agenda for PV came from the PV sector. Therefore, other or different aspects related to PV were not represented in setting the research agenda-setting.

Access to or sufficient supply of silicon, with its geopolitical dimension, was not a concern for the research networks. The geopolitical dimension was absent in setting the research agenda for the second period. The geopolitical dimension of scaling up c-Si production was also not included in the energy policy of EC. As the interviewee from Fraunhofer-ISE explained, this (i.e. the Si crisis) was part of a success story, due to an understanding of why the silicon crisis was not an issue. Moreover, the stakeholders involved in this process were convinced that the

---

[975] Apart from the empirical analysis in Chapters 4-7, see: Nakopoulou Efi and Arapostathis Stathis, "Reconfiguring Technologies by Funding Transitions: priorities, policies, and the renewable energy sources in the European Community funding schemes", *Journal of Energy History/Revue d'Histoire de l'Énergie* [Online], n°4, published 27 July 2020.

‘c-Si era’ had just begun. C-Si was **the** way forward and the means industrialize the PV sector (in terms of production). This provides a complementary understanding of why EU R&D continued to prioritize c-Si (directly or indirectly – e.g. the c-Si thin film agenda) and why actors sought solutions along the ‘value chain’ of c-Si. The ‘value chain’ used by the historical actors forming the networks can be understood as the ‘place’ where innovation is expected and sought. Value is thus created through innovation in these particular steps of the chain.

Broader geopolitical aspects or concerns do not seem to be considered by other DGs, even though geopolitics was the issue being studied. DG JRC did not include silicon in the list of critical minerals for ‘strategic energy technologies’ when it published its report for the transition to RES. The rationale for selecting the minerals studied (and by extension the minerals not included, although this was not stated) – notably Si was absent – was at best ‘lacking’ and at worst arbitrary.[976]

At the same time, we note that the research priorities and agenda were guided by an economic rationale reflected in the research aims. In the first period, the networks adopted an industrial rationale that directed research towards decreasing the cell/module costs in order to promote the competitiveness of the European industry. In the second period, the networks sought to respond to and solve production problems to enable the faster implementation of the installation targets set by energy policy.

In other DGs an economic rationale seems to be the priority too. For example, the DG Environment used an economic rationale when discussing the end-of-life cycle of PV installations. Relying on industry having an interest in recycling of end-of-life products (when increased volumes of waste will be generated) leads to several problems. The impact on the environment, society, health etc. was acknowledged but ‘forgotten’ in a DG report published to inform the recast of the WEEE Directive. As a result, the WEEE Directive left much room for inaction on the recycling of hazardous semiconductors (i.e. the cells). Instead of providing the mandatory means to build such an industry and the need for action to address the problem at hand, the EC has essentially legitimized this *in*action. In other words, we find that an economic rationale also takes precedence over other dimensions, contributing to the absence of policies with a long-term reach. It becomes clear that the policies that are developed are primarily motivated by economic considerations that benefit the industry, while the social,

---

[976] Regarding this point see the introductory section of Chapter 7. We are referring to the following report: R. L. Moss, E. Tzimas, H. Kara, P. Willis, J. Kooroshy, *Critical Metals in Strategic Energy Technologies: Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies*, Publications Office of the European Union (Luxembourg: 2011).

health, etc. aspects come second. This shows that the principle of 'problem first, action later' prevails not only in policy design but also in legislation. Thus, both the geopolitical dimension and the externalities of the technological choices were not a central concern for other DGs, even if the content was more closely linked to these dimensions or even if the externalities were recognized. This can also be attributed to the prevailing EU policy discourse (i.e. KBE) which emphasizes the role of knowledge in economic growth or development, while 'hiding' the material aspects, such as material resources, which are important. EU policy is (intentionally or unintentionally) blind to global supply chains and their externalities. The dominance and empowerment of the strong actors of the networks promoted by KBE can offer a complementary understanding of these non-holistic problems. But as these actors are perceived as (the) experts, issues of engagement, co-creation etc. may escape policy-makers.[977] Pfotenhauer, Laurent, Papageorgiou and Stilgoe have argued that grand societal challenges, such as climate change, both reflect the scalability zeitgeist of public policies and require scalable solutions.[978] This scalability will hinder other possible solutions and pathways and does not provide equal opportunities for intervention or distribution of benefits.[979] Moreover, they warn that "[a]ny site where scaling is made to look easy should thus raise red flags about a likely lack of comprehension or inclusiveness of perspectives."[980] Even though we do not employ the analytical category of 'scalability', our research findings complement some of the authors' theses. By examining dimensions that have been ignored while tracing where solutions have been proposed, who participated and who was left out of these processes, and the interplay between problem-definition and problem-solution, we suggest that there is a need for both more holistically defined problems and more holistically defined solutions. Moreover, based on our research, we can make concrete for inclusive and deliberative (democratic) decision-making processes in the different 'stages' of challenges.

The legitimization of the industry-led ETPs as the ones setting the research agenda (and research priorities) and directing research funding during the second period further promoted corporate and national (corporate and scientific) interests in research. In both periods, it was the actors of the networks that directed research. However, as we saw in chapter 3, RES are understood as locally sourced energies, which can further enrich our understanding of some of

---

[977] These issues have started being tackled in Horizon 2020 with the inclusion of RRI.

[978] Pfotenhauer Sebastian, Laurent Brice, Papageorgiou Kyriaki, Stilgoe Jack, "The politics of scaling", *Social Studies of Science*, 2022, p. 3-34.

[979] Pfotenhauer Sebastian, Laurent Brice, Papageorgiou Kyriaki, Stilgoe Jack, "The politics of scaling", *Social Studies of Science*, 2022, p. 3-34.

[980] Pfotenhauer Sebastian, Laurent Brice, Papageorgiou Kyriaki, Stilgoe Jack, "The politics of scaling", *Social Studies of Science*, 2022, p. 24.

the shortcomings of the research agenda. It is possible that actors only see the ‘end-product’ in isolation from its entire production chain with its corresponding geographies. The lack of transdisciplinarity and involvement of civil society and other stakeholders has led to overlooking important aspects or dimensions of research, including but not limited to geopolitics. At the same time, this allowed for the inclusion of local industrial interests, national strategies, existing capacities, etc. in the research agenda. However, as both the industrial and scientific communities involved in this process were geographically narrow and the individuals from the core of the technoscientific research networks were mainly from the c-Si sector, this challenges the notion of ‘inclusivity’ in setting the research agenda that will direct research funding.

As long as the ‘challenges’ are not defined holistically, we cannot expect holistic responses to the challenges facing the EU, which may encompass a variety of dimensions corresponding and directly related to the challenges at hand. The insofar non-holistically defined challenges have led to the marginalization or exclusion of different values that could lead to different choices and technological options. This also limits the technological solutions – and the values that inform these choices – with which we must respond to the crises and challenges. Promoting corporate interests and an economic rationale as guiding principles for policy-making limits both the scope and inclusiveness of challenges.

One way to address this problem is to define the challenges holistically. In other words, the Commission needs to actively involve more stakeholders and civil society, not only in setting the research agenda (e.g. ETPs), but also in defining the challenges. In addition, policy needs to address the long-term problems and challenges facing the EU. This requires not only the involvement of more actors in the process, but also a greater diversity of dimensions that can holistically define the challenges and holistically inform the possible solutions. An economic rationale alone cannot provide adequate solutions to the problems facing the EU, especially as its prioritization leads to a ‘devaluation’ of the social, health, environmental, etc. dimensions. The policy discourse advocated by the EU (i.e. KBE) directly downplays the importance of the material dimensions, leading to what can (at best) be called an economic policy that is partially blind to critical dimensions on which it depends. At the same time, technological options or choices need to incorporate more societal needs (hence technology needs to embody more and diverse societal and cultural values), while at the same time the challenges need to become more inclusive and holistic at the time of their definition. We cannot expect to have technological solutions to all problems, nor can we expect economics alone to be able or sufficient to solve all social problems, especially since they seem to be 'blind' to many dimensions that constitute the social.

From our analysis, it appears that the "social" dimension of the research networks comprised of universities, research centres and the industry (primarily). Both civil society and other stakeholders were not involved in the networks or in the decision-making processes for the research agenda. Crises offer opportune moments to create new platforms for open dialogue. In these moments, we need to promote open dialogues that involve more actors and social groups in defining the problems. This allows more (and different) values to enter into the definition of the problems, which in turn can lead to more inclusive and pluralistic solutions. In this way the **multiple forms of the social** can be brought closer to the technological and economic dimensions.

8.5 Future research recommendations

Since the suggestions for future research can go in a number of directions, we will limit ourselves here to some of the most exemplary suggestions. There are at least three types of knowledge: embodied, tacit and codified. It is the focus on the latter type of knowledge that 'demarcated the new research program from the older concept of a 'knowledge economy''.[981] For unlike the other two types, codified knowledge can be transferred and 'traded' on the market. Given the prominent role knowledge plays in constructing of the KBE, future research could examine the types of knowledge generated in particular 'knowledge hubs'. This research recommendation would draw from new 'sources' using different research methods (e.g. an anthropological study conducted through observation, fieldwork, a series of interviews, etc.).

Future research could provide comparative accounts of how the KBE is constructed in different cultural, political and technological contexts, focusing on different research areas and/or sectors (e.g. nanotechnology), which would contribute to understanding the construction of the KBE and its characteristics. Another suggestion for future studies would be to extend the current research to other RES and investigate the co-production between research and energy policy. This can be studied either at national or EU level. Another suggestion would be to combine and/or complement the existing research with similar analyses that extend to the other RES technologies. Mapping the entire production chain of all RES technologies would be an important contribution to understanding the complex geopolitical contexts resulting from the

---

[981] Leydesdorff Loet, "The Knowledge-Based Economy and the Triple Helix Model", *Annual Review of Information Science and Technology*, 2010, p. 368.

transition to RES. A mapping of material flows and the reconfiguration of geopolitics resulting from the RES transition that the EU is supporting. Lastly, research could extend to exploring the difficulties arising from the energy system transformation in different national contexts. This can provide useful insights into the inequalities arising from the reconfiguration of the energy system, while extending the analysis of energy justice and informing this analytical framework.

References

Agh Attila, “The increasing core-periphery divide and new member states: Diverging from the European Union’s mainstream developments”, *in* Core-Periphery Relations in the European Union: Power and Conflict in a Dualist Political Economy, Jose M. Magone, Bridgit Laffan and Christian Schweiger (eds.), Routledge/UACES contemporary European studies (London and New York: 2016), p. 117-129.

Bindseil Ulrich and Hantke Cordula, “The power distribution in decision-making among EU member states”, *European Journal of Political Economy*, 1997, p. 171-185.

Boffa C., Chadjivassiliadis J., Chemillie P., Stocker H.J., Weaire D., Wehenkel C., *Evaluation of the Community cost-shared research programme on solar, wind and biomass energy and of the Joint Research Centre’s programme on non-nuclear energies (1979-1985)*, Office for Official Publications of the European Communities (Luxembourg: 1987).

Bosoni Adriano, 31 August 2022, *World View*, Can the EU Avoid the Unanimity Trap?, Available online: https://worldview.stratfor.com/article/can-eu-avoid-unanimity-trap, (accessed 2 September 2022).

Browning Noah and Buli Nora, 22 June 2022, *Reuters*, EU signals shift to coal, accuses Russia of ‘rogue moves’ on gas’, Available online: https://www.reuters.com/business/energy/russian-gas-flows-europe-via-nord-stream-ukraine-unchanged-2022-06-22/, (accessed 30 June 2022).

Cai Yuzhuo and Etzkowitz Henry, “Theorizing the Triple Helix model: Past, present, and future”, *Triple Helix*, 2020, p. 189-226.

Camagni Roberto and Capelo Roberta, “Knowledge-Based Economy and Knowledge Creation: The Role of Space”, *in* Growth and Innovation in Competitive Regions: The Role of Internal and External Connections, U. Fratesi and L. Senn (eds.), Springer (Berlin: 2009), p. 145-166.

Chee Foo Yun and Murray Miranda, 2 September 2022, *Reuters*, EU Commission seeks emergency powers on supply crisis with threats of fines, Available online: https://www.reuters.com/markets/europe/eu-commission-plans-emergency-powers-avoid-crisis-bottlenecks-faz-2022-09-02/, (accessed 3 September 2022).

Cooke Philip and Leydesdorff Loet, “Regional Development in the Knowledge-Based Economy: The Construction of Advantage”, Journal of Technology Transfer, 2006, p. 5-15.

Decision No 1513/2002/EC of the European Parliament and of the Council of 27 June 2002 concerning the sixth framework programme of the European Community for research, technological development and demonstration activities, contributing to the creation of the

European Research Area and to innovation (2002 to 2006), Official Journal of the European Communities, Luxembourg, 29.08.2002.

Dosi Giovanni, Llerena Pratrick, Labini Mauro Sylos, "The relationships between science, technologies and their industrial exploitation: An illustration through the myths and realities of the so-called 'European Paradox'", *Research Policy*, 2006, p. 1450-1464.

European Commission, *Energy for the Future: Renewable Sources of Energy White Paper for a Community Strategy and Action Plan*, COM (97)599 final, 1997.

European Commission, *Europe 2020: A European strategy for smart, sustainable and inclusive growth*, COM(2010), Brussels, 3.3.2010.

European Commission, *Europe 2020 Flagship Initiative Innovation Union*, COM(2010), Brussels, 6.10.2010.

European Commission – DG for Research and Innovation, *Assessing Europe's University-Based Research – Expert Group on Assessment of University-Based Research*, Publications of the European Union (Luxembourg: 2010).

European Commission – DG for Research and Innovation, *State of the Innovation Union 2020: Accelerating change*, COM(2013) 149 final, Brussels, 21.3.2013.

European Commission – DG for Research and Innovation, *The role of Universities and Research Organizations as drivers for Smart Specialization at regional level*, Publications Office of the European Union (Brussels: 23 January 2014).

Farinelli Ugo, Gelus M., Muus L. T., Rorsch A., Stocker H. J., *The evaluation of the Communities' energy conservation and solar energy R&D sub-programmes*, Office for Official Publications of the European Communities (Luxembourg: 1980).

Felsenthal Dan S. and Machover Moshe, "The Weighted Voting Rule in the EU's Council of Ministers, 1958-95: Intentions and Outcomes", *Electoral Studies*, 1997, p. 33-47.

Florian Hanke, Rachel Guyet, Marielle Feenstra, "Do renewable energy communities deliver energy justice? Exploring insights from 71 European cases", *Energy Research & Social Sciences*, 2021, 102244.

Geert van der Veen, Patrick Eparvier, Matthias Ploeg, Paola Trucco, *Evaluation of the impact of projects funded under the 6th and 7th EU Framework Programmes for RD&D in the area of non-nuclear energy*, Final Report (Version 4, 19 June 2013), Technopolis Group (2014).

Godin Benoit, "The Knowledge-Based Economy: Conceptual Framework or Buzzword?", *Journal of Technological Transfer*, 2006, p. 17-30.

Gonzalez Sara, "The North/South divide in Italy and England: Discursive construction of regional inequality", *European Urban and Regional Studies*, 2011, p. 62-76.

Gruisen Philippe van and Crombez Christophe, “The Commission and the Council Presidency in the European Union: Strategic interactions and legislative powers, *European Journal of Political Economy*, 2021, 102040.

Hanke Florian, Guyet Rachel, Feenstra Marielle, “Do renewable energy communities deliver energy justice? Exploring insights from 71 European cases”, *Energy Research & Social Science*, 2021, 102244.

Hatch Gareth P., “Dynamics in the Global Market for Rare Earths”, *Elements*, 2012, p. 341-446.

Jesse Hoffman, Megan Davies, Thomas Bauwens, Philipp Spath, Maarten A. Hajer, Bleta Arifi, Amir Bazaz, Mark Swilling, “Working to align energy transitions and social equity: An integrative framework linking institutional work, imaginaries and energy justice”, *Energy Research & Social Sciences*, 2021, 102317.

Kalantzakos Sofia, China and the Geopolitics of Rare Earths, (New York: Oxford University Press, 2018).

Kauppi Heikki and Widgren Mika, “Voting rules and budget allocation in the enlarged EU”, *European Journal of Political Economy*, 2007, p. 693-706.

Knox Stephen, Hannon Matthew, Stewart Fraser, Ford Rebecca, “The (in)justices of smart local energy systems: A systematic review, integrated framework, and future research agenda”, *Energy Research & Social Science*, 2022, 102333.

Koutantou Angeliki and Triandafyllou Vassilis, 16 June 2022, *Reuters*, In a Greek coal mine, stocks build up ahead of peak summer demand, Available online: https://www.reuters.com/business/energy/greek-coal-mine-stocks-build-up-ahead-peak-summer-demand-2022-06-16/, (accessed 30 June 2022).

Kukovec Damjan, “Law and the Periphery”, *European Law Journal*, 2015, p. 406-428.

Kuus Merje, “Something old, something new: Eastness in European Union enlargement”, *Journal of International Relations and Development*, 2007, p. 150-167.

Laffan Brigid, “Core-Periphery dynamics in the Euro area: From conflict to cleavage?”, *in* Core-Periphery Relations in the European Union: Power and Conflict in a Dualist Political Economy, Jose M. Magone, Bridgit Laffan and Christian Schweiger (eds.), Routledge/UACES contemporary European studies (London and New York: 2016), p. 19-34.

Laredo Philippe, “The networks promoted by the framework programme and the questions they raise about its formulation and implementation”, *Research Policy*, 1998, p. 589-598.

Levidow Les, Birch Kean, Papaioannou Theo, "Divergent Paradigms of European Agro-Food Innovation: The Knowledge-Based Bio-Economy (KBBE) as an R&D agenda", *Science, Technology, & Human Values*, 2013, p. 94-125.

Leydesdorff Loet and Etzkowitz Henry, "The Triple Helix of Innovation: Introduction", *Science and Public Policy*, 1998, p. 358-364.

Leydesdorff Loet and Etzkowitz Henry, "The Triple Helix as a model for innovation studies", *Science and Public Policy*, 1998, p. 195-203.

Leydesdorff Loet, "The Knowledge-Based Economy and the Triple Helix Model", *Annual Review of Information Science and Technology*, 2010, p. 367-417.

Luo Jin and He Hongwei, "Trade Dispute on rare Earths Export from China to the United States, *Advances in Economics, Business, and Management Research*, 2018, p. 391-394.

Magone Jose M., "Centre-Periphery conflict in the European Union? Europe 2020, the Southern European Model and the euro-crisis", *in* European Union at the crossroads: The European perspectives after the global crisis, Attila Agh (ed.), Budapest College of Communication (Budapest: 2011), p. 71-122.

Manberger Andre and Johansson Bengt, "The geopolitics of metals and metalloids used for the renewable energy transition", *Energy Strategy Reviews*, 2019, p. 1-10.

Martin Ronald L., "The contemporary debate over the North-South divide: images and realities of regional inequality in late-twentieth-century Britain", *in* Geographies of England. The North-South Divide, Material and Imagined, Alan R. H. Baker and Mark Billinge (eds.), Cambridge Univesity Press (Cambridge, UK: 2004), p. 15-43.

Mazzucato Mariana and Semieniuk Gregor, "Public financing of innovation: new questions", *Oxford Review of Economic Policy*, 2017, p. 24-48.

Mazzucato Mariana and Semieniuk Gregor, "Financing renewable energy: Who is financing what and why it matters", *Technological Forecasting & Social Change*, 2018, p. 8-22.

Moss R. L., Tzimas E., Kara H., Willis P., Kooroshy J., *Critical Metals in Strategic Energy Technologies: Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies*, Publications Office of the European Union (Luxembourg: 2011).

Nakopoulou Efi and Arapostathis Stathis, "Reconfiguring Technologies by Funding Transitions: priorities, policies, and the renewable energy sources in the European Community funding schemes", *Journal of Energy History/Revue d'Histoire de l'Énergie* [Online], n°4, published 27 July 2020.

Organization for Economic Co-operation and Development, 9 September 2005, *OECD*, Knowledge-Based Economy, Available online: https://stats.oecd.org/glossary/detail.asp?ID=6864, accessed 11 September 2022.

Overland Indra, "The geopolitics of renewable energy: Debunking four emerging myths", *Energy Research & Social Science*, 2019, p. 36-40.

Pascariu Gabriel Carmen and Tiganasu Ramona, "Integration, Growth and Core-Periphery Pattern in EU's Economy: Theoretical Framework and Empirical Evidences", *in* Core-Periphery Patterns across the European Union: Case Studies and Lessons from Eastern and Southern Europe, Gabriela Carmen Pascariu and Maria Adelaide Pedrosa da Silva Duarte (eds.), Emerald Publishing Limited (Bingley, UK: 2017), p. 23-85.

Pfotenhauer Sebastian, Laurent Brice, Papageorgiou Kyriaki, Stilgoe Jack, "The politics of scaling", *Social Studies of Science*, 2022, p. 3-34.

Reuters, 27 June 2022, *Reuters*, G7 leaders debate fossil fuel investments amid energy crisis, Available online: https://www.reuters.com/world/g7-leaders-debate-fossil-fuel-investments-amid-energy-crisis-sources-2022-06-26/, (accessed 30 June 2022).

Schumacher Elisabeth, 23 June 2022, *Deutsche Welle*, Available online: https://www.dw.com/en/will-germany-return-to-nuclear-power/a-62223935, (accessed 30 June 2022).

Sepos Angelos, "The centre-periphery divide in the Eurocrisis", *in* Core-Periphery Relations in the European Union: Power and Conflict in a Dualist Political Economy, Jose M. Magone, Bridgit Laffan and Christian Schweiger (eds.), Routledge/UACES contemporary European studies (London and New York: 2016), p. 35-56.

Stegen Smith Karen, "Heavy rare earths, permanent magnets, and renewable energies: An imminent crisis", *Energy Policy*, 2015, p. 1-8.

Tidey Alice, 11 May 2022, *Euronews*, Explained: Why EU countries are at odds over treaty changes, Available online: https://www.euronews.com/my-europe/2022/05/11/explained-why-eu-countries-are-at-odds-over-treaty-changes, (accessed 2 September 2022).

Todorović Igor, 11 March 2022, *Balkan Green Energy News*, Europe switching on coal plants amid energy crisis, Available online: https://balkangreenenergynews.com/europe-switching-on-coal-plants-amid-energy-crisis/, (accessed 30 June 2022).

Tyfield David, The economics of science: a critical realist overview. Volume 1. Illustrations and philosophical preliminaries, Routledge (London: 2011).

Tyfield David, The economics of science: a critical realist overview. Volume 2. Towards a synthesis of political economy and science and technology studies, Routledge (London: 2011).

Tyfield David, “A Cultural Political Economy of Research and Innovation in an Age of Crisis”, *Minerva*, 2016, p. 149-167.

Zaporozhets Vera, Garcia-Valinas Maria, Kurz Sascha, “Key drivers of EU budget allocation: Does power matter?”, *European Journal of Political Economy*, 2016, p. 57-70.

Bibliography

Abnett Kate, 23 June 2022, *Reuters*, A dozen EU countries affected by Russian gas cuts, EU climate chief says, Available online: https://www.reuters.com/business/energy/russian-gas-cuts-have-hit-12-countries-eu-climate-chief-says-2022-06-23/, (accessed 30 June 2022).

Ackermann T., and Soder L., "An overview of wind energy-status 2002", *Renewable and Sustainable Energy Reviews,* 2002, p. 67-128.

Adamson Mathew, Palló Gábor, Hungary-Short Country Report, HoNESt Project, 2017.

Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile, *About us*, enea, Available online: https://www.enea.it/en/enea/about-us, (accessed 16 October 2019).

Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile, *History and Law references*, enea, Available online: https://www.enea.it/en/enea/history-and-law-references, (accessed 16 October 2019).

Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile – Centro Ricerche Casaccia, *Il Centro*, casaccia.enea, Available online: https://www.enea.it/it/centro-ricerche-casaccia, (accessed 16 October 2019).

Agh Attila, "The increasing core-periphery divide and new member states: Diverging from the European Union's mainstream developments", *in* Core-Periphery Relations in the European Union: Power and Conflict in a Dualist Political Economy, Jose M. Magone, Bridgit Laffan and Christian Schweiger (eds.), Routledge/UACES contemporary European studies (London and New York: 2016), p. 117-129.

Agora Energiewende and Ember, *The European Power Sector in 2020: Up-to-Date Analysis on the Electricity Transition*, 2021.

Andrée Dan, *Priority-setting in the European Research Framework Programmes*, VINNOVA Analysis VA – Swedish Governmental Agency for Innovation Systems (July 2009).

Aulich H., Schulze F., “Silicon feedstock for the photovoltaic industry”, *in* Seventeenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Munich, Germany, 22-26 October 2001, B. McNelis, W. Palz, H. A. Ossenbrink, P. Helm (eds.), Vol. I, WIP-Munich & ETA-Florence: 2002, p. 65-68.

Autant-Bernard Corinne, Billand Pascal, Frachisse David, Massard Nadine, “Social distance versus spatial distance in R&D cooperation: Empirical evidence from European collaboration choices in micro and nanotechnologies”, *Papers in Regional Science*, 2007, p. 495-519.

Automated photovoltaic cell and Module industrial Protocol to regain and secure European - Renewabke Energy market, ampere-h2020, *CEA-INES*, Available online: https://www.ampere-h2020.eu/partners/cea-ines-ampere-h2020.html, (accessed 2 February 2020).

Azur Space, azurspace, *Welcome*, Available online: http://www.azurspace.com/index.php/en/, (accessed 11 May 2021).

Banchoff Thomas, “The Politics of the European Research Area, ACES Working Paper 2002.3, August 2002, [working paper], Available online: http://aei.pitt.edu/8964/, p. 1-25.

Banchoff Thomas, “Institutions, Inertia and European Union Research Policy, *Journal of Common Market Studies*, 2002, p. 1-21.

Banchoff Thomas, “Politic Dynamics of the ERA”, *in Changing Governance on Research and Technology Policy: The European Research Area*, Jacob Edler, Stefan Kuhlmann, Maria Behrens (eds.), Edward Elgar (Cheltenham, U.K. and Northampton, Mass: 2003).

Barciela Fernando, 17 June 2013, El Pais, *Total eclipse of the sun*, Available online: https://english.elpais.com/elpais/2013/06/17/inenglish/1371471362_164500.html, (accessed 13 April 2021).

Belluque J. and Michel J., “Optimisation d’un ensemble concentrateur cellules solaires au silicium”, CECA-CEE-CEEA (Brussels, Luxembourg: 1982).

Bernreuter Johannes, 29 June 2020 [last updated 27 April 2022], berneuter, *Silicon Manufacturers: How the ranking of the top ten producers has been whirled around since 2004*, Available online: https://www.bernreuter.com/polysilicon/manufacturers/, (accessed 3 November 2021).

Bijker Wiebe E., Hughes Thomas P., Pinch Trevor (eds.), *The Social Construction of Technological Systems*, The MIT Press (Cambridge Massachusetts, London England: 1989).
Bindseil Ulrich and Hantke Cordula, “The power distribution in decision-making among EU member states”, *European Journal of Political Economy*, 1997, p. 171-185.

Blok K., “Renewable energy policies in the European Union”, *Energy Policy*, 2006, p. 251-255.

Bloomberg, *Euroinks srl*, Bloomberg. Available online: https://www.bloomberg.com/profile/company/1523Z:IM, (accessed 10 May 2021).

Boffa C., Chadjivassiliadis J., Chemillie P., Stocker H.J., Weaire D., Wehenkel C., *Evaluation of the Community cost-shared research programme on solar, wind and biomass energy and of the Joint Research Centre’s programme on non-nuclear energies (1979-1985)*, Office for Official Publications of the European Communities (Luxembourg: 1987).

Bogus K., Larue J. C., Crabb R. L., “SOLAR CELL CALIBRATION: RECENT EXPERIENCES AT ESTEC AND PROPOSAL OP A COMBINED SPACE AND TERRESTRIAL CALIBRATION PROCEDURE”, *in* Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Luxembourg, 27-30 September 1977, D. Reidel Publishing Company (Dordrecht Holland, Boston USA: 1978), p. 754-769.

Bondi Hermann, Amman Fernando, Jaumotte André, Marnet Chrysanth, Palomares Juan-José, Uffen Robert, Waldteufel Philippe, *Evaluation of the R & D programme in the field of Non-*

Nuclear Energy (1985-1988), Office for Official Publications of the European Communities, (Luxembourg: 1988).

Booth R. H., Bernardini O., Meyer-Henius U., Nuesser H., Williams R. H., Pereira de Moura D., *Evaluation of the JOULE Programme (1989-1992)*, Office for Official Publications of the European Communities (Luxembourg: 1994).

Bösch Frank and Graf Rüdiger, "Reacting to Anticipations: Energy Crises and Energy Policy in the 1970s. An Introduction*", Historical Social Research*, 2014, p. 7-21.

Bosoni Adriano, 31 August 2022, *World View*, Can the EU Avoid the Unanimity Trap?, Available online: https://worldview.stratfor.com/article/can-eu-avoid-unanimity-trap, (accessed 2 September 2022).

Boyle Miriam J. and Robinson M. E., "French Nuclear Energy Policy", *Geography*, 1981, p. 300-303.

Brand Karl-Werner, "Dialectics of institutionalisation: The transformation of the environmental movement in Germany", *Environmental Politics*, 1999, p. 35-58.

Breschi Stefano and Cusmano Lucia, "Unveiling the texture of a European Research Area: emergence of oligarchic networks under EU Framework Programmes", *International Journal Technology Management*, 2004, p. 747-772.

Breschi Stefano, Cassi Lorenzo, Malerba Franco, Vorontas Nicholas S., "Networked research: European policy intervention in ICTs", *Technology Analysis & Strategic Management*, 2009, p. 833-857.

Brey Philip, "The Technological Construction of Social Power", *Social Epistemology*, 2008, p. 71-95.

Breyer Ch., Birkner C, Kersten F., Gerlach A., Goldschmidt J. C., Stryi-Hipp G., Montoro Fraile D., Riede M., "Research and Development Investments in PV: a limiting factor for a fast PV diffusion?", 25th European Photovoltaic Solar Energy Conference / 5th World Conference on Photovoltaic Energy Conversion, Proceedings of the International Conference held in Valencia, Spain, 6-10 September 2010, G. F. de Santi, H. Ossenbrink and P. Helm (eds.), WIP Renewable Energies (Germany: 2010), p. 5385-5408.

Browning Noah and Buli Nora, 22 June 2022, *Reuters*, EU signals shift to coal, accuses Russia of 'rogue moves' on gas', Available online: https://www.reuters.com/business/energy/russian-gas-flows-europe-via-nord-stream-ukraine-unchanged-2022-06-22/, (accessed 30 June 2022).

Busquin Philippe, "Address at the Friedrich Ebert Foundation, Berlin, 18 January 2001", as cited in Thomas Banchoff, "Institutions, Inertia and European Union Research Policy", *Journal of Common Market Studies*, 2002, p. 1-21.

Bussiere Eric and Laer Arthe Van, "Research and technology, or the 'six national guardians' for 'the Commission, the eternal minor', *in* The European Commission 1958-72: History and Memories of an Institution, Michel Dumoulin (eds.), Publications Office of the European Union (Luxembourg: 2014), p. 491-506.

Cai Yuzhuo and Etzkowitz Henry, "Theorizing the Triple Helix model: Past, present, and future", *Triple Helix*, 2020, p. 189-226.

Call for tenders, (C 50, Volume 23), Official Journal of the European Communities, 28 February 1980.

Call for tenders (C50), 28 February 1980, Official Journal of the European Communities.

Calvo-Gallardo Elena, Arranz Nieves, de Arroyabe Juan Carlos Fernandez, "Analysis of the European energy innovation system: Contribution of the Framework Programmes to the EU policy objectives", *Journal of Cleaner Production*, 2021, 126690.

Calvo-Gallardo Elena, Arranz Nieves, de Arroyabe Juan Carlos Fernandez, "Innovation systems' response to changes in the institutional impulse: Analysis of the evolution of the European energy innovation system from FP7 to Horizon 2020", *Journal of Cleaner Production*, 2022, 130810.

Camagni Roberto and Capelo Roberta, "Knowledge-Based Economy and Knowledge Creation: The Role of Space", *in* Growth and Innovation in Competitive Regions: The Role of Internal and External Connections, U. Fratesi and L. Senn (eds.), Springer (Berlin: 2009), p. 145-166.

Caracostas Paraskevas and Muldur Ugur, *Koinonia: o anoichtos orizontas erevnas kai kainotomias* [Society: the open horizon of research and innovation], Ellinika Grammata (Athens: 2007).

Cartwright E., "Mining and its health consequences", *in* A Companion to the Anthropology of Environmental Health, M. Singer (ed.), John Wiley (Chichester, UK: 2016), p. 417–434.

Castello S., De Lillo A., Li Causi L., De Lia F., Tucci M., Guastella S., Paletta F., "PV Market, Industry and Research in Italy", *in* 24th European Photovoltaic Solar Energy Conference, 21-25 September 2009, Hamburg, Germany, Sinke W., Ossenbrink H., Helm P. (eds.), WIP Renewable Energies: 2009, p. 4427-4430.

Ceccaroli Bruno and Lohne Otto, "Solar Grade Silicon Feedstock", *in* Handbook of Photovoltaic Science and Engineering, Antonio Luque and Steven Hegebus (eds.), Wiley & Sons (Second Edition, UK: 2011), p. 153-204.

Ceccaroli Bruno, Ovrelid Eivind, Pizzini Sergio (eds.), *Solar Silicon Processes: Technologies, Challenges and Opportunities*, Taylor & Francis Group (Boca, Raton, London, New York: 2017).

Centrotherm, Centrotherm, *Company – Our mission*, Available online: https://www.centrotherm.de/en/company, (accessed 1 December 2020).

Chartier P., Bremont M., Chabot B., "The French Photovoltaic Programme", *in* Seventh EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Sevilla, Spain, 27-31 October 1986, A. Goetzberger, W. Palz and G. Willeke (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster, Tokyo: 1987), p. 1155-1161.

Chartier Philippe, Claverie Andre, Chabot Bernard, “From R&D to the Market: The French Photovoltaic Programme”, *in* Ninth EC Photovoltaic Solar Energy Conference, Proceedings of the international Conference held at Freiburg, Federal Republic of Germany, 25-29 September 1989, W. Palz, G. T. Wrixon and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1989), p. 1183-1186.

Chee Foo Yun and Murray Miranda, 2 September 2022, *Reuters*, EU Commission seeks emergency powers on supply crisis with threats of fines, Available online: https://www.reuters.com/markets/europe/eu-commission-plans-emergency-powers-avoid-crisis-bottlenecks-faz-2022-09-02/, (accessed 3 September 2022).

Chigondo Fidelis, “From Metallurgical-Grade to Solar-Grade Silicon: An Overview”, *Silicon*, 2018, p. 789-798.

Christoforidis Georgios C., Panapakidis Ioannis P., Papadopoulos Theofilos A., Papagiannis Grigoris K., Koumparou Ioannis, Hadjipanayi Maria and Georghiou George E., “A Model for the Assessment of Different Net-Metering Policies”, *Energies*, 2016, p. 1-24.

Chrysochoides Nicholas, Casey Thomas, Lapillonne Bruno, Roe Julie, *Clean, Safe and Efficient Energy for Europe: Impact assessment of non-nuclear energy projects implemented under the Fourth Framework Programme*, Office for Official Publications of the European Communities (Luxembourg: 2003).

Claverie A., Bal J. L., Chartier P., “Photovoltaics in France: Research, Development and Promotion”, *in* Thirteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Nice, France, 23-27 October 1995, W. Freiesleben, W. Palz, H. A. Overstraeten, P. Helm (eds.), Vol. I, H. S. Stephens & Associates (UK: 1995), p. 891-893.

Claverie A., Courtiade P., Vezin P., “Photovoltaic Rural Electrification in France”, *in* Proceedings of 1994 IEEE First World Conference on Photovoltaic Energy Conversion, Vol. II, p. 2283-2286.

Claverie A., “Photovoltaic Solar Cells: State of the Art, National Strategies and Perspectives”, *Solid State Phenomena*, 1994, p. 441-452.

Comello Stephen and Reichelstein Stefan, “Cost competitiveness of residential solar PV: The impact of net metering restrictions”, *Renewable and Sustainable Energy Reviews*, 2017, p. 46-57.

Commission Communication concerning the development programme — Call for proposals, (C29, Volume 38), Official Journal of the European Communities, 16 March 1985.

Commission Communication concerning the non-nuclear energy research and development programme – Call for proposals, (C146, Volume 29), Official Journal of the European Communities, 13 June 1986.

Commission of the European Communities, *Proposal from the Commission to the Council concerning a Second Year Energy Research and Development Programme*, COM (78) 388 final – Volume I, Brussels, 4 August 1978.

Commission of the European Communities - Directorate-General for Research, Science and Education, *Energy Research and Development Programme: Second Status Report (1975-1978)*, Vol. I, Martinus Nijhof Publishers (The Hague, Boston, London: 1979).

Commission of the European Communities - Directorate-General for Research, Science and Education, *Energy Research and Development Programme: Second Status Report (1975-1978)*, Vol. II, Martinus Nijhof Publishers (The Hague, Boston, London: 1979).

Commission of the European Communities, *Energy Research and Development Programme: Second Status Report*, Vol. II, Martinus Nijhof Publishers (The Hague, Boston, London: 1979).
Commission of the European Communities, *Assessment Report on the Community Demonstration Projects in the fields of Energy Saving and Alternative Energy Sources*, COM (82) 324 final/3, Brussels, 17 June 1982.

Commission of the European Communities, *Single European Act*, Office for Official Publications of the European Communities (Luxembourg: 1986).

Commission of the European Communities, *Energy in Europe: Energy policies and trends in the European Community*, Office for Official Publications of the European Communities (Luxembourg: 1989).

Commission of the European Communities, “White Paper: An Energy Policy for the European Union”, COM (95) 682 final, Brussels, 13.12.1995.

Commission of the European Communities, *Communication from the Commission ENERGY FOR THE FUTURE: RENEWABLE SOURCES OF ENERGY White Paper for a Community Strategy and Action Plan*, COM (97) 599 final, Brussels, 26.11.1997.

Commission of the European Communities, *Communication from the Commission to the Council, the European Parliament, the Economic and Social Committee and the Committee of the Regions: Towards a European research area*, COM (2000) 6 final, Brussels, 18 January 2000.

Commission of the European Communities, Communication from the Commission to the European Council and the European Parliament – An Energy Policy for Europe, COM(2007) 1 final, Brussels, 10.1.2007.

Communication from the Commission regarding the energy research and development programme adopted by the Council of the European Communities on 22 August 1975, Official Journal of the European Communities, 21.1.1976.

Cook Paul, “Rural Electrification and Rural Development”, *in* Rural Electrification Through Decentralized Off-grid Systems in Developing Countries, S. Bhattacharyya (ed.), Springer (London: 2013), p. 13-38.

Cooke Philip and Leydesdorff Loet, “Regional Development in the Knowledge-Based Economy: The Construction of Advantage”, Journal of Technology Transfer, 2006, p. 5-15.
Correlje Aad and van der Linde Coby, “Energy supply security and geopolitics: A European perspective”, *Energy Policy*, 2006, p. 532-543.

Costogue E., Ferber R., Hasbach W., Pellin R., and Yaws C., *Silicon Material Outlook Study for 1980-85 Calendar Years*, Jet Propulsion Laboratory: Report Prepared for the US Department of Energy, (November 1, 1979: JPL Publication 79-110).

Costogue E. N. and Ferber R. R., “Polycrystalline Silicon Material Availability and Market Pricing Outlook for 1980 through 1988”, *in* Fifth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Kavouri (Athens), Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 1027-1031.

Council Decision of 14 March 1989 on a specific research and technological development programme in the field of energy – non-nuclear energies and rational use of energy – 1989 to 1992 (Joule), Official Journal of the European Communities, 11.4.1989.

Council Resolution of 17 December 1974 concerning Community energy policy objectives for 1985 (C. 153), Official Journal of the European Communities, 9.7.1975.

Council Resolution of 16 September 1986 concerning new energy policy objectives for 1995 and convergence of the policies of the Member States (86/C 240/01), Official Journal of the European Communities, 25.09.1986.

Crespo L., “Spanish National Photovoltaic Program”, *in* Seventh EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Sevilla, Spain, 27-31 October 1986, A. Goetzberger, W. Palz, G. Willeke (eds.), Kluwer Academic Publishers, (Dordrecht, Boston, Lancaster, Tokyo: 1987), p. 1177-1184.

CRU Consulting, *Market Trend Report: Silver’s important role in solar power*, CRU International Limited (UK: June 2020).

Dalton Russel J. and Rohrschneider Robert, “The Environmental Movement and the Modes of Political Action”, *Comparative Political Studies*, 2003, p. 743-771.

Darghouth Naim R., Barbose Galen, Wiser Ryan, "The impact of rate design and net metering on the bill savings from distributed PV for residential customers in California", *Energy Policy*, 2011, p. 5243-5253.

de Arroyable Juan Carlos Fernandez, Schumann Martin, Sena Vania, Lucas Pablo, "Understanding the network structure of agri-food FP7 projects: An approach to the effectiveness of innovation systems", *Technological Forecasting & Social Change*, 2021, 120372.

Defazio D., Lockett A., Wright M., "Funding incentives, collaborative dynamics and scientific productivity: Evidence from the EU framework program", *Research Policy*, 2009, p. 293–305.

De Lillo A., Li Causi S., Castelllo S., Guastella S., "PV activities and future development in Italy", *in* 20th European Photovoltaic Solar Energy Conference, 6-10 June 2005, Barcelona, Spain, Palz W., Ossenbrink H., Helm P. (eds.), WIP-Renewable Energies: 2005, p. 3099-3102.

De Lillo A., Castello S., De Lia F., Guastella S., Paletta F., "Status and Perspectives of PV in Italy", *in* 25th European Photovoltaic Solar Energy Conference and Exhibition/5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Valencia, Spain, De Santi G. F., Ossenbrink H., Helm P. (eds.), WIP Renewable Energies: 2010, p. 5344-5347.

Debata Byomakesh, Patnaik Pooja, Mishra Abhisek, "COVID-19 pandemic! It's impact on people, economy, and environment", *Journal of Public Affairs*, 2020, p. 1-20.

Decision No 182/1999/EC of the European Parliament and of the Council of 22 December 1998 concerning the fifth framework programme of the European Community for research, technological development and demonstration activities (1998 to 2002), Official Journal of the European Communities, 1.2.1999.

Decision No 1513/2002/EC of the European Parliament and of the Council of 27 June 2002 concerning the sixth framework programme of the European Community for research, technological development and demonstration activities, contributing to the creation of the European Research Area and to innovation (2002 to 2006), Official Journal of the European Communities: Luxembourg, 29.08.2002.

Derrick A., Barlow R.W., McNelis B., Gregory J.A. (eds.), *Photovoltaics: A Market Overview*, James & James Science Publishers ltd (London: 1993).

DGXVII, "Thermie-Altener Renewable Energy Report", Office for Official Publications of the European Communities (Luxembourg: 1998).

Dharmadasa I. M., "Photovoltaic Solar Energy Conversion", *in* Advances in Thin-Film Solar Cells (1st Edition), Pan Stanford Publishing (Singapore: 2012), p. 1-24.

Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity, Official Journal of the European Communities, 30.1.1997.

Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market, Official Journal of the European Communities, 27.10.2001.

Directive 2003/54/EC of the European Parliament and of the Council of 26 June 2003 concerning common rules for the internal market in electricity and repealing Directive 96/92/EC, Official Journal of the European Union, 15.7.2003.

Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, Official Journal of the European Union, 5.6.2009.

Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC, Official Journal of the European Union, 14.08.2009.

Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE), Official Journal of the European Union, 24.7.2012.

Directive (EU) 2019/944 of the European Parliament and of the Council of 7 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EC (recast), Official Journal of the European Union, 14.06.2019.

Directorate General for Research and Innovation, *Non-nuclear energy programme (1990-94) JOULE II – Vol 1*, Office for Official Publications of the European Communities (Luxembourg: 1997).

Dollery A. A., "Photovoltaic Activities in the United Kingdom", *in* Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Luxembourg, 27-30 September 1977, D. Reidel Publishing Company (Dordrecht Holland, Boston USA: 1978), p. 522-531.

Dosi Giovanni, Llerena Pratrick, Labini Mauro Sylos, "The relationships between science, technologies and their industrial exploitation: An illustration through the myths and realities of the so-called 'European Paradox'", *Research Policy*, 2006, p. 1450-1464.

Dufo-Lopez Rodolfo and Bernal-Agustin Jose L., "A comparative assessment of net metering and billing policies. Study cases for Spain", *Energy*, 2015, p. 684-694.

Dusonchet Luigi and Telaretti Enrico, "Comparative economic analysis of support policies for solar PV in the most representative EU countries", *Renewable and Sustainable Energy Reviews*, 2015, p. 986-998.

Dutta Prasanta Kumar, Granados Samuel and Ovaska Michael, 16 February 2022, *Reuters*, Ukraine crisis: Russian gas threat in Europe, Available online: https://graphics.reuters.com/UKRAINE-CRISIS/GAS/gdpzynlxovw/, (accessed 14 July 2022).

Duvauchelle Christophe, Fraisse Jean-Luc, Barlier Yves, "Photovoltaic Integration in the Distribution Grid French Regulation and Network Requirements", *in* Twenty second European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Milan, Italy, 3-7 September 2007, G. Willeke, H. Ossenbrink, P. Helm (eds.), WIP Renewable Energies: 2007, p. 3505-3511.

EcoGreen Energy, 27 May 2022, *EcoGreen Energy*, Solar Energy Deployment in EU 2030, Available online: https://www.eco-greenenergy.com/solar-energy-deployment-in-eu-2030-global-energy-crisis/, (accessed 1 June 2022).

École polytechnique fédérale de Lausanne, epfl, *Silicon-based heterojunction solar cells*, Available online: https://www.epfl.ch/labs/pvlab/research/heterojunction_solar_cells/, (accessed 5 February 2020).

École polytechnique fédérale de Lausanne - PVLab, epfl.pvlab, *About us*, Available online: https://www.epfl.ch/labs/pvlab/about_us/, (accessed 5 February 2020).

Eid Cherrelle, Guillén Javier Reneses, Marín Pablo Frías, Hakvoort Rudi, "The economic effect of electricity net-metering with solar PV: Consequences for network cost recovery, cross subsidies and policy objectives", *Energy Policy*, 2014, p. 244-254.

Eikeland Per Ove and Skjaerseth Jor Birger, "The politics of low-carbon innovation: Implementing the European Union's strategic energy technology plan, *Energy Research & Social Science*, 2021, 102043.

Eisenbeiß G. and Batsch J., "The Photovoltaic Program of the Federal Republic of Germany", *in* Seventh EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Sevilla, Spain, 27-31 October 1986, A. Goetzberger, W. Palz and G. Willeke (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster, Tokyo: 1987), p. 1162-1169.

Eisenbeiß Gerd, "The PV Program of the Federal Republic of Germany", *in* Eighth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Florence, Italy, 9-13 May 1988, I. Solomon, B. Equer, and P. Helm (eds.), Vol. II, Kluwer Academic Publishers (Dordrecht, Boston, London: 1988), p. 1609-1614.

El Bassam Nasir, Maegaard Preben, Schlichting Marcia Lawton, Scope of the Book, *in* Distributed Renewable Energies for Off-Grid Communities, El Bassam Nasir, Maegaard Preben, Schlichting Marcia Lawton (eds.), 1st Edition, Elsevier (Oxford, UK: 2013), p. 1-6.

Elgstrand K., Sherson D. L., Jørs E., Nogueira C., Thomsen J. F., Fingerhut M., Burström L., Rintamäki H., Apud E., Oñate E., Coulson N., McMaster L., Clarke E. E., "Safety and Health in Mining: Part 1*", Occupational Health Southern Africa*, 2017, p. 10-20.

Energy Research Centre of the Netherlands, ECN, *Sustainable energy: for a clean future in which ECN plays a leading role*, Available online: https://www.ecn.nl/energy-research/index.html, (accessed 2 December 2019).

Enkhardt Sandra, 28 March 2018, *SolarWorld files for insolvency-again*, pv-magazine, Available online: https://www.pv-magazine.com/2018/03/28/solarworld-files-for-insolvency-again/, (accessed 3 November 2019).

European Commission – Directorate General for Energy, *Energy in Europe: Energy policies and trends in the European Community*, Office for Official Publications for the European Communities (Luxembourg: 1989).

European Commission, *Energy for the Future: Renewable Sources of Energy White Paper for a Community Strategy and Action Plan*, COM (97)599 final, 1997.

European Commission, *Communication from the Commission Climate Change – The EU Approach to Kyoto*, COM (97) 481 final, 1 October 1997.

European Commission – Directorate General for Energy, *THERMIE-ALTENER: Renewable Energy Report*, Office for Official Publications of the European Communities (Luxembourg: 1998).

European Commission, *Energy, environment and sustainable development: sub-programme Energy Information package*, March 1999 edition.

European Commission, *Work Programme: 6.1 Sustainable energy systems*, 2002.

European Commission – DG JRC, *PVNET Workshop Proceedings: 'RTD Strategies for PV'*, held at JRC Ispra, 30-31 May 2002.

European Commission, *Technology Platforms: from Definition to Implementation of a Common Research Agenda*, Office for Official Publications of the European Communities: Luxembourg, 2004.

European Commission – DG for Research Sustainable Energy Systems, *European Smart Grids Technology Platform: Vision and Strategy for Europe's Electricity Networks of the Future*, Office for Official Publications of the European Communities (Luxembourg: 2006).

European Commission, *Energy Research in the 7th framework programme*, 2007.

European Commission, *The raw materials initiative — meeting our critical needs for growth and jobs in Europe*, COM(2008) 699 final, Brussels, 4.11.2008.

European Commission, *Europe 2020: A European strategy for smart, sustainable and inclusive growth*, COM(2010), Brussels, 3.3.2010.

European Commission, *Europe 2020 Flagship Initiative Innovation Union*, COM(2010), Brussels, 6.10.2010.

European Commission – DG for Research and Innovation, *Assessing Europe's University-Based Research – Expert Group on Assessment of University-Based Research*, Publications of the European Union (Luxembourg: 2010).

European Commission - Directorate-General for Research and Innovation, *Towards a Responsible Research and Innovation in the Innovation and Communication Technologies and Security Technology Fields*, Rene von Schomberg, (eds.), Publications Office of the European Union (Luxembourg: 2011).

European Commission, *Tackling the Challenges in Commodity Markets and on Raw Materials*, COM(2011) 25 final, Brussels, 2.2.2011.

European Commission, *A Roadmap for moving to a competitive low carbon economy in 2050*, Brussels, 8.3.2011, COM (2011) 112 final.

European Commission – DG Environment, *Study on PV Panels Supplementing the Impact Assessment for a recast of the WEEE Directive*, Final Report, 14 April 2011.

European Commission, Directorate-General for Research and Innovation, *Towards a Responsible Research and Innovation in the Innovation and Communication Technologies and Security Technology Fields*, Rene von Schomberg, (ed.), Publications Office (Luxembourg: 2011).

European Commission, *Materials Roadmap Enabling Low Carbon Energy Technologies*, SEC(2011) 1609 final, Brussels, 13.12.2011.

European Commission – DG for Research and Innovation, *State of the Innovation Union 2020: Accelerating change*, COM(2013) 149 final, Brussels, 21.3.2013.

European Commission, *EU imposes provisional anti-dumping tariffs on Chinese solar panels*, Europa, 4 June 2013, Brussels, Available online: https://ec.europa.eu/commission/presscorner/detail/en/IP_13_501, (accessed 15 May 2020).

European Commission – DG for Research and Innovation, *The role of Universities and Research Organizations as drivers for Smart Specialization at regional level*, Publications Office of the European Union (Brussels: 23 January 2014).

European Commission, *On the review of the list of critical raw materials for the Eu and the implementation of the Raw Materials Initiative*, COM(2014) 297 final, Brussels, 26.5.2014.

European Commission, *Report from the Commission to the European Parliament and the Council Progress Towards Achieving the Kyoto and EU 2020 Objectives*, COM(2014) 689 final, Brussels, 28.10.2014.

European Commission, *A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy*, COM(2015) 80 final, Brussels, 25.2.2015.

European Commission, *On the 2017 list of Critical Raw Materials for the EU*, COM(2017) 490 final, Brussels, 13.9.2017.

European Commission, *A Clean Planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*, COM (2018) 773 final, Brussels, 28.11.2018.

European Commission, Directorate-General for Climate Action, *Going climate-neutral by 2050: a strategic long-term vision for a prosperous, modern, competitive and climate-neutral EU economy*, Publications Office of the European Union (Luxembourg: 2019).

European Commission, *The European Green Deal*, COM (2019) 640 final, Brussels, 11.12.2019.

European Commission, *Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability*, COM(2020) 474 final, Brussels, 3.9.2020.

European Commission – JRC, [last updated on 19 July 2022], Europa, *Smart Metering deployment in the European Union*, Available online: https://ses.jrc.ec.europa.eu/smart-metering-deployment-european-union, (accessed 20 July 2022).

European Commission, Europa, *Strategic Energy Technology Plan*, Available online: https://energy.ec.europa.eu/topics/research-technology-and-innovation/strategic-energy-technology-plan_en#european-technology-and-innovation-platforms, (accessed 14 March 2022).

European Commission, Europa, *Single Market and Standards*, Available online: https://ec.europa.eu/growth/single-market_en, (accessed 19 April 2022).

European Commission, Europa, *Climate Action – 2050 long-term targets*, Available online: https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2050-long-term-strategy_en, (accessed 10 April 2021).

European Environment Agency, (archived 15 December 2016), EEA Europa, "*Indicator Assessment: Overview of electricity production and use in Europe*", Available online: https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-1/assessment, (accessed 15 November 2021).

European Photovoltaics Industry Association, *Global Market Outlook: For Photovoltaics 2014-2018*, 2014.

Eurostat, (January 2022), Europa, *Renewable energy statistics*, Available online: (https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics) (accessed 18 March 2022).

Faaij A. P., "Bio-energy in Europe: changing technology choices", *Energy Policy*, 2006, p. 322–342.

Fabre E., Smet De L., Mertens R., "High Intensity Silicon Solar Cells", *in* Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Luxembourg, September 27-30, 1977, D. Reidel Publishing Company (Dordrecht, Holland/Boston, USA: 1978), p. 249-258.

Farinelli Ugo, Gelus M., Muus L. T., Rorsch A., Stocker H. J., *The evaluation of the Communities' energy conservation and solar energy R&D sub-programmes*, Office for Official Publications of the European Communities (Luxembourg: 1980).

Felsenthal Dan S. and Machover Moshe, "The Weighted Voting Rule in the EU's Council of Ministers, 1958-95: Intentions and Outcomes", *Electoral Studies*, 1997, p. 33-47.

Ferrazza F., De Lillo A., Farinelli U., "The Italian PV R&D Programme: Status and Perspectives", *in* 29th IEEE Photovoltaic Specialists Conference, 19-24 May 2002, New Orleans, USA, p. 15-20.

Firstman S. I. and Vachtsevanos G. J., "Distributed Photovoltaic Systems: addressing the utility interface issues", *in* Fifth EC Photovoltaic Energy Conference, Proceedings of the International Conference held at Kavouri, Athens, Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 424-431.

Flavin Christopher, "Photovoltaics: International Competition for the Sun", *Environment: Science and Policy for Sustainable Development*, 1983, p. 7-44.

Florian Hanke, Rachel Guyet, Marielle Feenstra, “Do renewable energy communities deliver energy justice? Exploring insights from 71 European cases”, *Energy Research & Social Sciences*, 2021, 102244.

Foley Gerald, “Rural electrification in the developing world”, *Energy Policy*, 1992, p. 145-152.

Fouquet Roger and Pearson Peter J. G., Editorial “Past and Prospective energy transitions: Insights from history”, *Energy Policy*, 2012, p. 1-7.

Fraunhofer ISE, 30 November 2018, *Press Release: Professor Adolf Goetzberger Turns 90: Pioneer of the Energy Transformation and Founder of Fraunhofer ISE*, ise-fraunhofer, Available online: https://www.ise.fraunhofer.de/en/press-media/press-releases/2018/professor-adolf-goetzberger-turns-90-pioneer-of-the-energy-transformation-and-founder-of-fraunhofer-ise.html, (accessed 5 October 2019).

Fraunhofer-ISE, 17 January 2022, Fraunhofer-ise, “*Public Net Electricity Generation in Germany in 2021: Renewables Weaker Due to Weather*”, Available online: https://www.ise.fraunhofer.de/en/press-media/news/2022/public-net-electricity-in-germany-in-2021-renewables-weaker-due-to-weather.html, (accessed 19 November 2020).

Fraunhofer ISE, *Photovoltaics Report*, Freiburg: 16 September 2020.

Fraunhofer ISE, *Photovoltaics Report*, Freiburg: 24 February 2022.

Fthenakis V. M., and Moskowitz P. D., “Photovoltaics: Environmental, Health and Safety Issues and Perspectives”, *Progress in Photovoltaics: Research and Applications*, 2000, 27-38.
Fthenakis V., and Zweibel K., *CdTe PV: Real and Perceived EHS Risks*, Presented at the National Center for Photovoltaics and Solar Program Review Meeting, Denver, Colorado (US), March 24-26, 2003, (NREL/CP-520-33561), p. 1-3.

Fuller S. and McCauley D., “Framing energy justice: perspectives from activism and advocacy”, *Energy Research and Social Science*, 2016, p. 1-8.

Gaiddon B., “New legal framework and market perspective for grid connected PV in France”, *in* Seventeenth Photovoltaic Solar Energy Conference, Proceeding of the International Conference held in Munich, Germany, 22-26 October 2001, B. McNelis, W. Palz, H. A. Ossenbrink, P. Helm (eds.), Vol I, WIP-Munich and ETA-Florence: 2002, p. 911-913.

Gaiddon B., l’Epine M. de, Jediczka M., “The Photovoltaic Market in France”, *in* Twentieth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Barcelona, Spain, 6-10 June 2005, W. Palz, H. Ossenbrink, P. Helm (eds.), Vol II, WIP Renewable Energies (Germany: 2005), p. 3064-3067.

Gan L., Eskeland G. S., Kolshus H. H., “Green electricity market development: Lessons from Europe and the US”, *Energy Policy*, 2007, p. 144-155.

Geert van der Veen, Patrick Eparvier, Matthias Ploeg, Paola Trucco, *Evaluation of the impact of projects funded under the 6th and 7th EU Framework Programmes for RD&D in the area of non-nuclear energy*, Final Report (Version 4, 19 June 2013), Technopolis Group (2014).

Geuna A., “Determinants of university participation in EU-funded R&D cooperative projects”, *Research Policy*, (1998), p. 677-687.

Gifford Jonathan, 10 May 2017, *Breaking: SolarWorld files for insolvency*, Available online: https://pv-magazine-usa.com/2017/05/10/breaking-solarworld-files-for-insolvency/, (accessed 3 November 2019).

Godin Benoit, “The Knowledge-Based Economy: Conceptual Framework or Buzzword?”, *Journal of Technological Transfer*, 2006, p. 17-30.

Goetzberger Adolf, “Solar Energy, the Citizen’s Energy”, *in* Fourteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Barcelona, Spain, 30 June – 4 July 1997, H. A. Ossenbrink, P. Helm and H. Ehmann (eds.), Vol. I, H. S. Stephens & Associates (Oxfordshire, UK: 1997), p. xxxvii-xl.

Gonzalez Sara, “The North/South divide in Italy and England: Discursive construction of regional inequality”, *European Urban and Regional Studies*, 2011, p. 62-76.

Greenpeace and EPIA, *Solar Generation: Solar Electricity for Over one billion people and two million jobs by 2020*, September 2006.

Gruisen Philippe van and Crombez Christophe, "The Commission and the Council Presidency in the European Union: Strategic interactions and legislative powers, *European Journal of Political Economy*, 2021, 102040.

Guido Brunner, "Opening Address", *in* Second EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Berlin (West), 23-26 April 1979, R. Van Overstraeten and W. Palz (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1979), p. 4-10.

Guy K., Amanatidou E., Psarra F., "Framework Programme 5 (FP5) impact assessment: a survey conducted as part of the five-year assessment of European Union research activities (1999–2003)", *Science and Public Policy*, 2005, p. 349–366.

Guzzetti Luca, *A brief history of European Union Research Policy*, Office for Official Publications of the European Communities (Luxembourg: 1995).

Habib Komal, Hamelin Lorie, Wenzel Henrik, "A dynamic perspective of the geopolitical supply risk of metals", *Journal of Cleaner Production*, 2016, p. 850-858.

Hanke Florian, Guyet Rachel, Feenstra Marielle, "Do renewable energy communities deliver energy justice? Exploring insights from 71 European cases", *Energy Research & Social Sciences*, 2021, 102244.

Hatch Gareth P., "Dynamics in the Global Market for Rare Earths", *Elements*, 2012, p. 341-446.

Hecht Gabrielle, "An elemental force: Uranium production in Africa, and what it means to be nuclear", *Bulletin of the Atomic Scientists*, 2012, p. 22-33.

Hecht Gabrielle, "Introduction", *in* Being Nuclear: Africans and the Global Uranium Trade, MIT Press (Cambridge Massachusetts, London England: 2012).

Hegedus Steven and Luque Antonio, “Achievements and Challenges of Solar Electricity from Photovoltaics”, *in* Handbook of Photovoltaic Science and Engineering, Antonio Luque and Steven Hegebus (eds.), Wiley & Sons (Second Edition, UK: 2011), p. 1-38.

Hermann Scheer, 2014, *About Hermann Scheer*, Hermann Scheer. Available online: http://www.hermannscheer.de/en/, (accessed 10 January 2020).

Hodgkinson Jane H. and Smith Michael H., “Climate change and sustainability as drivers for the next mining and metals boom: The need for climate-smart mining and recycling”, *Resources Policy*, 2021, 101205.

Hoffman Jesse, Davies Megan, Bauwens Thomas, Spath Philipp, Hajer Maarten A., Arifi Bleta, Bazaz Amir, Swilling Mark, “Working to align energy transitions and social equity: An integrative framework linking institutional work, imaginaries and energy justice”, *Energy Research & Social Sciences*, 2021, 102317.

Högselius Per, Hommels Anique, Kaijer Arne, van der Vleuter Erik (eds.), *The Making of Europe’s Critical Infrastructure: Common Connections and Shared Vulnerabilities*, Palgrave Macmillan (UK and US: 2013).

Högselius Per, Kaijer Arne, van der Vleuter Erik, *Europe’s Infrastructure Transition: Economy, War, Nature*, Palgrave Macmillan (UK and US: 2015).

Horner Rory and Carmody Padraig, “Global North/South”, *in* International Encyclopedia of Human Geography, (2nd ed.), Volume 6, Audrey Kobayashi (eds.), Elsevier (2019), p. 181-187.

Hughes Thomas P., *Networks of Power: Electrification in Western Society 1880-1930*, The John Hopkins University Press (Baltimore, London: 1983).

Hund Kirsten, La Porta Daniele, Fabregas Thao P., Laing Tim, Drexhage John, *Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition*, International Bank for Reconstruction and Development/The World Bank (Washington: 2020).

Hunt Lee P., “Silicon precursors: Their manufacture and properties”, in Handbook of semiconductor silicon technology, William C. O’Mara, Robert B. Herring, Lee P. Hunt (eds.), Noyes Publications (USA: 1990), p. 1-32.

Imamura M. S., Helm M. S. and Palz W., *Photovoltaic System Technology: A European Handbook*, Published by H. S. Stephens & Associates on behalf of the European Commission (Bedford, UK: 1992).

Institute for Concentration Photovoltaics Systems, isfoc, *History*, Available online: http://www.isfoc.net/index.php/en/isfoc-2/global-presentation/history, (accessed 13 April 2021).

Institute for Microelectronics and Microsystems – National Research Council of Italy, IMM-CNR, *LAMEL History*, Available online: https://www.bo.imm.cnr.it/unit/history, (accessed 15 December 2020).

Institute of Atomic and Molecular Physics, amolf, *History*, Available online: https://amolf.nl/about/history-of-amolf, (accessed 20 October 2019).

Institute of Atomic and Molecular Physics, amolf, *Professor Jaap Kistemaker (1917-2010)*, Available online: https://amolf.nl/about/history-professor-jaap-kistemaker, (accessed 20 October 2019).

Institute of Atomic and Molecular Physics, amolf, *Short portrait of Jaap Kistemaker*, Available online: https://amolf.nl/wp-content/uploads/2016/03/Short-portrait-of-Jaap-Kistemaker_Impact-60-years-AMOLF.pdf, (accessed 20 October 2019).

Instituto de Energia Solar (Universidad Politecnica de Madrid), ies.upm, *40 years leading PV solar energy: History*, Available online: https://www.ies.upm.es/IES_UPM/History, (accessed 13 May 2021).

Interuniversity Microelectronics Centre, 1 February 2017, *Harvesting sunlight from both sides of PV cells may give PV plants a significant energy boost*, imec, Available online: https://www.imec-int.com/en/imec-magazine/imec-magazine-february-2017/harvesting-sunlight-from-both-sides-of-pv-cells-may-give-pv-plants-a-significant-energy-boost, (accessed 7 November 2019).

Italian National Agency for New Technologies, Energy and Sustainable Economic Development – Cassaccia Research Centre, *The Centre*, old.enea, Available online: http://old.enea.it/com/ingl/center/Casaccia/centre.html, (accessed 16 October 2019).

Jäger-Waldau Arnulf, *PV Status Report 2003: PV Status Report 2003: Research, Solar Cell Production and Market Implementation in Japan, USA and the European Union*, Office for Official Publications Office of the European Communities (Luxembourg: 2003).

Jäger-Waldau Arnulf, *PV Status Report 2005*, Publications Office of the European Union (Luxembourg: 2005).

Arnulf Jäger-Waldau, *PV Status Report 2006*, Office for Official Publications Office of the European Communities (Luxembourg: 2006).

Jäger-Waldau Arnulf, *PV Status Report 2007*, Publications Office of the European Union (Luxembourg: 2007).

Jäger-Waldau Arnulf, *PV Status Report 2008*, Publications Office of the European Union (Luxembourg: 2008).

Arnulf Jäger-Waldau, *PV Status Report 2009,* Office for Official Publications of the European Union (Luxembourg: 2009).

Jäger-Waldau Arnulf, *PV Status Report 2010,* Publications Office of the European Union (Luxembourg: 2010).

Jäger-Waldau Arnulf, *PV Status Report 2011,* Publications Office of the European Union (Luxembourg: 2011).

Arnulf Jäger-Waldau, *PV Status Report 2014,* Publications Office of the European Union (Luxembourg: 2014).

Arnulf Jäger-Waldau, *PV Status Report 2016*, Publications Office of the European Union (Luxembourg: 2016).

Arnulf Jäger-Waldau, *PV Status Report 2017*, Publications Office of the European Union (Luxembourg: 2017).

Jäger-Waldau Arnulf, *PV Status Report 2018*, Publications Office of the European Union (Luxembourg: 2018).

Jäger-Waldau Arnulf, *PV Status Report 2019*, Publications Office of the European Union (Luxembourg: 2019).

Jäger-Waldau Arnulf, *PV Status Report 2021,* Publications Office of the European Union (Luxembourg: 2021).

Jäger-Waldau Arnulf, “R&D roadmap for PV”, *Thin Solid Films*, 2004, p. 448-454.

Jäger-Waldau Arnulf, *Status of PV Research, Solar Cell Production and Market Implementation in Japan, USA and the European Union*, Office for Official Publications of the European Communities (Luxembourg: 2002).

Jakobsen Stig-Erik, Fløysand Arnt, Overton John, “Expanding the field of Responsible Research and Innovation (RRI) – from responsible research to responsible innovation”, *European Planning Studies*, 2019, p. 2329-2343.

Jegen Maya, “Energy policy in the European Union: The power and limits of discourse”, *Les cahiers européens de Sciences Po*, n°2, 2014.

Jasanoff Sheila, “The idiom of co-production”, *in* States of Knowledge: The co-production of science and social order, Sheila Jasanoff (ed.), Routledge (London and New York: 2004), p. 1-12.

Jasanoff Sheila, “Ordering knowledge, ordering society”, *in* States of Knowledge: The co-production of science and social order, Sheila Jasanoff (ed.), Routledge (London and New York: 2004), p. 13-45.

Jenkins Kristen, McCauley Darren, Heffron Raphael, Stephan Hannes, Rehner Robert, “Energy justice: A conceptual review”, *Energy Research & Social Sciences*, 2016, p. 174-182.
Jenkins K., McCauley D., Forman A., “Energy justice: a policy approach”, *Energy Policy,* 2017, p. 631-634.

Joint Electron Tube Engineering Council, JEDEC, *JEDEC History – 1980s*, Available online: https://www.jedec.org/about-jedec/jedec-history/1980s, (accessed 10 November 2020).

Jesse Hoffman, Megan Davies, Thomas Bauwens, Philipp Spath, Maarten A. Hajer, Bleta Arifi, Amir Bazaz, Mark Swilling, “Working to align energy transitions and social equity: An integrative framework linking institutional work, imaginaries and energy justice”, *Energy Research & Social Sciences*, 2021, 102317.

Joppke Christian, “Nuclear Power Struggles after Chernobyl: The Case of West Germany”, *West European Politics*, 1990, p. 178-191.

Joppke Christian, “Social Movements during Cycles of Issue Attention: The Decline of the Anti-Nuclear Energy Movements in West Germany and the USA”, *The British Journal of Sociology*, 1991, p. 43-60.

Kaiser R., and Prange-Gstöhl H., “A paradigm shift in European R&D policy? The EU Bidget Review and the economic crisis”, *Science and Public Policy*, 2010, p. 253– 265.

Kalantzakos Sofia, *China and the Geopolitics of Rare Earths*, Oxford University Press (New York: 2018).

Kamp Linda M., Smits Ruud E. H. M., Andriesse Cornelis D., “Notions on learning applied to wind turbine development in the Netherlands and Denmark”, *Energy Policy*, 2004, p. 1625-1637.

Kandiyoti Rafael, “What price access to open seas? The geopolitics of oil and gas transmission from the Trans-Caspian republics”, *Central Asian Survey*, 2008, p. 75-93.

Kanellakis M., Martinopoulos G., Zachariadis T., “European energy policy: A review”, *Energy Policy*, 2013, p. 1020-1030.

Kang M. J., and Hwang J., “Structural dynamics of innovation networks funded by the European Union in the context of systemic innovation of the renewable energy sector”, *Energy Policy*, 2016, p. 471–490.

Kauppi Heikki and Widgren Mika, “Voting rules and budget allocation in the enlarged EU”, *European Journal of Political Economy*, 2007, p. 693-706.

Kleider Jean Paul, Alvarez Jose, Ankudinov Alexander Vitalievitch, Gudovskikh Alexander Sergeevitch, Gushchina Ekaterina Vladimirovna, Labrune Martin, Maslova Olga Alexandrovna, Favre Wilfried, Gueunier-Farret Marie-Estelle, Cabarrocas Pere Roca i, Terukov Eugene Ivanovitch, “Characterization of silicon heterojunctions for solar cells”, *Nanoscale Research Letters*, 2011, p. 1-9.

Klitkou Antje and Godoe Helge, “The Norwegian PV manufacturing industry in a Triple Helix perspective”, *Energy Policy*, 2013, p. 1586-1594.

Klugmann-Radziemska Ewa and Kuczyńska-Łażewska Anna, “The use of recycled semiconductor material in crystalline silicon photovoltaic modules production - A life cycle assessment of environmental impacts”, *Solar Energy Materials and Solar Cells*, 2020, 110259.

Knox Stephen, Hannon Matthew, Stewart Fraser, Ford Rebecca, “The (in)justices of smart local energy systems: A system review, integrated framework, and future research agenda”, *Energy Research & Social Sciences*, 2022, 102333.

Kobayashi Tetsuro, Hayashi Yutaka, Yui Naomasa, Yoshimura Kazuki, “Japanese Photovoltaic R&D Program Under the Sunshine Project”, *in* Ninth EC Photovoltaic Solar Energy Conference, Proceedings of the international Conference held at Freiburg, Federal

Republic of Germany, 25-29 September 1989, W. Palz, G. T. Wrixon and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1989), p. 1206-1208.

Koch W., Woditsch P., "Solar grade silicon feedstock supply for PV industry", *in* Seventeenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Munich, Germany, 22-26 October 2001, B. McNelis, W. Palz, H. A. Ossenbrink, P. Helm (eds.), Vol. I, WIP-Munich & ETA-Florence: 2002, p. 73-76.

Koepke R., "Photovoltaic Research and Development Projects in the Federal Republic of Germany", *in* Second Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Berlin (West), 23-26 April 1979, R. Van Overstraeten and W. Palz (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London, England: 1979), p. 1120-1127.

König Thomas, *The European Research Council*, Polity Press (Cambridge-UK, Malden-USA: 2017).

Koutantou Angeliki and Triandafyllou Vassilis, 16 June 2022, *Reuters*, In a Greek coal mine, stocks build up ahead of peak summer demand, Available online: https://www.reuters.com/business/energy/greek-coal-mine-stocks-build-up-ahead-peak-summer-demand-2022-06-16/, (accessed 30 June 2022).

Kukovec Damjan, "Law and the Periphery", *European Law Journal*, 2015, p. 406-428.

Kurtz S., *Opportunities and Challenges for Development of a Mature Concentrating Photovoltaic Power Industry*, Technical Report NREL/TP-520-43208, November 2009.

Kuus Merje, "Something old, something new: Eastness in European Union enlargement", *Journal of International Relations and Development*, 2007, p. 150-167.

Kuwano Y., Ohnishi M., Nakano S., Fukatsu T., Nishiwaki H., Tsuda S., "Amorphous Silicon Solar Cells Produced by a Consecutive, Separated Reaction Chamber Method", *in* Fourth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at

Stresa, Italy, 10-14 May 1982, W. H. Bloss and G. Grassi (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London, England: 1982), p. 704-708.

Laffan Brigid, “Core-Periphery dynamics in the Euro area: From conflict to cleavage?”, *in* Core-Periphery Relations in the European Union: Power and Conflict in a Dualist Political Economy, Jose M. Magone, Bridgit Laffan and Christian Schweiger (eds.), Routledge/UACES contemporary European studies (London and New York: 2016), p. 19-34.

Laird Frank and Stefes Christoph, “The diverging paths of German and United States policies for renewable energy: Sources of difference”, *Energy Policy*, 2009, p. 2619-2629.

LaMonica Martin, 21 December 2011, CNET, *Another one bites the dust: BP Solar shuts down*, Available online: https://www.cnet.com/news/another-one-bites-the-dust-bp-solar-shuts-down/, (accessed 7 April 2021).

Langsdorf Susanne, *EU Energy Policy: From the ECSC to the Energy Roadmap 2050*, Green European Foundation, December 2011.

Laredo Philippe, “The networks promoted by the framework programme and the questions they raise about its formulation and implementation”, *Research Policy*, 1998, p. 589-598.

Latour Bruno, *Science in Action*, Harvard University Press (Cambridge Massachusetts: 1987).
Levidow Les, Birch Kean, Papaioannou Theo, “Divergent Paradigms of European Agro-Food Innovation: The Knowledge-Based Bio-Economy (KBBE) as an R&D agenda”, *Science, Technology, & Human Values*, 2013, p. 94-125.

Leydesdorff Loet and Etzkowitz Henry, “The Triple Helix of Innovation: Introduction”, *Science and Public Policy*, 1998, p. 358-364.

Leydesdorff Loet and Etzkowitz Henry, “The Triple Helix as a model for innovation studies”, *Science and Public Policy*, 1998, p. 195-203.

Leydesdorff Loet, “The Knowledge-Based Economy and the Triple Helix Model”, *Annual Review of Information Science and Technology*, 2010, p. 367-417.

Lindmayer J., “Industrialisation of Photovoltaics”, *in* Third EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes France, 27-31 October 1980, W. Palz (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London, England: 1981), p. 178-185.

London Leslie and Kisting Sophia, “The Extractive Industries: Can We Find New Solutions to Seemingly Interactable Problems?”, *A Journal of Environmental and Occupational Health Policy*, 2016, p. 421-430.

Looney Robert, “Recent Developments on the Rare Earth Front, Evidence of a new technocratic mercantilism emerging in China?”, *World Economics*, Vol. 12, No.1, January-March 2001, p. 47-78.

Lorenzo E., “Photovoltaic Rural Electrification”, *Progress in Photovoltaics: Research and Applications*, 1997, p. 3-27.

Luiten E. E. M. and Blok K., “Energy R&D in the Netherlands”, Prepared for the US Department of Energy under contract DE-AC06-76RLO 1830, April 1999, Battelle Memorial Institute.

Luque Antonio, “Photovoltaics in 1986: Routes to low cost”, *in* Seventh EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Sevilla, Spain, 27-31 October 1986, A. Goetzberger, W. Palz and G. Willeke (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1987), p. 9-18.

Luque A., “Photovoltaics and its Research and Development Structure in Spain: the situation in 1988”, *Solar Cells*, 1989, p. 107-123.

Luo Jin and He Hongwei, “Trade Dispute on rare Earths Export from China to the United States, *Advances in Economics, Business, and Management Research*, 2018, p. 391-394.

Luukkonen T., “Old and new strategic roles for the European Union Framework Programme”, *Science and Public Policy*, 2001, p. 205–218.

Luukkonen T., “The European Research Council and the European research funding landscape”, *Science and Public Policy*, 2014, p. 29–43.

Magone Jose M., “Centre-Periphery conflict in the European Union? Europe 2020, the Southern European Model and the euro-crisis”, *in* European Union at the crossroads: The European perspectives after the global crisis, Attila Agh (ed.), Budapest College of Communication (Budapest: 2011), p. 71-122.

Makios V., “Feasibility study for small solar cell operated units”, *in* Photovoltaic Power Conversion, Proceedings of the EC Contractors’ Meeting held in Brussels, 17-17 November 1982, Roger van Overstraeten and Wolfgang Palz (eds.), Vol. III, D. Reidel Publishing Company (Dordrecht Holland, Bolton USA, London England: 1983), p. 236-244.

Manberger Andre and Johansson Bengt, “The geopolitics of metals and metalloids used for the renewable energy transition”, *Energy Strategy Reviews*, 2019, p. 1-10.

Manning D. A. C., Raw materials for the glass industry, *in* Introduction to Industrial Minerals, Springer (Dordrecht: 1995), p. 120-140.

Mancisidor I. d., Uraga d. P., Mancisidor I. d., Lopez P. d., “European Union’s renewable energy sources and energy efficiency policy review: The Spanish perspective”. *Renewable and Sustainable Energy Reviews*, 2009, p, 100-114.

Marin Alexandra and Wellman Barry, “Social Network Analysis: An Introduction”, *in* The SAGE Handbook of Social Network Analysis, John Scott and Peter J. Carrington (eds.), SAGE Publications (Los Angeles, London, New Delhi, Singapore, Washington DC: 2011), p. 11-25.

Martin Ronald L., “The contemporary debate over the North-South divide: images and realities of regional inequality in late-twentieth-century Britain”, *in* Geographies of England. The North-South Divide, Material and Imagined, Alan R. H. Baker and Mark Billinge (eds.), Cambridge Univesity Press (Cambridge, UK: 2004), p. 15-43.

Maycock Paul D., “The Current PV Scene Worldwide”, *in* Sixth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in London, UK, 15-19 April

1985, W. Palz and F.C. Treble (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1985), p. 21-27.

Mayer James W., "Ion implantation in Semiconductors", *in* 1973 International Electron Devices Meeting, 3-5 December 1973, Washington, DC, IEEE Publications, p. 3-5.

Mazzucato Mariana and Semieniuk Gregor, "Public financing of innovation: new questions", *Oxford Review of Economic Policy*, 2017, p. 24-48.

Mazzucato Mariana and Semieniuk Gregor, "Financing renewable energy: Who is financing what and why it matters", *Technological Forecasting & Social Change*, 2018, p. 8-22.

Mazzucato Marianna, *Missions. Mission-Oriented Research & Innovation in the European Union: A problem-solving approach to fuel innovation-led growth*, Publications Office for the European Union (Luxembourg: 2018).

Mazzucato Marianna, *Governing Missions. Governing Missions in the European Union*, Publications Office for the European Union (Luxembourg: 2019).

McFarland Andrew S., "Energy Lobbies", *Annual Review of Energy*, 1984, p. 501-527.

McCauley D., Heffron R., Stephan H., Jenkins K., "Advancing energy justice: the triumvirate of tenets", *International Energy Law Review*, 2013, p. 107-110.

McGowan Francis, "Can the European Union's Market Liberalism Ensure Energy Security in a Time of 'Economic Nationalism'?", *Journal of Contemporary European Research*, 2008, p. 90-106.

McGowan Francis, "Putting Energy Insecurity into Historical Context: European Responses to the Energy Crises of the 1970s and 2000s", *Geopolitics*, 2011, p. 486-511.

Mertens R. and Palmers G., "Roger van Overstraeten – Professor, Manager and Entrepreneur: his work in photovoltaics", *in* Sixteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Glasgow, UK, 1-5 May 2000, H. Scheer,

B. McNelis, W. Palz, H.A. Ossenbrink and P. Helm (eds.), Vol. I, James and James (London, UK: 2000), p. lvi-lvii.

Ministerio de Industria, Turismo y Comercio - Instituto para la Diverficación y Ahorro de la Energía, Plan de Energías Renovables en España 2005-2010, Agosto de 2005.

Mints Paula, "Overview of Photovoltaic Production, Markets, and Perspectives", *in* Semiconductors and Semimetals, G. Willeke and E.R. Weber (eds.), Elsevier (Oxford, UK: 2012), p. 49-84.

Mirasgedis S., Sarafidis Y., Georgopoulou E., Lalas D. P., "The role of renewable energy sources within the framework of the Kyoto Protocol: the case of Greece", *Renewable and Sustainable Energy Reviews*, 2002, p. 249–272.

Mittra B., Lucas N., Fells l., "European energy: Balancing markets and policy". *Energy Policy*, 1995, p. 689-701.

Mitzner Veera, "European research policy", *in* The European Commission 1986-2000: History and Memories of an Institution, Éric Bussière, Vincent Dujardin, Michel Dumoulin, Piers Ludlow, Jan Willem Brouwer and Pierre Tilly (eds.), Publications Office of the European Union (Luxembourg: 2014), p. 321-334.

Mitzner Veera, *European Union Research Policy: Contested Origins*, Palgrave MacMillan (2020).

Moore Robert M., "Czochralski-Silicon Solar Cell Modules: Present Cost and Future Prospects", *in* Third E.C. Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes, France, 27-31 October 1980, Wolfgang Palz (eds.), D. Reidel Publishing Company (Holland, Boston, London: 1980), p. 215-219.

Morris P. R., *A History of the World Semi-conductor Industry*, The Institution of Engineering and Technology (London, United Kingdom: 2008), IET History of Technology Series 12, Series Editor B. Bowens.

Moss R. L., Tzimas E., Kara H., Willis P., Kooroshy J., *Critical Metals in Strategic Energy Technologies: Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies*, Publications Office of the European Union (Luxembourg: 2011).

Mudd G. M., Weng Z., Memary R., Northey S. A., Guirco D., Mohr S., Mason L., *Future Greenhouse Gas Emissions from Copper Mining: Assessing Clean Energy Scenarios*, Prepared for CSIRO Minerals Down Under National Research Flagship by Monash University Institute for Sustainable Futures, University of Technology, October 2012.

Muniz A. S. G. and Vicente Maria Rosalia, "Exploring research networks in Information and Communication Technologies for energy efficiency: An empirical analysis of the 7th Framework Programme", *Journal of Cleaner Production*, 2018, p. 1133-1143.

Munoz E., Vidal P. G., Nofuentes G., Hontoria L., Perez-Higueras P., Terrados J., Almonacid G., Aguilera J., "CPV standardization: An overview", *Renewable and Sustainable Energy Reviews*, 2010, p. 518-523.

Muradin-Szweykowska M. and Horst E. W. ter, "The Netherlands Photovoltaic National Programme", *in* Tenth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Lisbon, Portugal, 8-12 April 1991, A. Luque, G. Sala, W. Palz, G. Dos Santos, and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1991), p.1390-1393.

Nakopoulou Efi and Arapostathis Stathis, "Reconfiguring Technologies by Funding Transitions: priorities, policies, and the renewable energy sources in the European Community funding schemes", *Journal of Energy History/Revue d'Histoire de l'Énergie* [Online], n°4, published 27 July 2020.

Nentwich Alfred, Schneeberger Michael, Szeless Andreas, Wilk Heinrich, "Photovoltaic activities of Austrian Electric Utilities – Projects and Experiences", *in* Ninth EC Photovoltaic Solar Energy Conference, Proceedings of the international Conference held at Freiburg, Federal Republic of Germany, 25-29 September 1989, W. Palz, G. T. Wrixon and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1989), p. 1119-1121.

Nentwich Alfred, Schneeberger Michael, Szeless Andreas, Wilk Heinrich, "30kW Photovoltaic Plant in the Alps of Austria", *in* Tenth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Lisbon, Portugal, 8-12 April 1991, A. Luque, G. Sala, W. Palz, G. Dos Santos, and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1991), p. 766-770.

New York State Department of Health, health.ny.gov, *Silicosis and Crystalline Silica Exposure and Mining: Information for Workers*, Available online: https://www.health.ny.gov/environmental/investigations/silicosis/mineworker.htm, (accessed 20 May 2022).

Newham Mark, *Photovoltaics: The Sunrise Industry*, Financial Times Business Information (London: 1986).

Nexwafe, nexwafe, *About us*, Available online: https://www.nexwafe.com/, (accessed 13 October 2019).

Thomas Nordmann, "Subsidies Versus Rate based Incentives; For Technology – Economical – and Market-Development of PV. The European Experience", *in* Proceedings of Third World Conference on Photovoltaic Solar Energy Conversion, Joint Conference of Thirteenth PV Science and Engineering Conference, Thirtieth IEEE PV Specialists Conference, Eighteenth European PV Solar Energy Conference, Osaka, Japan, 11-18 May 2003, Kosuke Kurokawa, Lawrence L. Kazmerski, Bernard McNelis, Masafumi Yamaguchi, Christopher Wronski, Wim C. Sinke (eds.), IEEE: 2003, [CD ROM file number: 8OD1102], (pdf) p. 1-4.

Nugent Neil, "European Union Law and the Courts", *in The Government and Politics of the European Union*, Neil Gugent (eds.), (6th Edition), Palgrave MacMillian (New York: 2006), p. 281-310.

Nugent Neil, "Policies", *in The Government and Policies of the European Union*, Neil Nugent, William E. Paterson (eds.), Palgrave Macmillan (Basingstoke: 2006), p. 351-391.

Office of the United States Trade representative, USTR, *WTO Case Challenging China's Export Restraints on Raw Material Inputs*, Available online: https://ustr.gov/about-us/policy-offices/press-office/fact-sheets/2009/june/wto-case-challenging-chinas-export-restraints-raw-materi, (accessed 15 May 2020).

Organization for Economic Co-operation and Development, 9 September 2005, *OECD*, Knowledge-Based Economy, Available online: https://stats.oecd.org/glossary/detail.asp?ID=6864, accessed 11 September 2022.

Ormala E., and Vonortas N. S., “Evaluating the European Union’s Research Framework Programmes: 1999-2003”, *Science and Public Policy*, 2005, p. 399–406.

Orton John, “Silicon, silicon and yet more silicon”, *in The Story of Semiconductors*, J. Orton (eds.), Oxford University Press (New York: 2004), p. 93-148.

Ossenbrink H., Mullejans H., Kenny R., Dunlop E., “Standards in the Photovoltaic Technology”, *in* Photovoltaic Technology, W. G. J. H. M. van Sark (ed.), Vol. I, *in* Comprehensive Renewable Energy (ed. A. Sayigh), Elsevier (Oxford: 2012), p. 787-803.

Overland Indra, “The geopolitics of renewable energy: Debunking four emerging myths”, *Energy Research and Social Science*, 2019, p. 36-40.

Paltsev Sergey, “The complicated geopolitics of renewable energy”, *Bulleting of the Atomic Scientists*, 2016, p. 1-6.

Palz W., “Overview of the European Community’s Activities in Photovoltaics”, *in* Fourth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Stresa, Italy, 10-14 May 1982, W. H. Bloss and G. Grassi (eds.), D. Reidel Publishing Company (Dordrecht, Holland/Boston, USA/London, England: 1982), p. 3-8.

Palz W., “European Achievements in Photovoltaics”, *in* Fifth EC Photovoltaic Energy Conference, Proceedings of the International Conference held at Kavouri, Athens, Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 21-24.

Palz W., “PV Highlights from a European Perspective”, *in* Second World Conference on Photovoltaic Solar Energy Conversion, Fifteenth European PV Solar Energy Conference, Twenty Seventh US IEEE Photovoltaics Specialists Conference, Tenth Asia/Pacific PV Science and Engineering Conference, Proceedings of the International Conference held at Vienna, Austria, 6-10 July 1998, J. Schmid, H. A. Ossenbrink, P. Helm, H. Ehmann and E. D. Dunlop (eds.), Vol. I, WIP Renewable Energies: 1998, [CD-ROM], p. xciii-xcv.

Palz Wolfgang, “Keynote Speech: Photovoltaics in Europe and the World”, *in* PV in Europe - From PV Technology to Energy Solutions Proceedings of the International Conference held in Rome, Italy, 7-11 October 2002, J. L. Bal, G. Silvestrini, A. Grassi, W. Palz, R. Vigotti, M. Gamberale and P. Helm (eds.), WIP-Munich & ETA-Florence, 2002, p. xxxix-xl.

Palz Wolfgang, *Power for the World: The Emergence of Electricity from the Sun*, Pan Stanford Publishing Pte. Ltd., 2011.

Palz Wolfgang, The Triumph of the Sun: The Energy of the New Century, Wolfgang Palz (eds.), Pan Stanford Publishing (Singapore: 2018).

Palz Wolfgang and Overstraeten Roger Van, “Photovoltaic Power Generation – R&D Programme in Europe”, *in* Ninth EC Photovoltaic Solar Energy Conference, Proceedings of the international Conference held at Freiburg, Federal Republic of Germany, 25-29 September 1989, W. Palz, G. T. Wrixon and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1989), p. 1202-1205.

Palz W., Overstraeten R. van, Palmers G., “PV-programmes of the European Commission”, *in* Twelfth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Amsterdam, The Netherlands, 11-15 April 1994, R. Hill, W. Palz, P. Helm (eds.), Vol. II, H. S. Stephens & Associates (UK: 1994), p. 1441-1444.

Pamblad Linus, Jacobsson Staffan, Sanden Bjorn, and Hall Maria, “Dynamics of the Swedish PV Innovation System – The impact of a recent market formation programme”, *in* Twenty first European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Dresden Germany, 4-8 September 2006, J. Poortmans, H. Ossenbrink, W. Palz and P. Helm (eds.), WIP Renewable Energies (Germany: 2006), p. 3136-3151.

Papoutsis Christos, [Introductory conference speech], *in* Second World Conference on Photovoltaic Solar Energy Conversion, Fifteenth European PV Solar Energy Conference, Twenty Seventh US IEEE Photovoltaics Specialists Conference, Tenth Asia/Pacific PV Science and Engineering Conference, Proceedings of the International Conference held at Vienna, Austria, 6-10 July 1998, J. Schmid, H. A. Ossenbrink, P. Helm, H. Ehmann and E. D. Dunlop (eds.), Vol. II, WIP Renewable Energies: 1998, [CD-ROM], p. xl-xliii.

Pascariu Gabriel Carmen and Tiganasu Ramona, “Integration, Growth and Core-Periphery Pattern in EU’s Economy: Theoretical Framework and Empirical Evidences”, *in* Core-Periphery Patterns across the European Union: Case Studies and Lessons from Eastern and Southern Europe, Gabriela Carmen Pascariu and Maria Adelaide Pedrosa da Silva Duarte (eds.), Emerald Publishing Limited (Bingley, UK: 2017), p. 23-85.

Parks Christine G., Conrad Karsten, Cooper Glinda S., “Occupational Exposure to Crystalline Silica and Autoimmune Disease”, *Environmental Health Perspectives*, 1999, p. 739-802.

Pavitt K., “The inevitable limits of EU R&D funding”, *Research Policy*, 1998, p. 559– 568.

Pérez-Higueras P.J., Muñoz E., Almonacid G., Vidal P.G., Banda P., Luque-Heredia I., Valera P., Cabrerizo M., “A Spanish CPV Regulatory Framework: Proposal of a Feed-in Tarriff”, 25th European Photovoltaic Solar Energy Conference and Exhibition/5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Valencia, Spain, De Santi G. F., Ossenbrink H., Helm P. (eds.), WIP Renewable Energies: 2010, p. 5421-5424.

Pérez-Higueras P.J., Muñoz E., Almonacid G., Vidal P.G., “High Concentrator PhotoVoltaics efficiencies: Present status and forecast”, *Renewable and Sustainable Energy Reviews*, 2011, p. 1810-1815.

Perlin John, *From Space to Earth: The Story of Solar Electricity*, AATEC Publications (Michigan: 1999).

Peter Kristian, Kopecek Radovan, Petres Roman, Fath Peter, Wefringhaus Eckard, “Long-term perspective for Photovoltaic R&D activities in Konstanz”, *in* Twenty second European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in

Milan, Italy, 3-7 September 2007, G. Willeke, H. Ossenbrink and P. Helm (eds.), WIP Renewable Energies: 2007, p. 3519-3520.

Pfeifer Sylvia and Clark Pilita, 21 December 2011, Financial Times, *BP to exit solar business after 40 years*, Available online https://www.ft.com/content/80cd4a08-2b42-11e1-9fd0-00144feabdc0, (accessed 7 April 2021).

Pfotenhauer Sebastian, Laurent Brice, Papageorgiou Kyriaki, Stilgoe Jack, "The politics of scaling", *Social Studies of Science*, 2022, p. 3-34.

Philipps Simon P., Bett Andreas W., Horowitz Kelsey, Kurtz Sarah, "Current Status of Concentrator Photovoltaic (CPV) Technology", Fraunhofer ISE and NREL, Version 1.2, February 2016.

Photovoltaic Technology Platform, *A Strategic Research Agenda for Photovoltaic Solar Energy Technology*, Office for Official Publications of the European Communities (Luxembourg: 2007).

Photovoltaic Technology Platform, *A Strategic Research Agenda for Photovoltaic Solar Energy Technology*, 2nd Edition, Office for Official Publications of the European Communities (Luxembourg: 2011).

Pizzini S., Califano F., Soncini G., "Italian Activities in Photovoltaics", *in* Second EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Berlin (West), 23-26 April 1979, R. Van Overstraeten and W. Palz (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1979), p. 1128-1134.

Pizzini Sergio, sergiopizzini, *Cirriculum Vitae*, Available online: http://www.sergiopizzini.eu/curriculum.html, (accessed 10 December 2020).

Pollard Kenneth Michael, "Silica, Silicosis, and Autoimmunity", *Frontiers in Immunology*, 2016, p. 1-7.

Poortmans J., Reber S., Gall S., Zahedi C., Alonso J., “European cluster on high- and intermediate temperature thin-film crystalline Si solar cells R&D: Overview of running projects and underlying roadmap”, *in* Nineteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Paris, France, 7-11 June 2004, W. Hoffmann, J. L. Bal, H. Ossenbrink, W. Palz and P. Helm (eds.), WIP Renewable Energies: 2004, p. 397-402.

Price Victoria Curzon, *Industrial Policy in the European Community*, The Macmillan Press (Houndmills, Basigtoke, Hampshire, London: 1981).

Prieto B., Silva B., Aira N., “Methodological aspects of the induction of biofuels for remediation of the visual impact generated by quartz mining”, *Science of the Total Environment*, 2006, p. 254-261.

Radvilaite Vilma, *EU budget 2014–2020 deal: opportunities for wind energy*, European Wind Energy Association, 2013.

Ragwitz M., and Miola A., “Evidence from RD&D spending for renewable energy sources in the EU”, *Renewable Energy*, 2005, p. 1635-1647.

Raman Sujatha, “Fossilizing Renewable Energies”, *Science as Culture*, 2013, p. 172-180.

Ranganathan V., “Rural electrification revisited”, *Energy Policy*, 1993, p. 142-151.

Reber Stefan, Duerinckx Filip, Alvarez Mario, Garrard Barry, Schulze Friedrich-Wilhelm, “EU project Sweet on Epitaxial Wafer Equivalents: Results and Future Topic of Interest”, *in* Twenty first European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Dresden, Germany, 4-8 September 2006, J. Poortmans, H. Ossenbrink, W. Palz and P. Helm (eds.), WIP Renewable Energies: 2006, p. 570-576.

Regulation (EU) No 1291/2013 of the European Parliament and the Council of 11 December 2013 establishing Horizon 2020 – the Framework Programme for Research and Innovation (2014-2020) and repealing Decision No 1982/2006/EC, 20.12.2013, Official Journal of the European Union, p. 104-173.

Renner Michael, “The New Geopolitics of Oil”, *Development*, 2006, p. 59-63.

Reuters Staff, 11 January 2009, *Reuters*, TIMELINE: Gas crises between Russia and Ukraine, Available online: https://www.reuters.com/article/us-russia-ukraine-gas-timeline-sb-idUSTRE50A1A720090111, (accessed 10 June 2022).

Reuters, 27 June 2022, *Reuters*, G7 leaders debate fossil fuel investments amid energy crisis, Available online: https://www.reuters.com/world/g7-leaders-debate-fossil-fuel-investments-amid-energy-crisis-sources-2022-06-26/, (accessed 30 June 2022).

Ricerca Sistema Energetico, RSE, *70 Anni di Tradizione nella Ricerca*, Available online: http://www.rse-web.it/storia.page, (accessed 8 May 2021).

Rodot M., “The French Program on Photovoltaic Conversion”, *in* Second EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Berlin (West), 23-26 April 1979, R. Van Overstraeten and W. Palz (ed.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1979), p. 1135-1140.

Rodríguez H., Fisher E., Schuurbiers D., “Integrating science and society in European Framework Programmes: Trends in project-level solicitations”, *Research Policy*, 2013, p. 1126– 1137.

Roediger-Schluga Thomas and Barber Michael J., “The structure of R&D collaboration networks in the European Framework Programmes”, *UNU-MERIT Working Papers* (No. 036), Maastricht (UNU-MERIT), 2006, p. 1-41.

Rüdiger Mogens, “From import dependence to self-sufficiency in Denmark, 1945−2000”, *Energy Policy*, 2019, p. 82-89.

Rusche Tim, “The European climate change program: An evaluation of stakeholder involvement and policy achievements”, *Energy Policy*, 2010, p. 6349-6359.

Sala G. and Luque A., “Past Experiences and New Challenges of PV Concentrators”, *in* Concentrator Photovoltaics, Antonio L. Luque and Viacheslav M. Andreev (eds.), Springer (Verlag, Berlin, Heidelberg: 2007), p. 1-23.

Salas V., Olias E., “Overview of the photovoltaic technology status and perspective in Spain”, *Renewable and Sustainable Energy Reviews*, 2009, p. 1049-1057.

Salomons W., “Environmental impact of metals derived from mining activities: Processes, predictions, prevention”, *Journal of Geochemical Exploration*, 1995, p. 5-23.

Sanchez Fernando, “Spanish National Photovoltaic Program”, *in* Ninth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Freiburg, Fed. Rep. of Germany, 25-29 September 1989, W. Palz, G. T. Wrixon, P. Helm (eds.), Kluwer Academic Publishers, (Dordrecht, Boston, London: 1989), pp. 1195-1196.

Sarno A., Apicella F., Cancro C., Fucci R., Pascarella F., Pellegrino M., Privato C., Roca F., The PhoCUS Standard Unit: Design, Realization and Preliminary Performance Analysis, *in* 20th European Photovoltaic Solar Energy Conference, 6-10 June 2005, Barcelona, Spain, Palz W., Ossenbrink H., Helm P. (eds.), WIP-Renewable Energies: 2005, p. 2032-2034.

Sassault Systemes, 2002, 3ds, *HCT Shaping Systems S.A., Innover tout en ameliorant la productivite*, Available online: https://www.3ds.com/fileadmin/customer-stories/import/pdf/HCT-SHAPING-SYSTEM-Flyer.pdf, (accessed 2 December 2020).

Scheer Hermann, “Welcome Address”, *in* Thirteenth European Solar Energy Conference, Proceedings of the International Conference held at Nice, France, 23-27 October 1995, W. Freiesleben, W. Palz, H. A. Ossenbrink and P. Helm (eds.), Vol. I, H. S. Stephens & Associates (UK: 1995), p. xxxvii-xxxviii.

Scheer Hermann, “Keynote Speech, *in* Sixteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Glasgow, UK, 1-5 May 2000, H. Scheer, B. McNelis, W. Palz, H.A. Ossenbrink and P. Helm (eds.), Vol. I, James and James (London, UK: 2000), p. xxv-xxviii.

Scheer Hermann, “Foreword” *in* Feed-in Tariffs: Accelerating the Deployment of Renewable Energy, Miguel Mendonca, Earthscan (UK and USA: 2007), p. x-xii.

Scheer Hermann, “Initiating a Solar Revolution in Germany”, *in* Solar Power for the World, Wolfgang Palz (eds.), (Pan Stanford: US, 2014), p. 287-300.

Scherngell Thomas and Barber Michael J., “Spatial interaction modelling of cross-region R&D collaborations: empirical evidence from the 5th EU framework programme”, *Papers in Regional Science*, 2009, p. 531-546.

Schmid J., “Photovoltaic System for a Solar House”, *in* Photovoltaic Power Conversion, Proceedings of the EC Contractors’ Meeting held in Brussels, 17-17 November 1982, Roger van Overstraeten and Wolfgang Palz (eds.), Vol. III, D. Reidel Publishing Company (Dordrecht Holland, Bolton USA, London England: 1983), p. 245-250.

Schmid J., “Photovoltaic System Design”, *in* Fifth EC Photovoltaic Energy Conference, Proceedings of the International Conference held at Kavouri, Athens, Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 410-416.

Schnebele Emily, 11 January 2018, Earth magazine, *Mineral Resource of the Month: Silicon*, Available online: https://www.earthmagazine.org/article/mineral-resource-month-silicon/, (accessed 1 March 2021).

Scholten Daniel and Bosman Rick, “The geopolitics of renewables: exploring the political implications of renewable energy systems”, *Technological Forecasting & Social Change*, 2016, p. 273-283.

Scholten Daniel, Bazilian Morgan, Overland Indra, Westphal Kirsten, “The geopolitics of renewables: New board, new game”, *Energy Policy*, 2020, 111059.

Schomberg Rene von, "A vision of responsible innovation", *in* Responsible Innovation, Richard Owen, John Bessant, Maggy Heintz (eds.), John Wiley (London: 2013), p. 51-74.

Schott T. and Neerf H. J., “The German Photovoltaic R&D Programme: Status and Prospects”, *in* Fourteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Barcelona, Spain, 30 June – 4 July 1997, H. A. Ossenbrink, P. Helm and H. Ehmann (eds.), Vol. I, H. S. Stephens & Associates (Oxfordshire, UK: 1997), p. 437-440.

Schrecker Ted, Birn Anne-Emanuelle, Aguilera Mariajose, “How extractive industries affect health: Political economy underpinnings and pathways”, *Health & Place*, 2018, p. 135-147.

Schumacher Elisabeth, 23 June 2022, *Deutsche Welle*, Available online: https://www.dw.com/en/will-germany-return-to-nuclear-power/a-62223935, (accessed 30 June 2022).

Schuster Gunter, “Opening Address from the Commission of the European Communities”, in Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Luxembourg, September 27-30, 1977, D. Reidel Publishing Company, (Dordrecht Holland, Boston USA: 1978), p. 26-28.

Schuster G., “The Future of Photovoltaics in Europe”, *in* Third EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes France, 27-31 October 1980, W. Palz (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1981), p. 4-9.

Schüring Michael, “Advertising the nuclear venture: the rhetorical and visual public relation strategies of the German nuclear industry in the 1970s and 1980s”, *History and Technology*, 2013, p. 369-398.

Science Applications Inc, *Characterization and Assessment of Potential European and Japanese Competition in Photovoltaics*, Solar Energy Research Institute (Colorado: 1979).

Seitz Frederik and Einspruch Normal G., “Bardeen and Shockley: New Careers”, *in* Electronic Genie: The tangled history of Silicon, Frederick Seitz and Norman G. Einspruch (eds.), University Illinois Press: 1998, p. 186-196.

Sens P. F., “The Dutch National Solar Energy and the International Energy Agency’s Solar Heating and Cooling Programme”, *in* First EC Conference on Solar Heating, Proceedings of the International Conference held at Amsterdam, April 30-May 4, 1984, C. Den Ouden (ed.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 7-10.

Sepos Angelos, “The centre-periphery divide in the Eurocrisis”, *in* Core-Periphery Relations in the European Union: Power and Conflict in a Dualist Political Economy, Jose M. Magone, Bridgit Laffan and Christian Schweiger (eds.), Routledge/UACES contemporary European studies (London and New York: 2016), p. 35-56.

SET-Plan TWP PV Implementation Plan – Final Draft (Approved by TWG members), 18 October 2017.

Shell, *The Evolution of the World’s Energy Systems*, Shell International (London: 1996).

Shockley W. and Queisser H. J., “Detailed Balance Limit of Efficiency of *p-n* Junction Solar Cells”, *Journal of Applied Physics*, 1961, p. 510-519.

Silvestrini G., Gamberale M., Frankl P., “Italian PV Roof Programme: First Results”, *in* 17th European Photovoltaic Solar Energy Conference, Munich, Germany, 22-26 October 2001, McNelis B., Palz W., Ossenbrink H. A., Help P. (eds.), Vol. III, WIP Renewable Energies and ETA: 2002, p. 2371-2374.

Single European Act, Official Journal of the European Communities, 29.06.1986.

SolarPower Europe, *Global Market Outlook for Solar Power 2021-2015*, 2021.

SolarPower Europe, 14 July 2022, *pv-magazine*, Key European Parliament Committee says Yes to 45% RES!, Available online: https://www.pv-magazine.com/press-releases/key-european-parliament-committee-says-yes-to-45-res/, (accessed 15 July 2022).

Solems, solems, *Company - About us*, Available online: https://www.solems.com/en/, (accessed 3 December 2020).

Solomon Ionel, “Opening Address”, *in* Eighth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in Florence, Italy, 9-13 May 1988, I. Solomon, B. Equer and P. Helm (eds.), Vol. I, Kluwer Academic Publishers (Dordrecht, Boston, London: 1988), p. 11-13.

Song Ligang and Zhou Yixiao, “The COVID-19 Pandemic and Its Impact on the Global Economy: What Does It Take to Turn Crisis into Opportunity?”, *China and World Economy*, 2020, p. 1-25.

Sovacool Benjamin K. and Dworkin Michael H., “Energy justice: Conceptual insights and practical applications”, *Applied Energy*, 2015, p. 435-444.

Sovacool B., Heffron R., McCauley D., Goldthau A., “Energy decisions reframed as justice and ethical concerns”, *Nature Energy*, 2016, (article number 6024), p. 1-6.

Sovacool B., Turnheim B., Hook A., Brock A., Martiskainen M., “Dispossessed by decarbonization: Reducing vulnerability, injustice, and inequality in the lived experience of low-carbon pathways”, *World Development*, 2021, 105116.

Sovacool Benjamin, “The history and politics of energy transitions: Comparing contested views and finding common ground”, WIDER Working Paper No. 2016/81, 2016, ISBN 978-92-9256-124-6, The United Nations University World Institute for Development Economics Research (UNU-WIDER), Helsinki, https://doi.org/10.35188/UNU-WIDER/2016/124-6.

Sovacool B., Heffron R., McCauley D., Goldthau A., “Energy decisions reframed as justice and ethical concerns”, *Nature Energy*, 2016, (article number 6024), p. 1-6.

Sovacool B., Turnheim B., Hook A., Brock A., Martiskainen M., “Dispossessed by decarbonization: Reducing vulnerability, injustice, and inequality in the lived experience of low-carbon pathways”, *World Development*, 2021, 105116.

Stahl Bernd Carsten, Akintoye Simisola, Bitsch Lise, Bringedal Berit, Eke Damian, Farisco Michele, Grasenick Karin, Guerrero Manuel, Knight William, Leach Tonii, Nyholm Sven, Ogoh George, Rosemann Achim, Salles Arleen, Trattnig Julia, Ulnicane Inga, “From

Responsible Research and Innovation to responsibility by design", *Journal of Responsible Innovation*, 2021, p. 175-198.

Starr M. R., "The Potential for Photovoltaics in Europe", *in* Fourth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Stresa, Italy, 10-14 May 1982, W. H. Bloss and G. Grassi (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1982), p. 40-50.

Starr Michael R. and Palz Wolfgang, *Photovoltaic Power for Europe: An Assessment Study*, Photovoltaic Power Generation, Vol. II, D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1983).

Stegen Smith Karen, "Heavy rare earths, permanent magnets, and renewable energies: An imminent crisis", *Energy Policy*, 2015, p. 1-8.

Stern Jonathan, "Natural Gas Security Problems in Europe: the Russian-Ukrainian Crisis of 2006", *Asia-Pacific Review*, 2006, p. 32-59.

Stern Jonathan, The Russian-Ukrainian gas crisis of January 2006, *Oxford Institute for Energy Studies*, 16 January 2006.

Stephen Knox, Matthew Hannon, Fraser Stewart, Rebecca Ford, "The (in)justices of smart local energy systems: A system review, integrated framework, and future research agenda", *Energy Research & Social Sciences*, 2022, 102333.

Stiftelsen for industriell og teknisk forskning, SINTEF, *About SINTEF*, Available online: https://www.sintef.no/en/sintef-group/this-is-sintef/, (accessed 5 February 2021).

Stsiapanau Andrei, Lithuania-Short Country Report, HoNESt Project, 2018.

Swanson Richard M., "Photovoltaic Concentrators", *in* Handbook of Photovoltaic Science and Engineering, Antonio Luque and Steven Hegebus (eds.), John Wiley & Sons (England: 2003), p. 449-503.

Tachmintzis Joanna of Mr Papoutsis' Cabinet on behalf of the European Commissioner for Energy, Christos Papoutsis, "Welcome Address", Thirteenth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Nice, France, 23-27 October 1995, W. Freiesleben, W. Palz, H. A. Overstraeten, P. Helm (eds.), Vol. I, H. S. Stephens & Associates (UK: 1995), p. xxxvi-xxxvii.

Tchalakov Ivan, Hristov Ivaylo, Bulgaria-SCR, HoNESt, 2019.

Technopolis and Fraunhofer ISI, *Interim Evaluation & Assessment of Future Options for Science in Society Actions Assessment of Future Options*, Technopolis Group (Brighton, UK: 2012).

Thaler Philipp, "The European Commission and the European Council: Coordinated Agenda setting in European energy policy", *Journal of European Integration*, 2016, p. 571-585.

The European Association for Industrial Silica Producers, eurosil, *Silica and Health*, Available online: https://eurosil.eu/silica-and-health/, (accessed 23 May 2022).

The European Association for Renewable Energy, *Our mission & history*, Eurosolar. Available online: https://www.eurosolar.de/en/index.php, (accessed 15 January 2020).

The European Commission 1958-72: History and Memories of an Institution, Michel Dumoulin (eds.), Publications Office of the European Union (Luxembourg: 2014).

The European Commission 1973-86: History and Memories of an Institution, Éric Bussière, Vincent Dujardin, Michel Dumoulin, Piers Ludlow, Jan Willem Brouwer and Pierre Tilly (eds.), Publications Office of the European Union (Luxembourg: 2014).

The European Commission 1986-2000: History and Memories of an Institution, Vincent Dujardin, Éric Bussière, Piers Ludlow, Federico Romero, Dieter Schlenker and Antonio Varsori (eds.), Publications Office of the European Union (Luxembourg: 2019).

The European Technology and Innovation Platform for Photovoltaics, etip-pv, *Our Vision*, Available online: https://etip-pv.eu/about/our-vision/, (accessed 5 October 2019).

Tidey Alice, 11 May 2022, *Euronews*, Explained: Why EU countries are at odds over treaty changes, Available online: https://www.euronews.com/my-europe/2022/05/11/explained-why-eu-countries-are-at-odds-over-treaty-changes, (accessed 2 September 2022).

Todorović Igor, 11 March 2022, *Balkan Green Energy News*, Europe switching on coal plants amid energy crisis, Available online: https://balkangreenenergynews.com/europe-switching-on-coal-plants-amid-energy-crisis/, (accessed 30 June 2022).

Tonini Alberto, "The EEC Commission and European Energy Policy: A Historical Appraisal", *in* Rosella Bardazzi, Maria Grazia Pazienza, Alberto Tonini (eds.), *European Energy and Climate Security: Public Policies, Energy Sources, and Eastern Partners* (New York, London: Springer, 2016), p. 13-35.

Tosun Jale, Biesenbender Sophie, Schulze Kai (eds.), *Energy Policy Making in the EU: Building the Agenda* (London: Springer, 2015).

Tyfield David, The economics of science: a critical realist overview. Volume 1. Illustrations and philosophical preliminaries, Routledge (London: 2011).

Tyfield David, The economics of science: a critical realist overview. Volume 2. Towards a synthesis of political economy and science and technology studies, Routledge (London: 2011).
Tyfield David, "A Cultural Political Economy of Research and Innovation in an Age of Crisis", *Minerva*, 2016, p. 149-167.

Treaty of Lisbon amending the Treaty on European Union and the Treaty establishing the European Community, Official Journal of the European Union, 17.12.2007, Available online: http://publications.europa.eu/resource/cellar/688a7a98-3110-4ffe-a6b3-8972d8445325.0007.01/DOC_19

Treble F. C., "Summary Report: 1980 Photovoltaic Solar Energy Conference", *in* Third EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Cannes France, 27-31 October 1980, W. Palz (eds.), D. Reidel Publishing Company, (Dordrecht Holland, Boston USA, London England: 1981), p. xxvii-xliii.

Treble F. C., “Conference Notebook”, *in* Fourth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Stresa, Italy, 10-14 May 1982, W. H. Bloss and G. Grassi (eds.), D. Reidel Publishing Company (Dordrecht Holland, Boston USA, London England: 1982), p. vii-ix.

Treble F. C., “The Future of Photovoltaics – A Report on the Panel Discussion”, *in* Fifth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference, held at Kavouri (Athens), Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 26-27.

Treble F. C., “Material Problems of the Photovoltaics Industry: A report on panel discussion B”, *in* Sixth EC Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in London, UK, 15-19 April 1985, W. Palz and F.C. Treble (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1985), p. 34-35.

Treble F. C., “The CEC Photovoltaic Pilot Projects”, *in* Sixth E.C. Photovoltaic Solar Energy Conference, Proceedings of the International Conference held in London UK, 15-19 April 1985, Wolfgang Palz and F.C. Treble (eds.), D. Reidel Publishing Company (Holland, Boston, London: 1985), p. 474-480.

Treble F. C., “IEC Standards for Photovoltaic Modules”, *in* Ninth E.C. Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Freiburg, Fed. Rep. of Germany, 25-29 September 1989, Wolfgang Palz, G. T. Wrizon, and P. Helm (eds.), Kluwer Academic Publishers (Dordrecht, Boston, London: 1989), p. 627-630.

Twidale Suzzane, 29 June 2022, *Reuters*, EU race to fill gas storage draws record supplies from Britain, Available online: https://www.reuters.com/markets/europe/eu-race-fill-gas-storage-draws-record-supplies-britain-2022-06-29/, (accessed 30 June 2022).

Umbach Frank, “Global Energy Security and the Implications for the EU”, *Energy Policy*, 2010, p. 1229-1240.
United Nations, “Paris Agreement”, 2015 (https://unfccc.int/sites/default/files/english_paris_agreement.pdf).

United Nations Climate Change, *United Nations Climate Change*, What is the Kyoto Protocol?, Available online: https://unfccc.int/kyoto_protocol%26from%3D, (accessed 10 June 2019).

United States Department of Labour - Occupational Safety and Health Administration, OSHA, *Safety and Health Topics/Silica, Crystalline*, Available online: https://www.osha.gov/silica-crystalline/health-effects, (accessed 25 May 2022).

United States Environmental Protection Agency, (last updated 23 June 2022), *Distributed Generation of Electricity and its Environmental Impacts*, EPA, Available online: https://www.epa.gov/energy/distributed-generation-electricity-and-its-environmental-impacts, (accessed 25 June 2022).

Univesitat Konstanz, uni-konstanz, *Photovoltaics Division*, Available online: https://www.hahn.uni-konstanz.de/en/, (accessed 15 October 2019).

US Geological Survey, “2010 Minerals Yearbook: Rare Earths”, (Washington DC: US Geological Survey, 2012).

US Geological Survey, “Mineral Commodity Summaries 1996”, (Washington DC: US Geological Survey, 1996.

US Geological Survey, “Mineral Commodity Summaries 2002”, (Washington DC: US Geological Survey, 2002).

US Geological Survey, “Mineral Commodity Summaries 2006”, (Washington DC: US Geological Survey, 2006).

US Geological Survey, “Mineral Commodity Summaries 2010”, (Washington DC: US Geological Survey, 2010).

US Geological Survey, “Mineral Commodity Summaries 2015”, (Washington DC: US Geological Survey, 2015).

US Geological Survey, “Mineral Commodity Summaries 2021”, (Washington DC: US Geological Survey, 2021).

Vachtsevanos G. J., Meliopoulos A. P., Paraskevopoulos B. K., “Distributed photovoltaic system impact upon utility load/supply management practices”, *in* Fifth EC Photovoltaic Energy Conference, Proceedings of the International Conference held at Kavouri, Athens, Greece, 17-21 October 1983, W. Palz and F. Fittipaldi (eds.), D. Reidel Publishing Company (Dordrecht, Boston, Lancaster: 1984), p. 383-392.

Van der Vleuten Erik, “Toward a Transnational History of Technology: Meanings, Promises, Pitfalls”, *Technology and Culture*, 2008, p. 974-994.

Veen Geert van der, Eparvier Patrick, Ploeg Matthias, Trucco Paola, *Evaluation of the impact of projects funded under the 6th and 7th EU Framework Programmes for RD&D in the area of non-nuclear energy*, Final Report (Version 4, 19 June 2013), Technopolis Group (2014).

Veraart Frank and Arapostathis Stathis, “Entangling Technological Infrastructures, Material Flows and Environmental Modernities”, Tensions of Europe Workshop, 2022.

Verbong G., Selm A. van, Knoppers R., Raven R., “Een kwestie van lange adem. De geschiedenis van duurzame energie in Nederland 1970–2000”, Aeneas Technical Publishers (Boxtel: 2001).

Verbong Geert and Geels Frank, “The ongoing energy transition: Lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960–2004)”, *Energy Policy*, 2007, p. 1025-1037.

Verbong Geert and Geels Frank W., Raven Rob, “Multi-niche analysis of dynamics and policies in Dutch renewable energy innovation journeys (1970-2006): hype-cycles, closed networks and technology-focused learning”, *Technology Analysis & Strategic Management*, 2008, p. 555-573.

Vikström Hanna, The Specter of Scarcity: Experiencing and Coping with Metal Shortages, 1870–2015, [Doctoral dissertation, KTH Royal Institute of Technology], 2017.

von Schomberg Rene, “A vision of responsible innovation”, *in* Responsible Innovation, Richard Owen, John Bessant, Maggy Heintz (eds.), John Wiley (London: 2013), p. 51-74.

Wakinuma Kutoma, de Castro Fabio, Jiya Tilimbe, Inigo Vincent B., Bryce Vincent, “Reconceptualizing responsible research and innovation from a Blobal South perspective”, Journal of Responsible Innovation, 2021, p. 267-291.

Water A. F. J. van de, Lysen E. H., Bosselaar L., “Solar Energy in the Netherlands: recent progress”, *Renewable Energy*, 1994, p. 1371-1378.

Wiesenfarth Maike, Philipps Simon P., Bett Andreas W., Horowitz Kelsey, and Kurtz Sarah, “Current status of concentrator photovoltaic (CPV) technology”, April 2017 (version 1.3), Fraunhofer ISE and NREL.

Willeke Gerhard P., “The Fraunhofer ISE Roadmap for Crystalline Silicon Solar Cell Technology”, *in* Twenty-Ninth IEEE Photovoltaic Specialists Conference, New Orleans (USA), 19-24 May 2002, p. 53-57.

Willeke Gerhard P. and Rauber Armin, “On the History of Terrestrial PV Development: With a Focus on Germany”, *Semiconductors and Semimetals*, 2012, p. 7-48.

Wilson H. R. and Wittwer V., “Conversion of Solar Energy Using Fluorescent Collectors: Installation of a Test Collector to Deliver Several Watts Power”, *in* Photovoltaic Power Generation, Proceedings of the EC Contractors’ Meeting held in Brussels, 16-17 November 1982, R. Van Overstraeten and W. Palz (eds.), Vol III, D. Reidel Publishing Company (Dordrecht, Holland/Boston, USA/ London, England: 1983), p. 267-227.

Woditsch P., Koch W., “Solar grade silicon feedstock supply for PV industry”, *Solar Energy Materials & Solar Cells*, 2002, p. 11-26.

Wolfe Philip R., “Profiles of Early PV Companies and Organizations”, *in* The Solar Generation: Childhood and Adolescence of Terrestrial Photovoltaics, John Wiley & Sons, Inc. (Hoboken, New Jersey: 2018), p. 199-270.

Wolfe Philip R., *The Solar Generation: Childhood and adolescence of terrestrial photovoltaics*, John Wiley & Sons (Hoboken, New Jersey), 2018.

Wollin K., "Photovoltaics in Germany: Research. Development and Application", *in* Twelfth European Photovoltaic Solar Energy Conference, Proceedings of the International Conference held at Amsterdam, The Netherlands, 11-15 April 1994, Robert Hill, W. Palz and P. Helm (eds.), Vol. II, H. S. Stephens & Associates (UK: 1994), p. 1469-1473.

Wolsink Maarten, "Dutch wind power policy: Stagnating implementation of renewables", *Energy Policy*, 1996, p. 1079-1088.

Xu Yan, Li Jinhui, Tan Quanyin, Peters Anesia Lauren, Yang Congren, "Global status of recycling waste solar panels: A review", *Waste Management*, 2018, p. 450-458.

Yordi B., Gillet W., Gerhold V., "Four years experience of the multi-MWp THERMIE programme", *in* 2nd World Conference on Photovoltaic Solar Energy Conversion/15th European PV Solar Energy Conference/27th US IEEE Photovoltaics Specialists Conference/10th Asia/Pacific PV Science and Engineering Conference, Proceedings of the International Conference held at Vienna, Austria, 6-10 July 1998, J. Schmid, H. A. Ossenbrink, P. Helm, H. Ehmann and E. D. Dunlop (eds.), Vol. II, WIP Renewable Energies: 1998, p. 2457-2462.

Zahedi Ahmad, "Solar photovoltaic (PV) energy; latest developments in the building integrated and hybrid PV systems", *Renewable Energy*, 2006, p. 711-718.

Zaporozhets Vera, Garcia-Valinas Maria, Kurz Sascha, "Key drivers of Eu budget allocation: Does power matter?", *European Journal of Political Economy*, 2016, p. 57-70.

Appendix A

Legislative material	Context and/or explanation provided
Council Regulation (EEC) No 1302/1978 of 12 June on the granting of financial support for projects to exploit alternative energy sources, in L. 158, 16.06.1978, (Official Journal of the European Communities), p. 3.	"Whereas **financial support should be granted after the research stage** for projects for exploiting alternative energy sources, in view of the financial risks involved in new techniques and technologies and the high capital cost of such projects; Whereas support for such projects, which would be undertaken **following studies and research giving favourable indications as to their industrial and commercial viability**, will help to strengthen confidence in the exploitation of these energy sources and to encourage their use in the Community." "Under the conditions laid down in this Regulation, the Community may grant financial support for demonstration projects to exploit alternative energy sources in the Community which by their nature may serve as examples and which prior studies and research have shown to offer prospects of industrial and commercial viability."
Council Regulation (EEC) No 1972/83 of 11 July 1983 on the granting of financial support for demonstration projects relating to the exploitation of alternative energy sources and to energy saving and the substitution of hydrocarbons, in L 195, 19 July 1983, (Official Journal of the European Communities). **&** Council Regulation (EEC) No 3640/85 of 20 December 1985 on the promotion, by financial support, of demonstration projects and industrial pilot projects in the energy field, in L. 350, 27 December 1985, (Official Journal of the European Communities).	Whereas demonstration links the research and development stage, sometimes tested on pilot plant, and the later investment stage ; whereas it differs from the research and development and pilot stages in the industrial scale of projects, the requirement of having prospects of economic viability, and from the investment stage in that the inherent risks are still too high for entrepreneurs; Whereas financial support should be granted, after the research and development stage, for suitable demonstration projects, in view of the considerable risks and investment which the application of innovatory techniques might entail;" (p.6) "For the purposes of this Regulation 'demonstration projects relating to solar energy' means projects in which solar energy is made available for thermal use through active or passive processes or technology (with the exception of solar concentrators), or is made available through photovoltaic processes." (p. 10)

Council Regulation (EEC) No 2008/90 of 29 June 1990 concerning the promotion of energy technology in Europe (Thermie programme), L. 185, 17 July 1990, (Official Journal of the European Communities)	“Whereas financial support should be granted in appropriate cases to projects for the promotion of advanced technology in the field of energy” (p. 1) “Whereas, notwithstanding the new impetus that the promotion of innovative energy technologies requires, the continuity of measures undertaken under demonstration projects and industrial pilot projects in the energy field … whereas such continuity must be achieved on the one hand through the pursuit of measures to promote and disseminate technologies that have received Community support under such Regulations; whereas it may also be achieved through support for the later stages of projects that have already received partial support under the same Regulations; whereas it must be possible in certain cases to support projects of the same sort as those covered by these Regulations provided they also fulfil the requirements of this Regulation” (p. 2)
COUNCIL DECISION of 23 November 1994 adopting a specific programme for research and technological development, including demonstration, in the field of non-nuclear energy (1994 to 1998), 94/806/EC, in L 334, 22 December 1994, (Official Journal of the European Communities).	“Whereas it is necessary, as the fourth framework programme indicates, to ensure complementarity between research and development and the demonstration and that the two phases of the RTD are integrated into the same energy RTD strategy in the Community; Whereas the programme for non-nuclear energies calls for a coherent strategy covering the whole process of innovation, from scientific breakthrough all the way to dissemination” (p. 87) “Demonstration actions are closer to the market and so they will be more diversified***: they are the extension of the RTD efforts*** carried out by the private sector or the public sector at the Community level in the Member States.” (p. 93) “Demonstration activities will cover in particular the large scale commercialization of remote stand-alone photovoltaic applications and grid connected systems, and will involve electricity utilities and other key players.” (p. 98)

Table 1. Changes in the definition of ‘demonstration’ during the first period based on Legislation, 1978-1998.

Based on the definitions provided by the legislative material listed in Table 1, we can see that the term ‘demonstration’ changes and so does its relation to research. In particular, in the first Council Regulation (1978) it was research that determined both the industrial and the commercial viability of the technologies. In this context, demonstration was an extension of the R&D phase that would essentially promote the further exploitation of the technologies deriving from the research phase. We have seen that during the second energy R&D programme the EC used the pilot projects to construct a market for PV, essentially having the role defined in the 1978 Council Regulation. Within this context, the demonstration projects were a continuation of the pilot projects, aiding the further installation of PV and by extension further increasing the European industry's market.[982] Thus, research was determining which technologies were ready (industrially and commercially) and was tasked with constructing a market for the new technologies. Demonstration was a continuation or extension of research, however unclear that still remains.

Throughout the 1980s (Council Regulations of 1983 and 1985) an effort was made to better link the R&D phase to the Demonstration phase, as well as to delineate where one begins and the other ends. Still, demonstration was the stage that followed R&D, but an effort was made to better define the difference(s) between the two phases. Towards this end, demonstration was now different from the R&D phase based on the 'industrial scale of [the] projects, the requirements of having prospects for economic viability, and from the investment stage in that the inherent risks are still too high for entrepreneurs'. Industrial scale can be interpreted in many different ways. It should be noted that a clarification as to what this scale meant in the case of PV (or any other RES) was not included in the corresponding Council Regulations. However, if we assume that 'industrial scale' can refer either to the actual scale of the technologies (i.e., how many kW or MW will be installed) or the consortia established to support the projects (i.e., large industrial consortia) we have some interesting findings that contradict this delineation.

Firstly, by 1983 when the second energy R&D programme was concluded the EC aided the installation of 1,1 MW of PV (pilot programme); with projects in the range of 30-300kW. By the same time the demonstration projects had accounted for the installation of 7,7kW of PV, whereas the second demonstration programme resulted in the installation of 379,9kW of PV; the largest-scale project was a single 100kW demonstration project. Even, in the following 1990s programmes the scale was not actually a factor for determining if a project was demonstration or R&D/pilot. A notable example is that of the WEGA project, funded under the First Framework Programme (NNE sub-programme). The WEGA project concerned the study and installation of three large-scale wind turbines, in the range of 1-2MW. In all the above examples, both for PV and wind turbines, the consortia supporting the projects comprised of major industrial actors from the respective fields. Additionally,

---

[982] We should note that under the first demonstration programme only four demonstration projects were selected and funded and only three of these projects were completed.

the research programmes – much like the demonstration programmes – used 'risk' as a justification for receiving EC funding support. In the context of the R&D programmes, risk was employed to justify the need for EC support and as an explanation of why research was necessary. Again, in the case of R&D, risk was directly associated with the financial risks that the industrial actors could not face alone.

In the 1990 Council Regulation the continuity between the R&D and Demonstration programmes was once more reassured, but not clearly defined. Demonstration was now in charge of the promotion and the dissemination of the new technologies. An explanation as to what promotion and dissemination meant is not provided. The way we understand the role of the demonstration programmes is that they achieved the above aims/objectives through the installation of PV systems. From FP2 to FP4 (JOULE I-JOULE III), the pilot component of the PV programmes did not comprise of the installation of PV systems with only minor exceptions. However, these PV system installations were small scare, in the range of a few kW. The main activity of the pilot programmes was to develop new and/or improved system components, bring the PV system costs down, develop management systems and gather data.

When the two programmes (i.e., JOULE and Thermie) merged under the Fourth Framework Programme further changes and/or additions were made to delineate R&D and Demonstration. In this context, the demonstration programmes were – as was explicitly stated in the Council Decision – as an extension of RTD. Essentially, the continuity from R&D to Demonstration was reinstated. Additionally, the two were understood as 'complementary' actions towards reinsuring the coherency of EC's energy strategy that were covering the entire 'innovation chain'. As such, demonstration was tasked with the dissemination of the technologies and overall actions that were 'closer to the market'.

Overall, based on the above, we can see that both the term 'demonstration' and its relation and/or link to R&D is loosely defined. Essentially, there was plenty of room to interpret a project either as pilot or demonstration; the examples about both the PV and wind turbine installations under the R&D programmes further reinforce this loosely defined delineation in action. Under FP4 we see for the first time a PV-specific reference as to what kinds of projects the EC would support under the demonstration programme. Two points are crucial: (a) the use of large-scale commercialisation and (b) the involvement of electric utilities and other key actors.

Essentially, this commercialisation comprised of the installation of PV systems – something that the Demonstration programmes started to do in the 1990s, whereas previously that was part of the pilot programmes – to help continue constructing a market. Alongside with that aim they also demonstrated the viability of these systems. An explanation as to why the installation of PV systems was transferred in the demonstration programmes in the 1990s, at the EC level, can be provided by the national level (i.e., national demonstration programmes that launch during this period – roof and/or roof-top programmes)