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DEPARTMENT OF AGRICULTURAL DEVELOPMENT, AGRI-FOOD &
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DOCTORAL DISSERTATION

Production of Sustainable Aviation Fuels (SAFs) via gasification-based pathways: a feasibility/scalability study & techno-economic assessment

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ΕΘΝΙΚΟ ΚΑΙ ΚΑΠΟΔΙΣΤΡΙΑΚΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΑΘΗΝΩΝ

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Abstract

International Air Transport Association (IATA) has set the target of net-zero carbon emissions by 2050 for the aviation sector. The major factor in achieving net-zero is anticipated to be the increasing deployment of sustainable aviation fuels (SAFs). SAFs refer to liquid biofuels (produced from sustainable biogenic feedstock) or e-fuels (produced from green hydrogen and CO_2) that are interchangeable replacements of conventional petroleum-derived jet fuel. IATA has adopted SAFs as the most promising strategy to reduce the environmental impact of the sector due to their compatibility with the extensive current infrastructure and the limitations of viable alternatives (e.g. electrification). Hydrogen aviation or electrification require deep and all-encompassing changes in the industry and can be considered only as long-term alternatives.

Hydroprocessed esters and fatty acids (HEFA), produced from the hydrotreatment of waste fats, oils, and greases, is the most cost-affordable SAF option and is expected to remain the most efficient pathway at least through 2030. However, HEFA technology is unable on its own to cover the growing SAF demand within the planned fuel transition of the sector due to the scarcity of appropriate (for HEFA) feedstock types that do not raise environmental/social concerns (e.g. edible raw material, land use change). Hence, the strategy set by the European Union underlines the need for the production/use of advanced biofuels (derived from biogenic residues/wastes) through the establishment of effective Biomass-to-Liquid (BtL) concepts. Reducing production costs is the primary difficulty associated with these concepts, as conventional BtL pathways typically entail significant capital and operational expenses.

Gasification is a key technology towards the commercial uptake of sustainable BtL plants. In this context, the present doctoral thesis aims to provide a thorough analysis concerning the feasibility of gasification-driven BtL technologies that includes a critical review on the current SAF production pathways, the interaction with key industrial stakeholders (e.g. refineries) via dedicated surveys, the assessment of cutting-edge gasification configurations, the election of appropriate biogenic residues to support large-scale BtL implementations, as well as the design and techno-economic assessment of a novel BtL scheme. In particular:

Chapter 1 lays the foundations of the performed research by presenting and evaluating the available alternatives towards the decarbonization of the aviation industry. A comparative analysis of the dominant SAF technologies is carried out considering financial efficiency, environmental

impact, and future projections. The current regulatory framework is reviewed and the impact of the recent initiative ‘ReFuelEU Aviation’ is assessed.

Chapter 2 is dedicated to the interaction with the relevant market and securing of industrial insight regarding the biofuels perspective. Five (5) target groups were selected to represent the key stakeholders towards the uptake of advanced biofuels; feedstock suppliers, refineries, fuel traders, final end-users, and policy makers. A questionnaire survey was performed and key facts for each target group were extracted.

Chapter 3 is separated into two parts. The first part evaluates the suitability of Dual Fluidized Bed (DFBG) and Chemical Looping (CLG) gasification technologies for commercial BtL applications through validated process models and upscaling reflections. The second part covers the screening of biogenic residues throughout Europe and the determination of appropriate feedstock types in terms of capacity, technical attributes, and market specifications. The primary biogenic sources that can be utilized for energy production via gasification are forestry and agricultural residues.

Chapter 4 introduces an innovative fuel synthesis BtL scheme based on the double-stage fermentation of the produced syngas (syngas → acetic acid → microbial oil) instead of the conventional Fischer-Tropsch (FT) or Alcohol-to-Jet (AtJ) synthesis. An initial performance evaluation is carried out and design considerations are discussed through the simulation of various operational scenarios.

Chapter 5 presents the elected design of the innovative BtL concept and conducts its techno-economic evaluation at full scale (200 MWth) based on reasonable upscaling considerations and models validated at pilot scale. Benchmarking with the FT and AtJ technologies is aimed, while a preliminary Greek BtL replication study is generated.

Gasification-driven BtL technologies, led by FT and AtJ that are already at pre-commercial level, are capable of growing significantly in the upcoming years due to their advanced feedstock flexibility. Key prerequisites for this to occur are the ongoing attempts for design optimization (reduction of production costs), the right policy incentives, and the effective integration with the current refining infrastructure.

Περίληψη

Η Διεθνής Ένωση Αερομεταφορών (IATA) έχει θέσει ως στόχο τις μηδενικές εκπομπές άνθρακα έως το 2050. Ο κύριος παράγοντας επίτευξης αυτού του στόχου αναμένεται να είναι η αυξανόμενη διείσδυση των βιώσιμων αεροπορικών καυσίμων (SAFs). Ο όρος SAFs αναφέρεται σε υγρά βιοκαύσιμα (που παράγονται από βιογενή πρώτη ύλη) ή ηλεκτροκαύσιμα (e-fuels) (που παράγονται από πράσινο υδρογόνο και CO_2) που είναι πλήρως εναλλάξιμα υποκατάστατα της συμβατικής (ορυκτής) κηροζίνης. Τα SAFs έχουν υιοθετηθεί ως η πιο ελπιδοφόρα στρατηγική για τη μείωση του περιβαλλοντικού αποτυπώματος του τομέα λόγω της συμβατότητάς τους με την εκτεταμένη τρέχουσα υποδομή και τους περιορισμούς των διαθέσιμων εναλλακτικών λύσεων (π.χ. ηλεκτροκίνηση). Η χρήση υδρογόνου ή η ηλεκτροκίνηση απαιτούν βαθιές και συνολικές αλλαγές στον κλάδο και μπορούν να θεωρηθούν μόνο ως μακροπρόθεσμες εναλλακτικές.

Η τεχνολογία τύπου HEFA, που βασίζεται στην υδρογόνωση χρησιμοποιημένων ελαίων/ζωικών λιπών, είναι η πιο οικονομικά προσιτή τεχνολογία παραγωγής SAF και αναμένεται να παραμείνει η πιο ώριμη και αποτελεσματική επιλογή τουλάχιστον μέχρι το 2030. Ωστόσο, η συγκεκριμένη τεχνολογία δεν επαρκεί για να καλύψει από μόνη της την ευρεία μετάβαση καυσίμου του κλάδου λόγω της περιορισμένης διαθεσιμότητας πρώτων υλών (για HEFA) που δεν εγείρουν περιβαλλοντικούς/κοινωνικούς προβληματισμούς (π.χ. βρώσιμη πρώτη ύλη, αλλαγή χρήσης γης). Ως εκ τούτου, η στρατηγική που καθορίστηκε από την Ευρωπαϊκή Ένωση υπογραμμίζει την ανάγκη για παραγωγή/χρήση προηγμένων βιοκαυσίμων (που προέρχονται από βιογενή υπολείμματα/απόβλητα) μέσω της ανάπτυξης αποτελεσματικών τεχνολογιών BtL (Biomass-to-Liquid). Η μείωση του κόστους παραγωγής είναι η κυριότερη πρόκληση αυτών των τεχνολογιών, καθώς τα σχήματα BtL συνήθως συνεπάγονται σημαντικά κεφαλαιουχικά και λειτουργικά έξοδα.

Η αεριοποίηση είναι μια βασική τεχνολογία για την ανάπτυξη βιώσιμων μονάδων BtL. Σε αυτό το πλαίσιο, η παρούσα διδακτορική διατριβή στοχεύει σε μια διεξοδική ανάλυση σχετικά με τη σκοπιμότητα τεχνολογιών BtL βασισμένων στην αεριοποίηση και περιλαμβάνει μια ανασκόπηση των κυρίαρχων τεχνολογιών παραγωγής SAF, την αλληλεπίδραση με σχετικούς βιομηχανικούς φορείς (π.χ. διυλιστήρια), την αξιολόγηση προηγμένων σχημάτων αεριοποίησης, την επιλογή κατάλληλων βιογενών υπολειμμάτων για την υποστήριξη βιομηχανικών εφαρμογών BtL, καθώς και το σχεδιασμό/τεχνοοικονομική αξιολόγηση μιας καινοτόμου BtL τεχνολογίας. Συγκεκριμένα:

Το ***Κεφάλαιο 1*** θέτει τα θεμέλια της παρούσας διατριβής παρουσιάζοντας κι αξιολογώντας τις διαθέσιμες εναλλακτικές για την αποδέσμευση της αεροπορικής βιομηχανίας από τον άνθρακα. Πραγματοποιείται μια συγκριτική ανάλυση των κυρίαρχων τεχνολογιών SAF λαμβάνοντας υπόψη την οικονομική απόδοση, τις περιβαλλοντικές επιπτώσεις, και τις μελλοντικές προβλέψεις. Επίσης, αξιολογείται ο αντίκτυπος της πρόσφατης πολιτικής πρωτοβουλίας 'ReFuelEU Aviation'.

Το ***Κεφάλαιο 2*** επικεντρώνεται στην αλληλεπίδραση με τη σχετική βιομηχανία. Επιλέχθηκαν πέντε (5) ομάδες-στόχοι για να εκπροσωπήσουν βασικά ενδιαφερόμενα μέρη σχετικά με την υιοθέτηση προηγμένων βιοκαυσίμων; προμηθευτές πρώτων υλών, διυλιστήρια, έμποροι καυσίμων, τελικοί χρήστες, και υπεύθυνοι χάραξης πολιτικής. Πραγματοποιήθηκε έρευνα με ειδικά διαμορφωμένα ερωτηματολόγια και εξήχθησαν βασικά στοιχεία για κάθε ομάδα-στόχο.

Το ***Κεφάλαιο 3*** χωρίζεται σε δύο μέρη. Το πρώτο μέρος αξιολογεί τη καταλληλότητα των τεχνολογιών αεριοποίησης DFBG και CLG για εφαρμογές BtL μέσω επικυρωμένων μοντέλων και αντανακλάσεων μεγαλύτερης κλίμακας. Το δεύτερο μέρος καλύπτει τον προσδιορισμό κατάλληλης πρώτης ύλης (διαλογή βιογενών υπολειμμάτων) ανά την Ευρώπη όσον αφορά τη διαθεσιμότητα, τα τεχνικά χαρακτηριστικά, και τις προδιαγραφές της αγοράς. Οι κύριες βιογενείς πηγές ενέργειας μέσω αεριοποίησης είναι τα υπολείμματα δασικής και γεωργικής προέλευσης.

Το ***Κεφάλαιο 4*** εισάγει ένα καινοτόμο σχήμα BtL που βασίζεται στη διβάθμια ζύμωση του αερίου σύνθεσης (αέριο σύνθεσης → οξικό οξύ → μικροβιακό έλαιο) αντί των συμβατικών σχημάτων Fischer-Tropsch (FT) ή Alcohol-to-Jet (AtJ). Πραγματοποιείται μια αρχική αξιολόγηση απόδοσης και εξετάζονται εκτιμήσεις σχεδιασμού μέσω της προσομοίωσης διαφόρων σεναρίων λειτουργίας.

Το ***Κεφάλαιο 5*** παρουσιάζει τον επιλεγμένο σχεδιασμό του νέου σχήματος BtL (200 MWth) και διεξάγει την τεχνοοικονομική αξιολόγησή του με βάση επικυρωμένα μοντέλα και λογικές θεωρήσεις αναβάθμισης κλίμακας. Στόχος είναι η συγκριτική αξιολόγηση με τις τεχνολογίες FT και AtJ, ενώ παρουσιάζεται και μια προκαταρκτική μελέτη ωρίμανσης ελληνικού BtL.

Οι τεχνολογίες BtL βασισμένες στην αεριοποίηση, καθοδηγούμενες από τις ήδη σε προ-βιομηχανικό επίπεδο FT και AtJ, μπορούν να ευδοκιμήσουν τα επόμενα χρόνια λόγω της ευελιξίας τους σε πρώτη ύλη. Βασικές προϋποθέσεις για να συμβεί αυτό είναι οι συνεχείς προσπάθειες για βέλτιστο σχεδιασμό (μείωση του κόστους παραγωγής), κατάλληλα πολιτικά κίνητρα, και η αποτελεσματική σύνδεση με τις υπάρχουσες υποδομές διύλισης.

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Table of Contents

List of abbreviations

S.I. (International System of Units) abbreviations for units and standard notations for chemical elements, formulae, and chemical abbreviations are used in this work. Other abbreviations are listed below.

AR	Air Reactor
AtJ	Alcohol-to-Jet
ATR	Autothermal Reformer
BtL	Biomass-to-Liquid
CapEx	Capital Expenditures
CC	Carbon Conversion
CFB	Circulating Fluidized Bed
CGE	Cold Gas Efficiency
CHJ	Catalytic Hydrothermolysis Jet
CLG	Chemical Looping Gasification
CU	Carbon Utilization
DFBG	Dual Fluidized Bed Gasification
DSP	Downstream Processing
EFE	Energetic Fuel Efficiency
EU	European Union
FAME	Fatty Acid Methyl Esters
FOGs	Fats, Oils, and Greases
FR	Fuel Reactor
FT	Fischer-Tropsch
HEFA	Hydroprocessed Esters and Fatty Acids
HRSG	Heat Recovery Steam Generator
HVO	Hydrotreated Vegetable Oil
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
ILUC	Induced Land-Use Change

LHV	Lower Heating Value
MJSP	Minimum Jet fuel Selling Price
MOSP	Minimum Oil Selling Price
MSW	Municipal Solid Waste
NECP	National Energy and Climate Plan
NPV	Net Present Value
NUTS	Nomenclature of Territorial Units for Statistics
OC	Oxygen Carrier
OpEx	Operational Expenditures
PSA	Pressure Swing Adsorption
PtL	Power-to-Liquid
RED	Renewable Energy Directive
SAFs	Sustainable Aviation Fuels
SIP	Synthesized Iso-Paraffin
SMR	Steam Methane Reformer
ST	Steam Turbine
TAGs	Triglycerides (microbial oil)
TCI	Total Capital Investment
TRL	Technology Readiness Level
UCOs	Used Cooking Oils
WGS	Water-Gas Shift

Scope – Preface

Transport accounts for about a third of the EU's total greenhouse gas (GHG) emissions. Road transport constitutes the highest proportion (>70%) of overall transport emissions, followed by aviation (around 14%) and maritime (around 13%). While electrification shows remarkable penetration into road transport, which comes up with the fastest decarbonization rates, aviation and maritime are included among the most challenging sectors to decarbonize. The recent initiatives 'ReFuelEU Aviation' and 'FuelEU maritime', that set the decarbonization plan of aviation and maritime sectors respectively, have identified the key role of 'drop-in' liquid fuels towards instant industrial compliance of these sectors with the environmental policies and regulations. 'Drop-in' liquid fuels refer to interchangeable substitutes for conventional petroleum-derived fuels (e.g. diesel, kerosene) that are produced from sustainable resources; biogenic feedstock (biofuels) or green hydrogen + CO_2 (e-fuels) [1].

International Energy Agency (IEA) has claimed that biofuels by 2050 could provide 27% of total transport fuel, mainly replacing diesel and jet fuel. However, during the implementation of the present dissertation, it was observed that 'drop-in' liquid biofuels are in an advantageous position in the aviation sector compared to other sectors (e.g. maritime). International Air Transport Association (IATA) has identified the production of drop-in sustainable aviation fuels (SAFs) as the most promising strategy to reduce the environmental impact of the sector due to their compatibility with the extensive current infrastructure and the absence of viable alternatives (e.g. electrification) that will not disrupt the strict and particular protocols of airline operations. In contrast, even though liquid biofuels remain high on the agenda of the maritime sector, their advantage over emerging alternatives (e.g. methanol, hydrogen, ammonia, LNG) is not as clear as in aviation. Hence, in the absence of sustainable alternatives, aviation field seems the appropriate sector for 'drop-in' advanced biofuels and e-fuels to thrive and lead the decarbonization of the sector. The ambitious targets of net-zero carbon emissions for 2050 by IATA, the quantified biofuels/e-fuels blending mandates at airports by 'ReFuelEU Aviation', and the continuous escalation of market/research activity related to SAFs confirm this claim [2-4].

Hydroprocessed esters and fatty acids (HEFA), Fischer-Tropsch (FT), Alcohol-to-Jet (AtJ), and Power-to-Liquid (e-jet) are the identified leading SAF technologies towards the targeted fuel transition of the aviation sector. E-jet pathways currently struggle to present affordable production costs, but projections for rapid reductions in hydrogen and green electricity prices form a promising future. HEFA fuel, produced from the hydrotreatment of waste fats, oils, and greases (FOGs), is the most cost-competitive option and is expected to remain the most efficient pathway, at least through to 2030. However, the limited supply of feedstock and lack of cultivation areas turn HEFA into a feedstock-constrained pathway that is unable on its own to support the needs of a large-scale fuel transition. Therefore, there are reasonable claims that the next two decades could be dominated by technologies handling advanced feedstock (e.g. biogenic residues/wastes) through effective Biomass-to-Liquid (BtL) concepts [5, 6].

Gasification is widely considered a proper and flexible technology for the conversion of residual biomass to bio-energy (syngas). The low energy density and the corrosive nature of pyrolysis bio-oil or the high costs (catalysts, high pressures) of liquefaction have established biomass gasification as the dominant technology to host BtL concepts. The main challenge related to these concepts is the reduction of the production costs since the current BtL pathways usually involve intense capital and operational expenses. FT and AtJ are justifiably the dominant emerging gasification-driven BtL technologies, but they also present drawbacks that slow down their large-scale deployment [7, 8].

The aim of the present PhD thesis can be condensed into the following points:

- A comprehensive overview of the current alternative aviation fuels, along with a comparative analysis of the leading SAF technologies considering techno-economic assessment, environmental impact, future forecasts, market trends, and relevant policies.
- Identification of key stakeholders towards the implementation of advanced biofuel technologies as well as understanding of the main industry concerns/needs.
- Investigation of advanced gasification technologies and screening of biogenic residues around Europe, able to support large-scale BtL applications in terms of performance and feedstock capacities.
- Modeling, optimization, and techno-economic assessment of a novel gasification-driven BtL scheme. Benchmarking with the established gasification-derived SAF technologies (i.e. FT, AtJ) and preliminary Greek BtL replication study.

My participation, on behalf of CERTH (Centre for Research & Technology Hellas), in the European Union's Horizon 2020 projects *'BioSFerA'* [9] and *'CLARA'* [10], that were both dedicated to the pilot demonstration of gasification-driven BtL technologies, allowed the acquisition of relevant experimental/industrial insight. The experimental/pilot results were utilized for the validation of the developed models and upscaling considerations that serve the scope of the present dissertation.

The performed research has received financial support from the European projects *'BioSFerA'* (Grant Agreement No. 884208) and *'CLARA'* (Grant Agreement No. 817841), funded by the European Union's Horizon 2020 research and innovation program.

List of Publications

Publications making up the core of this dissertation:

- **Detsios, N.**; Maragoudaki, L.; Rebecchi, S.; Quataert, K.; De Winter, K.; Stathopoulos, V.; Orfanoudakis, N.G.; Grammelis, P.; Atsonios, K.; 'Techno-economic Evaluation of Jet Fuel Production via an Alternative Gasification-Driven Biomass-to-Liquid Pathway and Benchmarking with the State of the Art Fischer-Tropsch and Alcohol-to-Jet concepts'. *Energies*, **2024**, 17, 1685. https://doi.org/10.3390/en17071685

- **Detsios, N.**; Theodoraki, S.; Maragoudaki, L.; Atsonios, K.; Grammelis, P.; Orfanoudakis, N.G. 'Recent Advances on Alternative Aviation Fuels/Pathways: A Critical Review'. *Energies*, **2023**, 16, 1904. https://doi.org/10.3390/en16041904

- **Detsios, N.**; Maragoudaki, L.; Atsonios, K.; Grammelis, P.; Orfanoudakis, N.G. 'Design considerations of an integrated thermochemical/biochemical route for aviation and maritime biofuel production'. *Biomass Conversion and Biorefinery*, **2023**. https://doi.org/10.1007/s13399-023-03754-4

- **Detsios, N.**; Zisopoulos, G.; Atsonios, K.; Nikolopoulos, N.; Grammelis, P.; Kaltenmorgen, J.; Ströhle, J.; Epple, B.; Orfanoudakis, N.G. 'Dynamic process simulations and control of a lignite/waste to Fischer Tropsch liquids plant'. *Fuel Processing Technology*, **2022**. 236: p. 107395. https://doi.org/10.1016/j.fuproc.2022.107395

- **Detsios, N.**; Atsonios, K.; Grammelis, P.; Dieringer, P.; Ströhle, J.; Nikkanen, V.; Orfanoudakis, N.G. 'A comparative analysis and assessment of Dual Fluidized Bed and Chemical Looping Gasification: Design considerations for commercial use and applicability in BtL schemes'. – *31st European Biomass Conference & Exhibition (EUBCE)*, 5-8 June **2023**, Bologna, Italy https://doi.org/10.5071/31stEUBCE2023-4AO.5.2.

- **Detsios, N.**; Maragoudaki, L.; Atsonios, K.; Grammelis, P.; Orfanoudakis, N.G. 'Παραγωγή Βιώσιμων Αεροπορικών Καυσίμων (SAFs) μέσω βιολογικής επεξεργασίας αερίου σύνθεσης'. – *Energy Materials and NATural rEsources (EMANATE)*, ΕΚΠΑ, 11-12 May **2023**, Chalkida, Greece https://hub.uoa.gr/emanate-conference/

- **Detsios, N.**; Grammelis, P.; Orfanoudakis, N.G. 'Βιώσιμα Αεροπορικά Καύσιμα (SAFs): Μια άμεση πρόκληση'. – *2ο Συνέδριο για την Κλιματική Κρίση*, ΕΚΠΑ, 10-11 April **2023**, Athens, Greece https://hub.uoa.gr/second-conference-on-climate-crisis-about-the-assistance-of-the-nkua-for-its-treatment/

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Other publications:

- o Gogulancea, V.; Rolfe, A.; Jaffar, M.; Brandoni, C.; Atsonios, K.; **Detsios, N.**; Dieringer, P.; Huang, Y. 'Techno-economic and Environmental Assessment of Biomass Chemical Looping Gasification for Advanced Biofuel Production'. *International Journal of Energy Research*, **2023**, 6101270. https://doi.org/10.1155/2023/6101270

- o Atsonios, K.; Nesiadis, A.; **Detsios, N.**; Koutita, K.; Nikolopoulos, N.; Grammelis, P. 'Review on dynamic process modeling of gasification based biorefineries and bio-based heat & power plants'. *Fuel Processing Technology*, **2020**. 197: p. 106188. https://doi.org/10.1016/j.fuproc.2019.106188

- ▪ **Detsios, N.**; Atsonios, K.; Grammelis, P.; Kougioumtzis, M.A.; Dieringer, P.; Heinze, C.; Ströhle, J. 'Advanced Fischer-Tropsch biofuels production from syngas derived from Chemical Looping Gasification: A preliminary process simulation study'. – *28th European Biomass Conference & Exhibition (EUBCE)*, 6-9 July **2020**, Virtual https://doi.org/10.5071/28thEUBCE2020-3BV.4.8.

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Chapter 1

A critical review of recent advances on alternative aviation fuels

1.1 Introduction

The global aviation industry seems to be a constantly and rapidly expanding sector in recent years. The International Air Transport Association (IATA) claims that the request for air connectivity will continue to grow. Indicatively, according to the IATA annual review of 2019, the counted number of more than 4 billion passengers for 2018 is the biggest ever while the transport of 64 million tons of cargo to markets around the world, for the same year, represents a 3.4% growth compared to the already extraordinary high number of cargo transfers for 2017. The huge decline (~66%) in global revenue passenger kilometers observed in 2020 cannot be considered indicative, since the COVID-19 pandemic delivered the largest shock to air travel and aviation industry since the Second World War [11, 12].

The increasing demands of air traffic lead to increasing demands of aviation fuels (jet fuels). Approximately 80 billion gallons of jet fuel, classified as kerosene-type and naphtha-type, are produced annually worldwide. The extensive use of petroleum-derived jet fuels has resulted in a remarkable decline in petroleum reserves. Furthermore, the large consumption of jet fuel generates notable amounts of greenhouse gases (GHG) making the airline sector responsible for 3% of the total current GHG emissions [13]. The Paris Agreement's objectives related to climate change put aviation, along with other sectors, under great pressure and environmental inspection. In Europe, the pressure is particularly intense and is expected to keep growing. Aviation industry is committed to achieving a 50% reduction in CO_2 emissions by 2050 compared to 2005 level. While it is important to have a holistic view on climate metrics and target to the parallel reduction of both CO_2 and NO_x emissions via modern aircraft design and improved engine operational measures, the priority for the aviation sector in order to meet its environmental targets is the decarbonization of liquid fuels that are fully compatible with the current infrastructure (drop-in fuels). The slow incremental changes in already-mature engine technology and the long lifetime (>25 years) of existing fleets validate this priority as a much faster and probably cost-efficient way to reduce emissions [14]. Therefore, the present review study focuses on the ongoing efforts for development of low-carbon liquid fuels of the same quality as existing ones without underestimating in any way the importance of parallel advances on aircraft engine operation (i.e. fuel efficiency improvements, engine-out emissions) [15, 16].

At the moment, aviation fuels are mainly comprised of kerosene fuels (i.e. Jet A or Jet A-1), but as petroleum residues are diminishing and therefore, their prices are going up, it is being understood that a turn to sustainable aviation fuels (SAFs) is auspicious and imperative. IATA has identified the production of drop-in sustainable liquid fuels as the most promising strategy to reduce the environmental impact of the sector, since on the one hand conventional fuel efficiency improvements are not sufficient to meet the targets for decarbonizing the industry and on the other hand electrification along with modern design of aircrafts or hydrogen involvement require extended infrastructure restructuring of the whole industry. Investments are in place to expand SAF annual production from the current 125 million liters to 5 billion by 2025. With effective government incentives, production could reach 30 billion liters by 2030, which would be a tipping point for SAF production and utilization [17]. Relative market-oriented studies seem to confirm the projected SAF rapid evolution within the next years, by claiming that SAF market is expected to increase from $216 million to more than $14 billion by 2030 [18].

Within this study, a critical review on the available pathways towards the decarbonization of the aviation industry is attempted. A comparative analysis from the techno-economic and environmental point of view are performed for the identified main technologies. The main objective of this paper is to provide a complete overview of the current alternative aviation fuels as well as to decode partially the ‘next day’ of aviation.

Even though there are relevant studies into the literature that aim to round up the latest advances of the field [5, 19-23], the present study is not only powered by them but also aims to link these advances with the current market status, identify the main ambassadors of each technology, and record the latest key agreements/announcements. The motivation for this approach is the belief that SAFs have ceased to be considered only as possible future alternatives of mainly research interest, but are already present in the market and there are strong indications that SAFs market will be one of the most active emerging markets of the current decade. As further novel aspects of this work can be regarded: i) the synthesis of the data collected within this study with previous forecasting studies in order to perform future projections regarding the evolution of fuel production costs for selected technologies, ii) adhering to data and studies reported only after 2015 in order to draw the most up-to-date conclusions and considerations, iii) extensive focus on the current regulatory framework and policy approaches for sustainable aviation [6] along with underlining of their importance towards a successful fuel transition, and iv) reference to the progress related to hydrogen and electrification involvement in the aviation sector.

1.2 Summary of alternative aviation fuels & current status

The current tendencies for a more sustainable aviation industry include the so-called 'drop-in' alternative aviation fuels, hydrogen, and the potential aviation electrification (i.e. hybrid or full-electric aircrafts) (Figure 1). The 'drop-in' alternative aviation fuels or sustainable aviation fuels (SAFs) refer to completely interchangeable substitutes for conventional petroleum-derived jet fuel (i.e. Jet A or Jet A-1) that are produced from sustainable resources (e.g. biogenic feedstock, renewable hydrogen + CO_2). The fact that no adaptations are required for the existing fuel systems (i.e. engines, fuel distribution network) establishes SAFs as dominant alternatives towards the decarbonization of the aviation field. Hydrogen is a long-term sustainable fuel option, but requires extended modifications in current fuel infrastructure and overall aircraft design. Finally, aircraft propulsion via electrification in pure or hybrid mode could be an emerging option; nevertheless, energy storage limitations remain a major concern especially for long-distance applications.

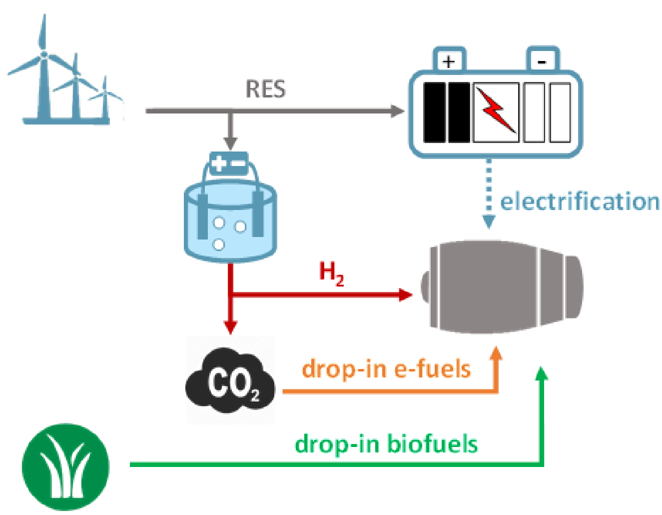


Figure 1. Alternatives towards the decarbonization of the aviation field.

1.2.1 Sustainable Aviation Fuels (SAFs)

SAFs have recently started to attract great interest and have been identified by IATA as the most promising strategy to reduce CO_2 emissions in the aviation sector. Jet fuels, produced from renewable or recyclable feedstock, can deliver up to an 80% reduction in carbon emissions over the complete life cycle of the fuel while the International Energy Agency (IEA) claims that biofuels by 2050 could provide 27% of total transport fuel, mainly replacing diesel, kerosene and jet fuel [24]. Currently, most SAFs technologies are still being tested or are at a prototype level, but they are making good progress, with some of them (e.g. HEFA) being already used in commercial flights as blending components [25]. However, one of the challenges being faced with the production of SAFs is creating fuel from renewable sources, like biomass, at an affordable price. Moreover, the feedstock used for producing the SAFs must not raise the question of food vs. fuel or cause deforestation, or any other environmental/societal harm. Another major concern is producing a fuel that matches the energy density of conventional fuels and their qualities such as low freezing point and good cold flow properties. The ASTM D7566 specification has been developed over many years following a strict testing regime and approval process dedicated to SAFs safety compliance towards their implementation in commercial aviation. The expected scale-up of SAFs production in the coming years requires the parallel intensification of quality control in order to ensure that the new fuel technologies introduced are safe [26, 27].

1.2.1.1 Biofuels

Hydroprocessed Esters and Fatty Acids (HEFA)

Hydroprocessed renewable jet fuels (HRJs or HEFA) are produced by the hydrogenation of vegetable oils, used cooking oils (UCOs), animal fats, waste grease, algal oil, or bio-oil. They are high-energy biofuels that can be used in conventional aircraft engines without further engine modification. Some of their weaknesses (such as low lubricity) are overcome by blending HRJs with other conventional fuels. Using HEFA as an aviation fuel has already been tested by many airline companies in passenger flights. However, it should be mentioned that the feedstock for HEFA is usually costly, often raises the question of food vs. fuel, and its cultivation can cause severe land-use change. Biodiesel is also produced from fatty acids via esterification, but it is considered insufficient as an aviation fuel as its energy density is very low compared to conventional fuels, and its freezing point is very high [5, 22].

Fischer-Tropsch Fuels (FT fuels)

FT fuels are liquid hydrocarbons that are produced by the catalytic conversion of syngas (mixture of CO and H_2), which in turn can be generated from a variety of biogenic feedstock via gasification. They are non-toxic, typically sulfur-free, and contain very few aromatics compared to diesel and gasoline, which results in lower emissions when used in jet engines. Fischer–Tropsch-synthesized kerosene with aromatics (FT-SPK/A) is a variation of the FT process in which a synthetic alternative aviation fuel containing aromatics is produced. The products in the FT process range from methane to long-chain hydrocarbons. The FT process is highly exothermic, meaning that the heat of reaction has to be quickly removed in order to avoid overheating and methane emissions. Like HEFA, FT fuels have low lubricity due to the absence of sulfur [5, 19].

Alcohol-to-Jet (AtJ)

The AtJ process turns alcohols into jet fuel through the following reactions: dehydration, oligomerization, hydrogenation, isomerization, and distillation. The involved alcohols can be produced through conventional processes involving the fermentation of sugars deriving from sugar- and starch-rich crops such as sugarcane, corn, and wheat, or through advanced routes from lignocellulosic feedstock (e.g., hydrolysis). Alcohols can also be generated via gas fermentation by utilizing the carbon and hydrogen content of gases such as industrial off-gases. AtJ routes are attractive as they can convert various types of alcohols (so far, ethanol and isobutanol have been approved) from a wide range of sources into jet fuel as well as other hydrocarbons [5, 20].

Direct Sugars to Hydrocarbons/Synthesized Iso-Paraffins (DSHC/SIP)

Genetically modified microorganisms (such as algae, bacteria, or yeast) can be used to convert sugar into hydrocarbons or lipids. Currently, biological routes almost exclusively use conventional sugar feedstock, although cellulosic sugars are being tested as well. The complexity and low efficiency of converting lignocellulosic sugars into fuels through DSHC translates into high feedstock cost and high energy consump-tion, which makes DSHC the most expensive alternative fuel route [5].

Others

The latest additions among the approved technologies (pathways) for SAF production are catalytic hydrothermolysis jet (CHJ) and hydroprocessed hydrocarbons (HC-HEFA). In the CHJ process (also called hydrothermal liquefaction), clean free fatty acid (FFA) oil from the processing of waste/energy oils is combined with the preheated feed water and then passed to the hydrothermal reactor. There, under high temperature and pressure conditions, a single phase is formed consisting of FFA and supercritical water wherein the FFAs are cracked, isomerized, and cyclized into paraffin, isoparaffin, cycloparaffin, and aromatic compounds. The HC-HEFA pathway refers to the hydroprocessing of bio-derived hydrocarbons (unlike the fatty acids or fatty acid esters found in HEFA production) that come from oils found in a specific alga (i.e., Botryococcus braunii). Other also possible pathways for bio-jet fuel production are under various stages of the ASTM evaluation process. A typical example is synthetic kerosene via aqueous phase reforming (APR-SK) [5, 28].

So far, only specific SAFs have secured ASTM certification for commercial use (via blending). SAFs are met as blending components in mixtures with conventional aviation fuels rather than 100% bio-based compounds. Because the penetration of SAFs in the market is still limited and actually HEFA-driven, SAF can be blended at up to 50% with traditional jet fuel and all quality tests are completed as per a traditional jet fuel. However, along with the timely scale-up for the other certified jet fuel pathways, the safety research should be extended to evaluate the miscibility of fuels containing different synthetic compounds as well. The availability of a larger number of alternative certified blends would make possible their simultaneous presence in a fuel tank or aircraft, and in that case, even the slightest alteration in fuel quality should have been anticipated [29]. The SAF technology certification timeline is illustrated in Figure 2.

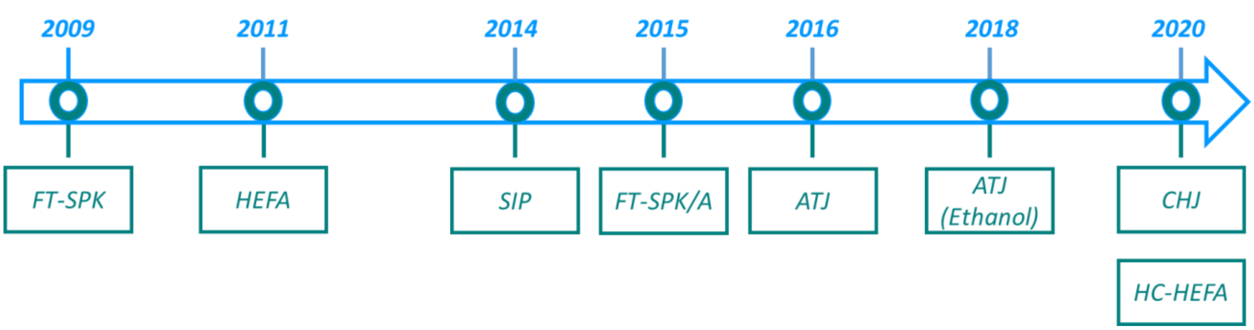


Figure 2. SAF technology certification timeline.

1.2.1.2 Electrofuels (e-fuels)

Electrofuels or e-fuels are an emerging class of carbon-neutral drop-in replacement fuels that are made by storing electrical energy from renewable sources in the chemical bonds of liquid or gas fuels. E-fuels result from the combination of 'green or e-hydrogen', produced by electrolysis of water with renewable electricity, and CO_2, which can be obtained from various sources including biomass combustion, industrial processes (e.g., flue gases from fossil oil combustion), biogenic CO_2, and CO_2 captured directly from the air. E-fuel production routes consist of e-hydrogen reacting with captured CO_2, followed by different conversion routes according to the final desired e-fuel such as the methanization route for e-methane; methanol synthesis for e-methanol, e-DME, e-OME; or the reverse water–gas shift (RWGS) reaction to produce syngas + Fischer–Tropsch synthesis to produce e-liquid hydrocarbons, such as e-gasoline, e-diesel, or e-jet. E-jet production usually refers to the methanol route (e-methanol upgrade to jet) or the FT route (RWGS + Fischer–Tropsch) [5, 6].

1.2.2 Hydrogen

The use of hydrogen in aviation, both as a source of propulsion power and as onboard power, has the potential to diminish noise pollution and GHG emissions and improve efficiency, as long as hydrogen is produced from renewable energy sources. Following thermal and biochemical methods, biohydrogen can be produced from a variety of biomass resources. It can be used either as liquid fuel for turboengines, or in fuel cells (FCs). In the first case, because of hydrogen's low volumetric energy density, major aircraft changes are required in order to accommodate the cryogenic tanks to store liquid hydrogen (LH_2). In addition, storing liquid hydrogen entails risks, as it burns in low concentrations upon mixing with air, and it needs a constant low temperature in order to be kept in the liquid phase. The additional weight of these tanks means extra energy consumption in comparison to kerosene aircrafts. As for the FCs, they can be used to power onboard electrical equipment or an electric propulsion system. They could be used in parallel with or in place of auxiliary power units (APUs), which consist of a small gas turbine supplying power when the aircraft is stationary or while cruising (as backup) [5].

1.2.3 Electrification (Hybrid or Full-Electric Aircrafts)

Many auxiliary aviation systems are being gradually electrified, because of the relatively lightweight and improved efficiency compared to mechanical systems. In addition, electric propulsion is being investigated given that it can come up with many benefits, such as noise reduction and emission savings. Electric aircrafts are divided into hybrid and full electric. Hybrid aircrafts have an electric motor with a battery and a turbofan (in series or parallel), thereby allowing for the downsizing of jet engines and increased fuel economy. Full-electric aircrafts could lead to zero onboard emissions and noise reduction. However, electric aircrafts face two severe challenges: the low energy density of batteries and the limitations on the distance traveled. Even the most promising batteries have an energy density far short of kerosene, while issues such as battery charging and infrastructure need a considerable amount of consideration [5].

1.2.4 Market Overview and Technology Readiness Level (TRL)

An overview of the current alternative fuel routes for the aviation sector, as described above, is presented in Figure 3.

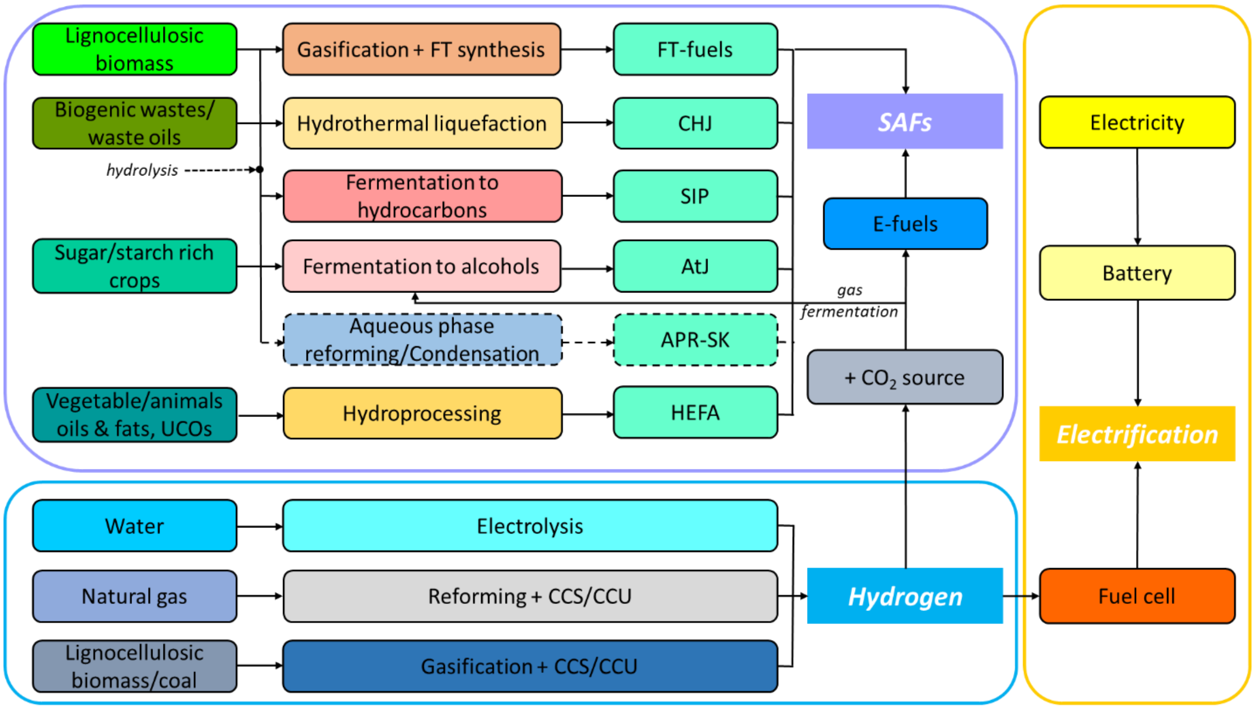


Figure 3. Overview of alternative fuel routes for the aviation sector.

Concerning the technological maturity of the current tendencies in aviation, each route has seen different growth. Starting with SAFs, while HEFA is the only alternative fuel in commercial use, the FT and AtJ market developments are also particularly intense.

The HEFA technology is currently the most mature, with HEFA fuels being the only alternative already used commercially (TRL 9). HEFA-jet is produced on a batch basis by several commercial-scale facilities worldwide [30]. It can be blended up to 50% with conventional fuel, but flight trials have recently been performed with 100% HEFA. In particular, aviation leaders such as Airbus, Rolls Royce, and the German Aerospace Center (DLR) launched the first 100% SAF commercial passenger jet flight with the HEFA-fuel provided by Neste [31]. Neste reaches an annual capacity of 1 million tons of SAF and production will increase to 2.2 million tons annually by the end of 2026. Neste's SAF is available at many major airports, including San Francisco International Airport (SFO), Heathrow Airport (LHR), and Frankfurt Airport (FRA) and is currently being used by many leading commercial airlines including KLM, Lufthansa, Delta, and American Airlines [32]. There are also synergies with leading fuel distributors that provide Neste's SAF to the market [33, 34].

As for the Fischer–Tropsch fuels, the bio-based gasification with FT synthesis is now just approaching commercialization (TRL 7-8), while the jet fuel produced through the FT route has been certified and can be blended up to 50% with fossil kerosene. The collaboration between British Airways and Velocys [35] aims to establish the first commercial Fischer-Tropsch BtL plant in the UK. Other notable commercial plants that are based on FT liquid production using sustainable feedstock are found in the USA (i.e., Red Rock Biofuels, Sierra Biofuels) [36].

Alcohol-to-jet fuels have been certified by ASTM (i.e., from ethanol and isobutanol) and can be blended up to 50%. This is another route that is approaching commercialization (TRL 7-8) [5]. In 2018, Virgin Atlantic completed the first commercial flight with AtJ fuel produced by Lanzatech [37]. Lanzatech is also the technology provider of the project FLITE that targets the installation of Europe's first of its kind AtJ production plant at pre-commercial scale. In 2012 and 2014, both the US Air Force and the US Navy used bio-jet fuel produced by the AtJ pathway to conduct the first tests [38].

Lanzatech, via a spin-off called LanzaJet, aims to be amongst the leaders in the emerging SAF market. LanzaJet AtJ technology can process any source of sustainable ethanol, including ethanol produced from municipal solid waste, agricultural residues, industrial off-gases, and biomass. The recent establishment of the world's first ethanol to SAF (AtJ) commercial production facility by LanzaJet in Soperton (Georgia, USA) [39] is a significant step towards the engagement of other paths besides HEFA for the commercial uptake of SAFs. British Airways will purchase SAF from LanzaJet's US plant in Georgia to power a number of the airline's flights. The deal also involves LanzaJet conducting early-stage planning for a potential large-scale commercial SAF biorefinery in the UK [40]. Another key player in the AtJ pathway is the Colorado renewable fuels producer Gevo. The Oneworld Alliance members will use Gevo's SAF for operations in California including San Diego, San Francisco, San Jose, and Los Angeles International airports. Delivery of the fuel is expected to commence in 2027 for a five-year term [41].

Regarding SIP, there are two different production routes. The first, using conventional sugar feedstock, is at the pre-commercial level (TRL 7), while the second, based on cellulosic feedstock, is still at the prototype level (TRL 5). The certified route includes sugar fermentation to farnesene, which, after hydroprocessing to farnesane, can be blended up to 10% with fossil kerosene. Lufthansa performed a commercial flight with a 10% farnesane blend from Amyris/Total in 2014 [42]. However, at present, potential SIP developers tend to target the chemical, pharmaceutical, food, and feed markets [5].

The technological maturity of e-fuels, or power-to-liquid (PtL) routes as they are also called, depends mostly on the maturity of the single components and the design configuration chosen. For example, routes where the CO_2 comes from concentrated sources, such as CO_2 waste streams from industrial processes, biogas upgrading, or beer brewing, are available for commercial use, while others such as CO_2 captured directly from the air remain at an earlier level (TRL 5-7) [5]. In general, PtL can be characterized by a relatively high technological maturity, since the majority of the individual process steps for kerosene synthesis via PtL are proven technologies with high TRLs. E-fuel routes are already being implemented in over 40 pilot and demonstration projects in Europe [43]. The barriers towards full commercialization are the amount of capital-intensive equipment to deploy the technology, the need for a substantial increase in renewable electricity production, and the rather low energy efficiency due to the inherent thermodynamic conversion losses that occur during e-fuel production. Technologies at the lowest level of development include electrolytic or electro-photocatalytic CO_2 conversion.

There are also commercial applications, such as Carbon Recycling International, which has produced over 4 kt of methanol per year since 2012 and aspires to commission the world’s first 110 kt/year recycled carbon methanol production plant after 2021 [44]. Energy supplier Uniper, Siemens Energy, and aircraft manufacturer Airbus are teaming up with chemical and energy company Sasol ecoFT to realize a commercial project to produce SAF for Germany named ‘Green Fuels Hamburg’. From 2026, the production facility in its initial configuration is projected to produce at least 10,000 t of PtL-SAF annually [45].

Table 1 summarizes the current technology status of SAFs and the latest highlights of each route.

Table 1. Current technology status of SAFs.

SAFs	Fuel	Technology Readiness Level (TRL)	Highlights
Biofuels	HEFA	9	Commercial passenger jet flight test with 100% HEFA fuel [31] Projection for annual production of 2.2 million tons by the end of 2026 (Neste) [32]
	FT-fuels	7-8	Projections for the first commercial Fischer–Tropsch BtL plant in the UK (Velocys) [35]
	AtJ	7-8	First commercial flight with AtJ fuel [37] Recent establishment of the world's first ethanol to SAF commercial production facility by LanzaJet [39] Oneworld Alliance members will utilize Gevo's SAF for operations in California from 2027, for a five year-term [41]
	DSHC/SIP	5-7 (depending on the sugar type)	Commercial flight with 10% farnesane blend from Amyris/Total (2014) [42]
E-fuels	e-jet, e-methanol *	5-8 (depending on the CO_2 source)	World's first 110 kt/year recycled carbon methanol production plant [44] 'Green Fuels Hamburg' [45]

*considering methanol upgrade to SAF.

Although hydrogen aviation is not a new concept, it will require significant research and development (R&D), investments, and accompanying regulations to ensure safe, economic H_2 aircrafts and infrastructure mastering the climate impact [46]. Airbus has performed a study called *'Cryoplane'* in order to examine the concept of hydrogen-fueled turbo-engines, which led to the adoption of a minimal-change approach to the wing configuration and engine design [47]. However, the main research activities of hydrogen involvement in aviation are related to the development of hydrogen fuel cell aircrafts, as it is a much lighter way to power the electric airplanes than batteries. Fuel cell systems are tested as auxiliary power units in commercial aircrafts, even though they have not been deployed in serial production. H_2 propulsion with fuel cell systems is also tested for urban air mobility (unmanned air vehicles and 'taxi'-drones) [46]. One such project is the HY4, a four-seater hydrogen fuel cell aircraft, developed by DLR, which completed its first flight in 2016 [48]. Moreover, ZeroAvia USA has launched the HyFlyer project, which aims to decarbonize medium-range, six-seater aircrafts by replacing the conventional propeller with a fuel cell system [49]. In general, the immediate priorities for hydrogen aviation R&D are the development of lightweight tank systems, reliable fuel distribution components, H_2

propulsion turbines with low NO_x emission and long lifetimes, and high-power fuel cell systems [50].

Since the 1960s, many aviation auxiliary systems have gradually been electrified, while electric propulsion systems have seen development as well. However, concerning the latter, they all remain at a demonstration level [51]. Regarding the development of hybrid electric aircrafts, Airbus, Rolls-Royce, and Siemens AG collaborated to launch the flight demonstrator E-Fan X [52]. In addition, Boeing and NASA have partnered up in order to develop a hybrid electric aircraft, named *'SUGAR Volt'*, with twin engines designed to burn fuel when the power demand is high (e.g., take-off) and to run on electricity while traveling [53]. Other industries have experimented with building full-electric aircrafts, mostly for civil non-commercial aviation and urban air-taxis, such as Kitty Hawk USA that developed a two-seater to be used by Air New Zealand as an air-taxi [54]. Moreover, Airbus has taken on an air-taxi project called Vahana [55], while Lilium GmbH and Eviation Aircraft Ltd. have produced full-electric, five- and nine-seater aircrafts, respectively, meant for regional commuting [56-58]. In order for electric aircrafts to be more commercially available, challenges such as the plane's mass reduction or the expansion of the batteries' energy density must be faced. As already mentioned, there is a limitation in the envisaged travel distance and in order to tackle this, electric aircrafts could be used for commercial regional flights or for pilot training. Such an aircraft is the Pipistrel Alpha Electro, which is a two-seater, full-electric aircraft with a range of about 160 km on a single charge [59]. Concerning the endeavor to increase the energy density of batteries, OXIS Energy has made significant progress in developing solid-state lithium–sulfur batteries, which have an increased density and can be used in electric buses, electric trucks, aircraft, and marine trials [60].

In general, it can be observed that SAFs are technologically in a favorable position towards the decarbonization of the aviation industry. Their compatibility with the extended current infrastructure is a great advantage that is able to offer instant industrial compliance with the international policies and regulations. Hydrogen aviation or electrification require deep and comprehensive changes in the industry and can only be considered as long-term alternatives.

1.3 Comparative Analysis and Insight

Taking into account the already-mentioned dominant position of SAFs in comparison with hydrogen aviation or electrification at least for the near future, a comparative analysis is performed among the most active SAF technologies on the market in terms of cost and environmental efficiency. The latest EU proposal, 'ReFuelEU Aviation' [6], identifies the key role of HEFA, Fischer–Tropsch, AtJ, and e-fuels in the emerging jet fuel market and therefore the focus of the present study is on these routes as well. The selected metrics for the comparison are: minimum jet fuel selling price (MJSP), expressed in EUR/L, for the techno-economic assessment, and GHG emissions, expressed in gCO2eq/MJ of produced fuel, for the environmental assessment.

Due to the intense activity in the SAF sector from the market, research, and legislative point of view, there is a wealth of data available in the literature concerning the main characteristics of each technology. The differences among the examined studies in terms of system boundaries, economic and life cycle assumptions, and processing steps sometimes made direct comparisons challenging. However, the large volume of collected data and the inclusion of studies only after 2015 allowed the extraction of solid conclusions and relevant future projections.

1.3.1 Techno-Economic Assessment (Literature Review)

Aiming to make the present review as up-to-date as possible, only techno-economic studies after 2015 have been taken into consideration. A wide collection of predictions regarding SAF MJSPs via multiple feedstocks has been carried out and is presented in Table 2.

Table 2. Techno-economic studies concerning estimated MJSP for HEFA, FT, AtJ, and e-jet routes.

Route	Year	Feedstock	MJSP
HEFA	2019	Vegetable oil	1.39 EUR/L [61]
	2016	Vegetable oil	1.84 EUR/L [62]
	2015	UCOs	1.03 EUR/L [63]
	2018	Jatropha oil Palm oil	1.60 EUR/L 0.81 EUR/L [64]
	2017	UCOs Tallow Soybean oil	0.94 EUR/L 1.10 EUR/L 1.23 EUR/L [65]
	2017	UCOs	1.29 EUR/L [66]
	2019	UCOs Soybean oil	0.88 EUR/L 1.09 EUR/L [67]
	2018	Jatropha oil Palm oil	1.44 EUR/L 1.04 EUR/L [68]

FT	2022	Municipal solid waste Agricultural residues	1.55 EUR/L 2.01 EUR/L [69]
	2022	Rice husk	2.22 EUR/L [70]
	2015	Wood chips	1.24 EUR/L [71]
	2016	Lignocellulose feedstock	1.97 EUR/L [62]
	2019	Municipal solid waste Agricultural residues	1.34 EUR/L 1.80 EUR/L [67]
	2022	Forestry residues	2.47 EUR/L [72]
	2022	Lignocellulose feedstock	2.22 EUR/L [73]
	2021	Municipal solid waste Agricultural residues Forestry residues	1.55 EUR/L 2.00 EUR/L 1.82 EUR/L [74]
	2022	Rice husk Pyrolysis bio-oil	2.22 EUR/L 2.34 EUR/L [75]
	2021	Corn stover	3.64 EUR/L [76]
AtJ	2016	Corn grain (1-G ethanol) Corn stover (2-G ethanol)	1.21 EUR/L 1.71 EUR/L [77]
	2022	Corn grain (1-G ethanol) Lignocellulose (2-G ethanol)	0.90 EUR/L 2.30 EUR/L [78]
	2016	Sugarcane (1-G ethanol) Lignocellulose (2-G ethanol) Lignocellulose (2-G ethanol)	2.02 EUR/L 1.98 EUR/L 2.75 EUR/L [62]
	2015	Forestry residues (2-G ethanol) Wheat straw (2-G ethanol)	1.98 EUR/L 2.72 EUR/L [63]
	2015	Woody biomass (2-G mixed alcohols)	1.28 EUR/L [71]
	2020	Sugarcane (1-G ethanol) Lignocellulose (2-G ethanol) Steel off-gases (2-G ethanol)	1.27 EUR/L 1.71 EUR/L 1.53 EUR/L [79]
E-jet	2022	CO_2 + H_2 (FT route/Methanol route)	2.10–2.30 EUR/L [80]
	2020	CO_2 + H_2 (FT route/Methanol route)	2.13 EUR/L [81]
	2021	CO_2 + H_2 (FT route)	2.77–4.89 EUR/L [82]
	2022	CO_2 + H_2 (FT route)	2.33–3.17 EUR/L [83]
	2021	CO_2 + H_2 (FT route/Methanol route)	2.25–5.00 EUR/L [84]
	2021	CO_2 + H_2 (FT route)	3.39 EUR/L [85]
	2019	CO_2 + H_2 (FT route/Methanol route)	2.94 EUR/L [86]
	2018	CO_2 + H_2 (Methanol route) CO_2 + H_2 (FT route)	2.45–3.28 EUR/L 2.60–3.37 EUR/L [87]

The HEFA process envisages the hydroprocessing of various oils to produce jet fuel as the primary product. Studies that involve first-generation (i.e., palm oil, soybean oil) as well as second-generation (i.e., UCOs) feedstock oils have been identified and an MJSP range of 0.81–1.84 EUR/L was obtained. UCO-driven cases appear to be the most cost-competitive HEFA options, with values below 1 EUR/L seeming possible. It was noticed that the feedstock cost accounts for more than 50% of the levelized production costs in every relative techno-economic study, leading to the conclusion that HEFA costs are driven mainly by the costs of the purchased oils.

The FT process is based on the promotion of residue-based biofuels (or so-called advanced biofuels). In particular, a wide variety of biogenic residues is appropriate feedstock for the gasification process that subsequently feeds the FT pathway with syngas. The gasification-driven FT process incurs high capital expenses (i.e., more than 50% of the production costs), but as already mentioned, is flexible regarding the type of feedstock used. This flexibility involving multiple feedstocks (e.g., forestry residues, agricultural residues, municipal solid waste) results in a relatively wide range of production costs, as also observed in the present review (1.24–3.64 EUR/L). The lowest obtained MJSPs refer to the involvement of municipal solid waste (MSW) as feedstock, since MSW is usually available free of charge and has the potential for negative costs [88, 89].

AtJ production costs depend mainly on ethanol costs. While first-generation (1-G) ethanol, which is obtained via the fermentation of sugar/starch crops (e.g., sugarcane, corn grain), is a merchandised and mature product, the conversion of lignocellulosic feedstock via hydrolysis and subsequent fermentation or the conversion of off-gases via gas fermentation to ethanol (2-G) is a more complex and usually more costly pathway. However, multiple AtJ pathways based on sustainable feedstock (2-G ethanol) also appear to result in affordable or at least competitive production costs. A group of techno-economic studies involving 1-G as well as 2-G ethanol was gathered and an MJSP range of 0.90–2.75 EUR/L was obtained for the AtJ route.

Concerning e-fuels, the main routes identified for e-jet production are the FT route and the methanol route. The FT route encompasses the RWGS or co-electrolysis followed by FT synthesis, while the methanol route involves methanol formation and subsequent upgrade to jet. A wide MJSP spectrum of 2.10–5.00 EUR/L was obtained from the identified power-to-liquid (PtL) studies. E-jet fuels exhibit the greatest uncertainty due to the wide range of potentially involved technologies including CO_2 capture from concentrated sources or direct air capture (DAC), solid oxide electrolyzer cell (SOEC) or RWGS, and, of course, the diverging prices of green electricity. Green hydrogen and its associated costs (i.e., hydrogen plant, green electricity) account for more than 70% of the levelized e-jet production costs in most of the studies.

Utilizing any available cost breakdown from the identified techno-economic studies, a general range was set regarding the CapEx (Capital Expenditures), OpEx (Operational Expenditures), and feedstock contributions to the production costs of each technology (Table 3). The dependence of HEFA technology on the feedstock cost has already been mentioned, while the feedstock flexibility of the FT and AtJ pathways leads to wide ranges with CapEx as the main cost indicator. Concerning e-jet, the securement of green hydrogen is clearly the most influential cost parameter and is driven by renewable electricity prices and electrolyzer hardware [90]. The average values from Table 3 are used for the cost allocation of each technology, presented in Figure 4.

Table 3. CaPeX, OpEx, and feedstock range of contribution to the production costs.

	HEFA *	FT	AtJ	E-Jet **
CapEx range (%)	22–40	54–81	45–75	5–20
OpEx range (%)	8–10	12–21	2–14	5–15
Feedstock range (%)	51–69	0–32	20–44	70–85

*hydrogen-associated costs are considered CapEx- and OpEx-related costs within HEFA process.
**hydrogen-associated costs are considered feedstock-related costs within e-jet process.

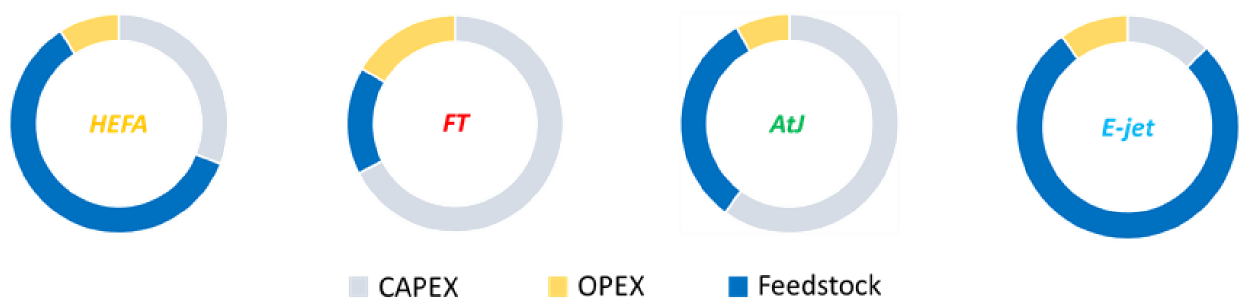


Figure 4. Average CapEx, OpEx, and feedstock contribution to the MJSP formation.

All the reported MJSPs of Table 2 have been imported into Figure 5 along with the generated trend lines of each route sourcing from the corresponding set of prices. Moreover, the global average price evolution of conventional jet fuel (Jet A-1) in recent years was added, as extracted from [91].

It is clear that HEFA-produced SAF is the most cost-competitive option and the only route so far that can consistently compete with conventional jet fuel prices. Moreover, the fact that the relevant literature (HEFA) after 2019 is sparse is another indicator that HEFA has already penetrated the market and can be considered the only state-of-the-art commercial SAF. The respective trend lines for the FT and AtJ routes lie well within the range of 1.50–2.00 EUR/L. As already mentioned, FT and AtJ are two technologies that have approached commercialization, subsequently causing intense research and market interest. The feedstock flexibility of these two routes results in potential deviations regarding the assessment of their exact production costs, but it is rather safe to claim that cost-effective feedstock (e.g., MSW, residues) can lead to cost-competitive FT and AtJ implementations. The ongoing technological advances and the inherent scale effect are expected to further reduce production costs and turn the FT and AtJ routes into viable choices. The e-jet generated trend line moves around 3 EUR/L and illustrates the already-mentioned current uncertainty that characterizes this kind of fuel due to the dynamic cost diversity of the potentially involved technologies. Almost every identified techno-economic study struggles to determine affordable e-jet production costs at present, but they all highlight the significant cost reduction potential in the future, driven mainly by lower-cost electrolyzers and scale effects.

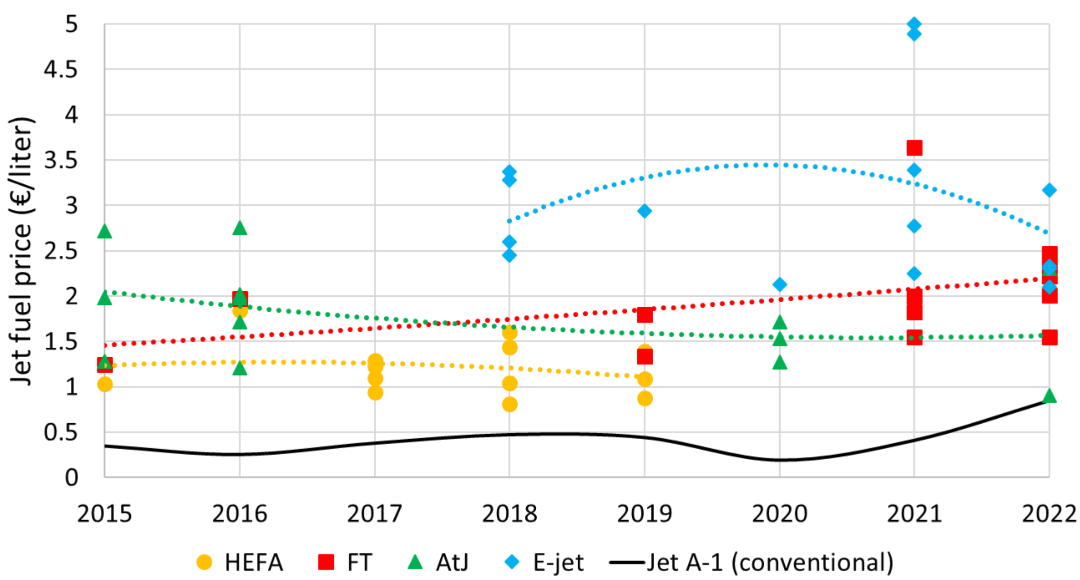


Figure 5. Available MJSP estimations for SAF and Jet A-1 global average price evolution in recent years.

In general, it can be safely posited that technological advances and favorable legislative frameworks have drastically assisted SAFs in terms of closing the gap with conventional jet fuel in terms of production costs. There is a sense that the envisaged intensification of carbon costs and blending mandates will eventually enable a break-even between SAF and fossil jet fuel. The latter is expected to be the decisive step for the direct unlocking of SAFs in the fuel market.

1.3.2 Environmental Assessment (Literature Review)

Although the techno-economic assessment of SAF technologies reveals that these pathways are yet to consistently compete with fossil jet fuel in financial terms, their potential environmental advantage over conventional fuels is more clear. Life cycle analysis (LCA) is crucial for the environmental assessment of these pathways, since it can quantify the GHG emissions to the environment of each technology, including all stages from feedstock production to end product use. The GHG emissions attributable to each technology are typically measured in grams of carbon dioxide equivalents per megajoule of the produced fuel (g CO_2eq/MJ).

Conventional jet fuel produced from petroleum resources has a carbon intensity within the range of 85–95 g CO_2eq/MJ. About 80% of the mentioned carbon intensity comes from the combustion of fossil fuel, while the remaining GHG emissions are attributed to the fuel extraction, the processing of the fuel in refineries, and its subsequent transportation. Given that the calculations of the GHG emissions of conventional jet fuel differ between the conducted studies, the International Civil Aviation Organization's (ICAO) policy for the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) has decided to use a baseline of 89 g CO_2eq/MJ [92].

HEFA jet fuel, as stated previously, is one of the most prominent alternatives to replace conventional jet fuel in the near future. At present, its price is the lowest compared to the other existing SAFs. However, as for its environmental analysis, the GHG emissions attributed to its use vary depending on the feedstock involved in its production. For example, HEFA jet fuel produced from waste fats, oils, and greases (FOGs) generally has significantly low life-cycle GHG emissions, given that this process avoids the GHG emissions attributed to crop production. On the other hand, the production of HEFA from vegetable oils typically has higher GHG emissions. It should be noted that in the HEFA conversion process, a large volume of the emissions comes from the production of the required hydrogen [92]. Thus, depending on the source of hydrogen or the source of electricity at the regional grid, the GHG emissions of the HEFA fuel can vary greatly. CO_2 emission savings from HEFA fuels are estimated to be around 25–85% of the corresponding conventional jet fuel emissions [93], forming an average of 10–66 g CO_2eq/MJ, which is in general accordance with the emission savings for HEFA reported in the recent dominant proposal 'ReFuelEU Aviation' [6].

Jet fuels produced through the gasification–FT pathway from agricultural residues, non-food energy crops, or solid waste generally achieve the lowest GHG emissions among the approved fuel technologies for SAFs. The CO_2 emission savings are estimated to be approximately 85–91% of the corresponding conventional jet fuel emissions, leading to an average of 5–16 g CO_2eq/MJ [93]. It should be noted that the utilization of MSW for FT fuels could lead to a wide range of emissions depending on their biogenic content. The conversion step is considered the most environmentally intense for the FT pathway [94].

AtJ pathways generally have higher GHG emissions than HEFA and FT fuels, mainly due to the energy- and GHG-intensive biochemical processes for the production of alcohols. Depending on the feedstock, a wide range of GHG emission savings can be found in the literature, varying from 26% to 73% of the petroleum jet baseline [6, 93]. For example, sugary crops (e.g., sugar beet, sugarcane) show a better emission mitigation potential compared with starch crops such as maize and cereals, since this type of feedstock is more efficient to grow and process. Jet fuel produced from lignocellulosic crops and residues also has a relatively low carbon footprint because of the low GHG emissions related to fertilizer use, feedstock cultivation, and collection [95]. Carbon-containing waste gases (e.g., steel mill off-gases) are also environmentally good candidates for AtJ, since no emissions linked to feedstock cultivation/collection are included, thus providing a high emission reduction. However, a large portion of the GHG emissions of these pathways is attributed to the electricity required for gas compression.

E-fuels can make a significant contribution to reducing GHG emissions in the aviation sector. Studies indicate that the overall direct GHG emissions of an e-fuel production pathway from renewable electricity and CO_2 are approximately 1 g CO_2eq/MJ of final fuel [96], delivering more than 95% emission savings related to the fossil jet reference. This estimation only accounts for transportation, distribution, and dispensing, since only renewable sources are involved in the production of the fuel. However, due to the large amount of renewable electricity that is required for the production of this type of fuel, LCA studies often include the emissions deriving from the construction of the production facilities and power stations. According to [97], the carbon footprint of the e-jet pathway via the FT route, including GHG emissions from asset construction, is estimated to be from 5 to 10 g CO_2eq/MJ of the final fuel when using electricity from offshore wind in Norway and a wind/PV hybrid power station in Germany, respectively. It can be conceived that the environmental performance of e-fuels is highly dependent on the source of electricity generation. Indicatively, if grid-average electricity were used for the production of e-fuels, the GHG emissions could exceed the fossil jet baseline (approx. 130 g CO_2eq/MJ) [92]. The use of renewable electricity is a clear prerequisite for the achievement of GHG reductions.

For sustainability reasons, according to the Renewable Energy Directive (RED), first-generation biofuels produced from edible energy crops, such as sugar, starch, and oil crops, should not be supported [6]. When the cultivation of crops for biofuels replaces traditional crops for food production, a change in how the land is used occurs, which can have dire environmental impacts. In order to meet the growing demand for aviation fuel, agricultural land is often expanded to places with high carbon stock, such as forests, peatland, and wetlands. This induced land-use change (ILUC) releases carbon from disturbed biomass and soil, causing further GHG emissions and raising concerns about the loss of biodiversity in these areas. Even though HEFA is the most technologically ready alternative to petroleum jet, its use is bound by environmental concerns related not only to high direct GHG emissions, but also to significant ILUC emissions. ATJ pathways can also release considerable amounts of ILUC emissions, especially when produced from food crops. In some cases, ILUC emissions can completely negate the GHG emission savings, surpassing even the baseline for conventional petroleum jet fuel [92, 94]. Land-use change can also be caused by some second-generation biofuels that are produced from energy crops, such as switchgrass, but with low GHG intensity. FT fuels are mostly produced from lignocellulosic crops or residues and wastes, thus leading to low or zero ILUC emissions. Negative ILUC emissions can also be generated if marginal areas are used for cultivation, causing an increase in carbon stock in the soil [98]. Under RED III, crop-based biofuels with significant ILUC emissions are capped at the 2019 level and will be phased-out by the year 2030. It should also be stated that the magnitude of the ILUC emissions depends greatly on the feedstock used, the economic model used for their calculation, and the modeler’s assumptions, which highlights the uncertainty in the assessment [99].

Except for the ILUC emissions associated with the crop-derived biofuels, there are also indirect emissions linked with the use of by-products, residues, and wastes as feedstock, as well as renewable electricity. In fact, many of these materials have valuable existing uses and their diversion from these uses can sometimes generate indirect emissions from the materials that will be used in their place. Some of these materials can be substituted by crops or fossil fuels resulting in higher GHG emissions. For instance, the displacement of FOGs, such as animal fats, corn oil, and palm fatty acid distillates, from their existing uses in other markets (e.g., oleochemicals, heat and power, animal feed) would be likely to cause high indirect emissions when replaced by virgin vegetable oils or fossil fuels. Generally, lignocellulosic feedstock, such as agricultural and forestry residues, if collected in quantities that do not affect soil quality, can be diverted with less indirect emissions compared with FOGs, since fewer markets exist for these materials. Carbon-containing industrial flue gases, such as steel mill off-gases, also entail some indirect emission risks since many industries use them for onsite energy generation. Therefore, substituting these gases with other energy sources may lead to higher GHG emissions. Electrofuels may also cause displacement effects if renewable electricity is diverted from existing uses and replaced by a marginal source of electricity. For this reason, it is important to ensure that the renewable electricity used for e-fuel production is both new and additional. On the other hand, when MSW from landfills are used as feedstock, negative displacement emissions may occur due to the avoidance of methane emissions from anaerobic digestion at some landfills [92].

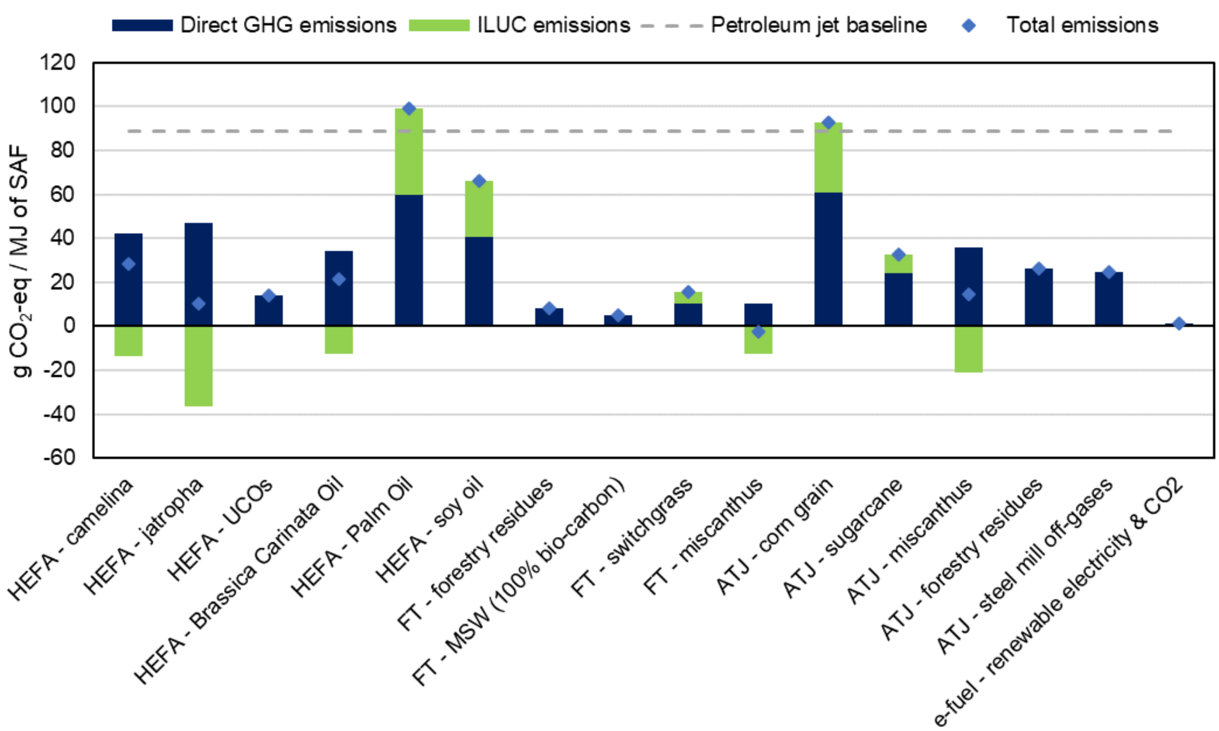


Figure 6. Well-to-Wing GHG emissions of various SAF pathways related to petroleum jet baseline.

Figure 6 illustrates the Well-to-Wing emissions (i.e., emissions over the entire life cycle of fuels; from production to combustion) of the SAF production pathways from various feedstock types. The data for the direct emissions were extracted from [79, 87, 92, 93]. For the ILUC emissions, values estimated by ICAO were used [93]. Displacement emissions were not included since they are extremely sensitive to assumptions about the uses from which the materials are diverted, and therefore difficult to estimate.

1.3.3 Future Projections

Forecasting regarding a newly emerging market, such as SAFs, that is not yet fully formed is quite a challenging task. However, the key characteristics of each technology allow for some cautious predictions regarding their development and their margins of competitiveness [100, 101]. Therefore, this section deals with the future projections of the HEFA, FT, AtJ, and e-jet pathways based on the available forecasting studies. At this point, it should be noted that as research on the SAF technologies progresses and more data are collected over the years, strategies such as big data analytics (BDA) could be useful to improve the performance of these technologies and accelerate their scale-up [102].

HEFA jet fuel is the most cost-competitive option and is expected to remain the most efficient pathway, at least through to 2030. Nevertheless, its dependence on feedstock costs is an inhibiting factor towards a decisive reduction in the overall production costs since HEFA feedstock (i.e., oils) is a factor with low cost-reduction potential. The limited supply of feedstock and lack of cultivation areas turn HEFA into a feedstock-constrained pathway. Indicatively, HEFA facilities use the majority of their capacities to produce biodiesel. A rather stiff selling price is expected for HEFA jet fuel in the coming years due to the absence of any obvious aspect for cost improvement. Hydrogen (green) seems to be the only variable from the HEFA production route with remarkable cost-reduction potential and is by no means sufficient to drastically affect the production costs [103-105].

FT and AtJ technologies involve intense capital expenses and at first glance, their cost-reduction potential seems rather moderate. However, on the one hand, the feedstock constraints that do not let HEFA meet the accelerated SAF scale-up requirements on its own, and on the other hand, the high feedstock flexibility of the AtJ and FT routes, are expected to speed up the commercial establishment and subsequently the beneficial scale effect of these technologies. While almost all

SAF production is currently sourced from the HEFA pathway and waste FOGs are expected to constitute the largest source of feedstock until 2030, there are claims that the next two decades will be dominated by technologies handling advanced feedstock (e.g., MSW, biogenic residues) such as FT and AtJ. Agricultural residues constitute the largest quantities of the available feedstock, but their exploitation will be delayed due to the time lag associated with the commissioning of such new large-scale biorefineries. Of course, the inhibiting factors for the extended reduction of production costs, such as the high costs related to gasification for FT or lignocellulosic ethanol for AtJ, will continue to question the financial competitiveness of these routes. Already-announced investments in new AtJ and FT facilities raise confidence that SAF's competitiveness from these routes can be significantly increased [106-109].

PtL costs are almost entirely driven by the costs of purchased hydrogen. Therefore, the great cost-reduction potential of hydrogen, primarily due to remarkably decreased renewable electricity prices and secondarily due to electrolyzer hardware cost reductions, is able to decisively upgrade the future competitiveness of e-jet pathways. Their undisputed beneficial environmental impact along with their independence from bioenergy availability are expected to rapidly reduce their current, admittedly non-affordable, production costs. The pace of cost reductions will depend on the speed of the global shift to sustainable energy, but considering that the price of renewable electricity continues to decline, e-fuel pathways are set to start producing significant volumes after 2035. Of course, e-fuels are unlikely to achieve steady establishment in the SAF market without dedicated policy support, such as a sub-target within the overall blending mandate [22, 103, 107, 110].

Within the present review, the average MJSPs for each technology (HEFA, FT, AtJ, and e-jet) were calculated based on the reported values in Table 2 and were assumed to be representative of the financial status of each pathway at the beginning of the current decade (2020). Thus, 1.21 EUR/L for HEFA, 1.91 EUR/L for FT, 1.81 EUR/L for AtJ, and 2.99 EUR/L for e-jet are considered the current average prices, while the applied future projections were mainly based on [22, 103] (Figure 7). The low cost-reduction potential of HEFA reflects on the rather optimistic forecast for a price reduction of only up to 23% over a 30-year period. FT technology's heavy dependence on CapEx due to gasification and usually intense gas-cleaning requirements does not leave much room for bold predictions regarding drastic improvement of production costs (25%

price reduction forecast over a 30-year period), but extended feedstock flexibility combined with great capabilities of GHG reduction promise competitiveness. The even greater feedstock flexibility, also involving industrial off-gases, for the AtJ routes allows forecasts for a price reduction of up to 33% over a 30-year period. The most optimistic forecasts concern e-fuels (up to a 67% price reduction over a 30-year period), directly linked to the equally optimistic forecasts for green electricity costs that include 50% reductions by the end of the current decade. Moreover, the expected beneficial, but difficult to accurately predict, scale effect for FT, AtJ, and e-fuels should be noted since these technologies have not yet reached their full-scale potential. On the other hand, the technology risk is low for the mature HEFA technology, but higher for the other pathways. In general, there are a number of uncertainties when forecasting for the next 10 years, let alone 30 or more. Producing SAF will almost certainly continue to be more expensive than refining fossil jet fuel, but the necessity for SAFs for the immediate environmental compliance of the aviation sector indicates a continuous concerted effort to ensure they become as competitive as possible.

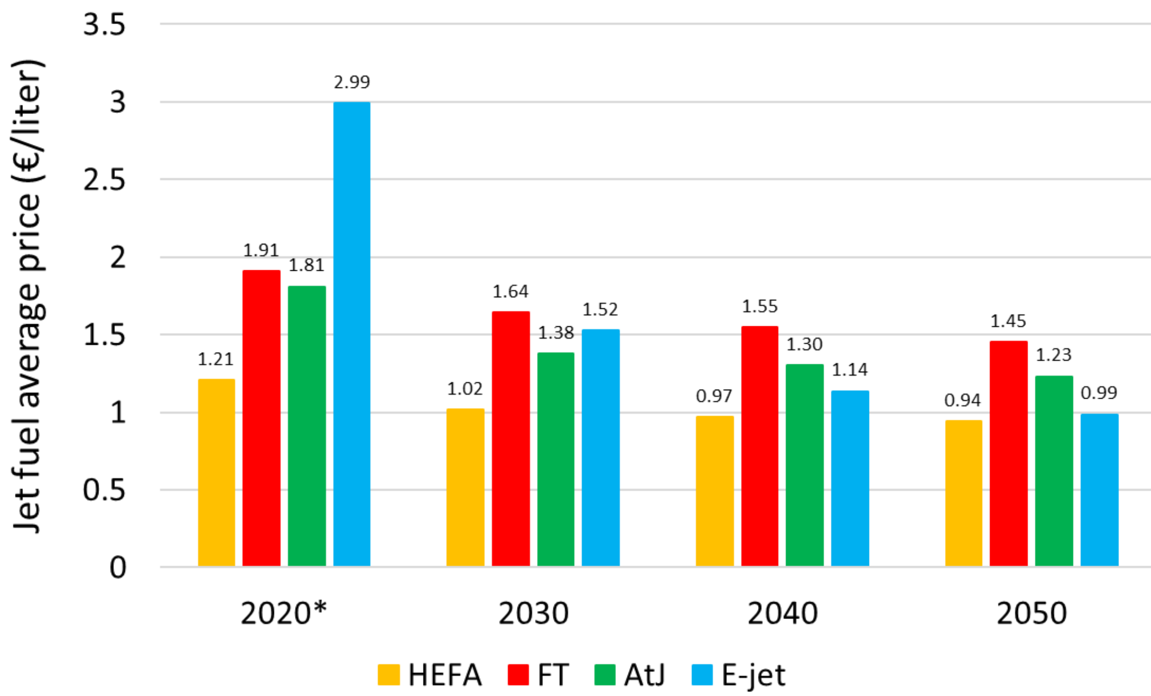


Figure 7. Future projections for the average selling price of HEFA, FT, AtJ, and e-jet pathways (the average selling price for each pathway, extracted from Table 2, was assumed representative for 2020).

1.4 Current Regulatory Framework and Policy Approaches for Sustainable Aviation Transport

1.4.1 Background

In December 1997, the Kyoto Protocol [111] was signed and came into force later in 2005, with a commitment to reduce GHG emissions. According to the Kyoto Protocol, CO_2 was the only GHG emission considered for reduction, requiring signatory countries to take action to limit or reduce international aviation CO_2 emissions. In 2009, the Renewable Energy Directive (RED I), also known as Directive 2009/28/EC, was signed, which was a European Union Directive mandating specific levels of the use of renewable energy. The directive required that 20% of the total energy consumption in the EU must derive from renewable energy sources. Besides this, it also stated that the transport sector must be supplied with 10% of renewable energy by 2020, either from transport biofuels or from the electrification of the sector, although there was no specific target for aviation. In 2015, the Paris Agreement was signed, a pledge of the world's governments to further reduce emissions in a response to climate change, which set a target to 'hold the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels' [112].

To ensure that the EU will meet its emissions reduction commitments under the Paris Agreement and keep the global leadership in renewables, the European Commission released a proposal for a revised Renewable Energy Directive (RED II) in 2016, which finally entered into force in December 2018. This recast, covering the period from 2021 to 2030, raised the overall share of energy from renewable sources to 32% by 2030 [113]. For the first time, the RED II established a multiplier factor for renewable aviation fuels to incentivize their uptake. The use of SAF has also been encouraged by the implementation of two market-based measures, namely, the EU ETS for aviation (2012) and CORSIA (2021) at the EU and international level, respectively. However, these policy actions were rather insufficient to drive SAF into the aviation market.

On 14 July 2021, the European Commission published the 'Fit for 55' package, which is a set of policy proposals to deliver the EU's ambition of reducing net GHG emissions by at least 55% by 2030 and achieving climate neutrality by 2050. Among these proposals, an amendment of the RED II directive, as well as a dedicated regulation for sustainable aviation transport, namely, 'ReFuelEU Aviation' [6], have been included. The latter aims to provide the aviation industry with clear and consistent measures that will strengthen SAF production and use, and will contribute significantly to mitigating the carbon intensity of the air transport sector.

1.4.2 RED III: Current EU Energy Policy Framework

The key element of the current active RED (RED III) is the adoption of the collective target for at least 42.5% renewable energy consumption across all sectors in Europe by 2030. With regard to the transport sector, RED II had set the minimum share of renewable road and rail transport fuels to 14% by 2030. The RED III expands the transport energy to include aviation and maritime, while also changing the renewable energy target from 14% to 29% by 2030 or a reduction in GHG intensity by 14.5% within the same timeframe. Concerning the aviation sector, a multiplier of 1.2 for advanced biofuels and 1.5 for e-fuels supplied to the aviation industry was introduced in order to stimulate the deployment of SAFs in the EU [114].

A combined 5.5% share of advanced biofuels and e-fuels is aspired in final consumption of all energy supplied to transport, with a sub-target of 1% for e-fuels. Transport fuels produced from used cooking oil or animal fats are capped at 1.7% to cope with the limited availability of feedstock. A cap for food and feed crop-based biofuels (1G) is also imposed in each member state, freezing their consumption at the 2020 national level (plus 1%), without exceeding 7%. The consumption of high-ILUC-risk biofuels, such as palm oil-derived fuels, should be gradually phased out to 0% in 2030, while biofuels produced from low-ILUC-risk feedstock are exempted from this restriction [115, 116].

1.4.3 Other Existing International and EU Policy Actions for Sustainable Aviation

The use of SAF is also encouraged by other global and EU policy actions. For example, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is a market-based emission mitigation mechanism for the global airline industry that was developed by the International Civil Aviation Organisation (ICAO) and started in 2021. This plan focuses on the concept of compensating emissions that are above a certain threshold by financing a reduction in emissions elsewhere or by using SAF. CORSIA ran through a voluntary pilot phase (2021-2023), which will be followed by a voluntary first phase (2024-2026) and a mandatory second phase (2027-2035). CORSIA intends to offset over 80% of air traffic growth after 2020 [117]. The compatibility of the RED III sustainability framework with that of CORSIA has to be considered in order to avoid overlaps and uncertainty for producers and investors.

At the EU level, there is the EU Emissions Trading System (ETS), launched in 2005, which constitutes the first and largest international emissions trading system. The EU ETS is based on the ‘cap and trade’ principle, meaning that an upper limit is placed on the GHG emissions of certain sectors covered by this system. This limit is gradually being reduced over the years, so that the total number of GHGs emitted in the atmosphere is slowly decreased. Every year, companies must surrender as many allowances as their annual emissions, otherwise they will be subject to heavy fines. Emission allowances are given for free or auctioned off to companies, which can later be traded between one another if needed. Despite the ETS being set up in 2005, aviation CO_2 emissions have only been covered by it since 2012. The EU ETS provides economic incentives to airlines if SAF is used for their flights, thereby allowing them to qualify as ‘zero-emissions’. More specifically, airlines do not have to surrender any emission allowances for CO_2 when SAFs are used to substitute for conventional jet fuel. This practice could potentially boost the uptake of SAFs in flights if the profit from having to buy fewer allowances, or selling the extra ones, equals or even exceeds the additional cost of the SAFs [118].

1.4.4 ReFuelEU Aviation Initiative

The current regulatory framework on renewable energy as well as the EU ETS and CORSIA policy actions may have not been sufficient for producers and suppliers to push large SAF volumes to the aviation sector [119]. Thus, the Commission released the ‘ReFuelEU Aviation’ initiative, as part of the ‘Fit for 55’ package, to secure the long-term growth of sustainable air transport [6]. With ‘ReFuelEU Aviation’, it will be the first time that the EU has mandated SAF blending at European airports. Fuel suppliers will be obliged to ensure that all aviation fuel supplied to aircraft operators includes a minimum share of SAF with a submandate referring to e-fuels. According to the regulation proposed by the Commission, and approved by the Council of the European Union and the European Parliament, these mandates will start with a minimum volume of SAF at 2% in 2025, increasing in five-year intervals to eventually achieve a minimum volume of 70% in 2050, of which 35% will consist of electrofuels (Figure 8). Feed and food crop-based fuels are not eligible for these mandates. A transitional period of 5 years (until the end of 2029) is envisaged, during which fuel suppliers may supply the minimum share of SAF as an average over all the aviation fuel they supplied across EU airports [120].

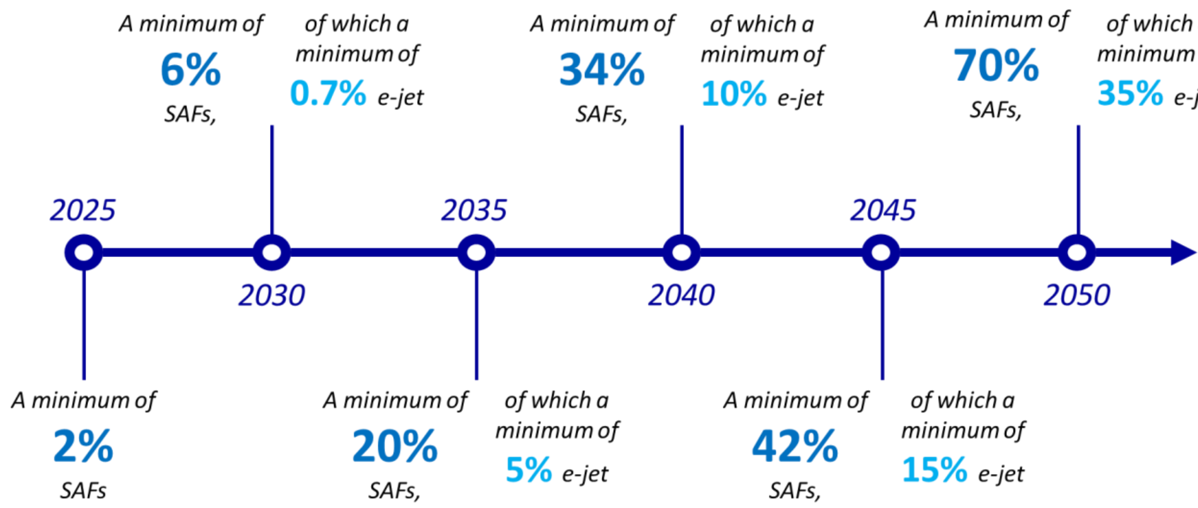


Figure 8. Proposed timeline of SAF mandates as reported in ReFuelEU Aviation.

The proposal also aims to battle fuel tankering practices and ensure a level playing field for sustainable air transport. 'Fuel tankering' occurs when aircraft operators uplift more jet fuel than necessary at a given airport where prices are low, avoiding partial or full refueling at destinations with more expensive fuel. Excessive amounts of fuel lead to increased fuel consumption due to the extra weight on board, which, in turn, leads to additional emissions. Except for the detrimental environmental effects, fuel tankering undermines fair competition between airlines or airports. To prevent these practices and ensure that the SAF mandates will not harm the EU aviation market because of the expected higher fuel costs, ReFuelEU proposes a clear and uniform obligation for all airlines (EU and non-EU) departing from EU airports to uplift jet fuel prior to departure. The uplifted amount of jet fuel will be limited to the amount required for the safe operation of the planned flight. According to the draft regulation, the yearly quantity of fuel uplifted by aircraft operators at a given EU airport must be at least 90% of the yearly aviation fuel required. Reporting obligations are also set for both aircraft operators and fuel suppliers, as well as noncompliance financial penalties [121].

The main objective of 'ReFuelEU Aviation' initiative is to increase both demand and supply of SAF while ensuring a level playing field across the EU air transport market. Relying on the sustainability framework of RED III and being in alignment with the EU ETS and CORSIA policy actions, ReFuelEU will hopefully manage to drive the EU to the decarbonization of the aviation sector.

1.5 Conclusions

This review presents and evaluates the available pathways towards the decarbonization of the aviation industry. The performed analysis is based on the admission that SAFs (drop-in biofuels and e-fuels) are the only available option for instant compliance of the aviation industry with the international policies and regulations. Hydrogen aviation or electrification require deep and comprehensive changes in the industry and can only be considered long-term alternatives. The already-announced investments and agreements indicate that SAFs are a recognized and well-accepted necessity, and the challenge now is to scale up their production and gradually penetrate the market with a lasting and beneficial impact.

HEFA, FT, AtJ, and e-jet are the identified leading technologies towards the targeted fuel transition of the aviation sector. While HEFA is currently the only market-proven pathway and the most cost-competitive option, its feedstock constraints and the questionable environmental contribution (GHG emissions reduction) of some of these fuels raise skepticism. Indicatively, some of the HEFA feedstocks that offer the greatest environmental benefit and financial competitiveness, such as UCOs, are also among the most limited. In any case, HEFA jet fuel is expected to remain the most efficient pathway, at least through to 2030. Fuels derived from biogenic wastes and residues (lignocellulosic feedstock) via the FT and AtJ routes usually provide solid reductions of GHG emissions, but the corresponding conversion processes seem quite costly. However, it is foreseen that the wide feedstock flexibility of these technologies and the related technological advances will limit their production costs and will keep pace with future SAF demand that is expected to arise due to HEFA constraints. Finally, e-jet pathways currently struggle to present affordable production costs, but their undisputed environmental benefits combined with the projections for rapid reductions in hydrogen and green electricity prices form a well-oriented and promising future.

The involvement and accelerated scale-up of multiple SAF pathways is anticipated. Supportive public policies are necessary in this regard. The ‘ReFuelEU Aviation’ initiative, signed by the European Council in October 2023, is the first policy proposal that speaks clearly for mandatory SAF blending at European airports and shows an intention for decisive institutional support of SAFs. While neither policy on its own is the solution to scaling SAF production, the correct and concerted combination of incentives could provide a strong long-term signal for a smooth transition away from fossil jet fuel. Stakeholders across the aviation sector agree that SAFs are a critical component in the industry's decarbonization efforts. An effective harmonized system should be designed in order to achieve not only the commercial uptake of SAFs, but also deliver economic benefits to the industry and beyond.

SAFs represent a reasonable and valuable perspective that requires a framework of sustainable establishment from the technical, financial, environmental, and sociopolitical points of view. The successful and timely formation of this framework will rely on the agility and commitment of all of the involved stakeholders within the aviation industry to ensure the safe and effective fuel transition of the sector.

Chapter 2

Identification of stakeholders and market needs

2.1 Introduction

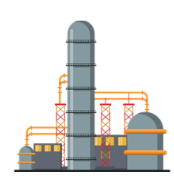
This Chapter is dedicated to the identification of the key stakeholders towards the deployment of advanced biofuel technologies in the aviation/maritime sectors. Stakeholders can be described as any party or field that can either affect or be affected by the widespread production/use of advanced biofuels. Then, relevant questionnaires are developed in order to define their requirements and specifications. The analysis that is performed is a rather questionnaire-oriented analysis. Literature data are utilized for the enhancement of the analysis, but the primary focus of this Chapter is the interaction with the industry and the market itself. The understanding of the needs and expectations from main stakeholders can offer a different and more trustworthy perspective on how to set and review some objectives of the present dissertation. The aim is to secure a reliable data gathering that can offer clear guidance, set implementation priorities and maximize the impact of the survey.

2.2 Identification of Target Groups as Stakeholders of the survey

Aiming to form an appropriate and solid stakeholders body, the following five (5) Target Groups have been selected:

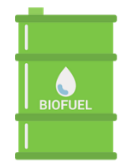
Feedstock suppliers:

One of the major issues associated with the use of any biomass resources is its supply chain management. Regional and seasonal availability of biomass as well as storage issues are key parameters that set up the economic efficiency and environmental sustainability. The feedstock suppliers have been identified as the Target Group, which is mainly responsible to plug in the gap between the biomass availability and its demand. The feedstock flexibility is a critical aspect towards the applicability and sustainability of full-scale Biomass-to-Liquid (BtL) scenarios.



Refineries:

The co-processing (conventional/renewable fuels parallel processing) possibility involving the existing infrastructure, the technical characteristics of the most common aviation and maritime fuels, the potential blending challenges as well as the current legal framework governing the operation of the refineries are aspects that should surely be taken into consideration when attempting to come up with a new way of producing sustainable transport fuels. The refining industry, due to its existing distribution system, infrastructure, and expertise has a significant and enduring role to play in the renewable liquid fuels of the future. The claims that the next two decades will be dominated by technologies handling advanced feedstock are based on the fact that the refineries can act as hubs of low-carbon oils.



Fuel traders:

This Target Group acts as an intermediary between the refineries and the fuel market. In other words, the interest of fuel traders lies in a set of specifications that the produced fuel should surely meet in order to reach the market. This set of specifications might be related to technical parameters (viscosity, density, flash point, etc.), storage facilities and properties, or possibly fuel cleaning requirements and costs. Another parameter that has been already mentioned and will surely play a key role in facilitating the introduction of the candidate fuel into the market is its blending ability, meaning its compatibility with the existing fuels and infrastructure in terms of operation and storage.

Final end-users:

They are the targeted final recipient of the produced fuel. They are aviation airlines and airports (or ship owners and ports for the maritime sector). It is maybe the most vulnerable Target Group, since every aspect of the selected fuel must comply with the user demands concerning prices, performance, supply chain, storage ability and existing infrastructure compatibility. As for the latter, some end-users could possibly be willing to proceed to partial retrofitting of their infrastructure either because a new fuel could offer a more favorable balance among the other mentioned demands or because of obligations deriving from relevant policies.

Policy makers:

This Target Group affects each of the previous mentioned stakeholders as it contains the strategy that is followed to reinforce biofuel production and establish guidelines for the sustainable development of the field. Biomass distribution, processing, fuel blending percentages are all indicative matters that are subject to legislative obligations/prohibitions and may also vary from country to country. The current and forthcoming transportation fuel policies should be under constant monitoring from potential producers and investors. The existence of an enabling policy framework with clear legislative signals that will create market incentives and trigger the grow-up of sustainable fuel production technologies is undeniably of massive importance.

2.3 Survey development

Five (5) questionnaires were developed, one for each Target Group, and have been shared to appropriate representatives of each group. Of course, confidentiality issues were respected, as and when requested.

2.3.1 Questionnaire of Feedstock suppliers

A – Feedstock suppliers **Considering the type of your organization, please provide the requested information concerning your product/s distribution and characteristics:**
1. In which type of activity would you classify your business? ○ Farmer ○ Transporter ○ Wood supply industry ○ Distributor, wholesaler ○ Other: ………………………….
2. What type of product do you distribute or you could be able to distribute? ○ Cereal bales ○ Forestry products ○ Pruning bales ○ Pruning chips ○ Pellets ○ Other: ………………………….

3. What type of service do you provide for this product?

- ○ Transport to end user
- ○ Transport and storage
- ○ Commercialization
- ○ Other: ……………………………

4. Which is the estimated quantity of this product that you are capable of distributing annually (t/year)?

5. Up to which point the seasonality affects your productivity and how you handle this issue?

6. Could you give an estimation of the average energy content of your distributed products (MJ/t)?

7. Which is according to your opinion the most important barrier that prevents biomass feedstock price decrease?

- ○ cultivation costs
- ○ harvesting costs
- ○ logistics costs
- ○ labor costs
- ○ biomass pre-treatment (i.e. drying, pelletizing, torrefaction) investment cost
- ○ Other: ……………………………

Any other issue/comments:

2.3.2 Questionnaire of Refineries

B – Refineries

Considering your commercial fuel production experience, please provide the requested information concerning biofuels and their challenges:

1. What type of fuels are the final products of your refineries?
2. Which is your estimated annual production (t/year), and which are the average energy contents of your final products (MJ/t)?
3. Is it imposed any obligatory biobased percentage in your final products and, if yes, how much is this percentage?
4. Do you perform co-processing (conventional/renewable fuels parallel processing)? If yes, what kind of renewable fuels are these? If no, would you be interested to this initiative?
5. Which are, according to you, the main challenges from the technical point of view for biofuels establishment?
Any other issue/comments:

2.3.3 Questionnaire of Fuel traders

C – Fuel traders **Considering the type of fuels that you usually trade, please provide the requested information concerning technical and supply requirements:**
1. What type of fuels do you mainly trade for aviation or maritime use?

2. Which are the main specifications that must be followed in order an aviation/maritime fuel to reach the market?
3. In the fuels that you trade, are there any cleaning requirements or they can be directed straight to the bunker?
4. How much important is for you the blending ability of the fuels that you trade? ○ utmost important ○ very important ○ medium important ○ low important ○ no important at all
Any other issue/comments:

2.3.4 Questionnaire of Final end-users

D – Final end-users **Considering the type of fuel that you usually use for your activities, please provide the requested information concerning your infrastructure fuel compatibility, fuel standards and performance:**
1. Which is the type of fuel that you usually involve in your infrastructure?
2. Which are the main criteria that lead your fuel selection and define its performance?
3. Which is the annual fuel consumption for your activities?

4. Are you satisfied from the prices and the supply chain of the fuels that you currently use?
5. Do you use fuel blendings and, if yes, which is their typical composition?
6. Which fuel parameter improvement could lead you to investigate alternative options for your fuel?
7. How much negotiable would you be in partial retrofitting of your existing infrastructure due to new fuel requirements?
Any other issue/comments:

2.3.5 Questionnaire of Policy makers

E – Policy makers **Considering the present and the forthcoming legislative framework, please provide the required information concerning biofuels placement in the energy map:**
1. Which is currently the highest permissible blending ratio (conventional/biofuel), and which are the main obstacles for higher biofuels involvement?
2. Which is your prediction concerning the forthcoming transportation fuel policies, and how these will affect aviation and maritime sectors?

3. How important is the role of liquid biofuels towards the energy transition in aviation and maritime sector?

- utmost important
- very important
- medium important
- low important
- no important at all

4. Which is your current strategy for promoting advanced liquid biofuels?

- subsidy/national funds
- tax relaxation policies
- compulsory blending of renewable and conventional fuels
- Other: ……………………………

Any other issue/comments:

2.4 Data collection and analysis

Potential stakeholders from all around Europe have been called to respond to relative with their activities questionnaires and provide valuable information that will enhance the impact of the survey and assist in the extraction of key facts. In total, fourteen (14) answered questionnaires have been obtained and attached in the Appendix (Section A-1). At least one questionnaire was secured from each group. Their spread around Europe is illustrated in Figure 9.

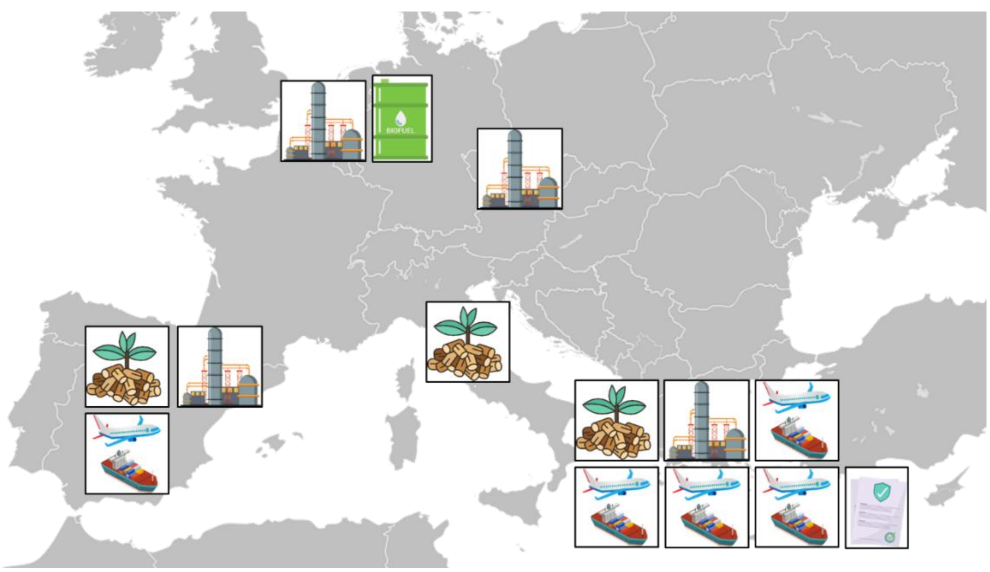


Figure 9. Distribution of the stakeholders representatives around Europe.

In particular, three (3) representatives from Feedstock suppliers, four (4) for the Refineries, one (1) for Fuel traders, five (5) for Final end-users, and one (1) for policy makers participated to the survey.

2.4.1 Feedstock suppliers

An Italian straw supplier[1], a Spanish vineyard prunings supplier[2], and a Greek olive supplier[3] provided information related to their activities, the seasonality impact as well as their opinion for feedstock price shaping. Availability and distribution ability of cereal bales, pruning chips, and pellets have been quoted.

A critical parameter that should be investigated for every potential biogenic feedstock supply chain, is the seasonality of the distributed products. Seasonality can affect the available quantities as well as the quality of the provided feedstock. Sufficient storage for biomass is necessary to accommodate seasonality of production and ensure regular supply to the biomass utilization plant. Pruning is usually carried out from December to March and then prunings have to remain for a certain time (2-3 months) on the soil to get rid of high moisture content. Moreover, it was mentioned from one respondent that prunings cannot remain at the soil after a certain time since there is the danger of soil infection and soaking from rain. Another seasonality derived possible issue that could arise; it is referred for example that olive tree pruning is not performed every year in the same volume and consequently the distributed quantities can be affected. Nevertheless, large biomass providers such as the Spanish and Italian supplier that offer commercialization of their products (e.g. pellets), have found the way (strategic location, network, storage facilities) to deal with seasonality issues and secure an annual average productivity accomplishment that can form solid and sustainable biomass supply chains. Pellets, apart from their compositional advantages (e.g. higher energy density, homogeneous quality), present superior storage properties that can limit seasonality impact.

The most notable barrier towards extended biomass involvement in energy production is feedstock costs. The low energy density of biomass feeds comes up with remarkably high logistics costs. Moreover, feedstock pre-treatment to increase energy density can be additional expenses to the

[1] https://www.gruppoab.com/stories/an-interesting-experience-in-the-field-of-bio-cogeneration-at-the-service-of-agri/
[2] https://www.avebiom.org/en/asociados/athisa-biogeneracion-pellet-combustibles-de-la-mancha
[3] https://ktimagolemi.com/

already existing cultivation, harvesting, and labor costs. All these factors burden the final feedstock price and downgrade its market competitiveness [122]. Hence, it was asked from the respondents to express their opinion regarding the impact of these costs and at which grade they regulate the final feedstock price (Figure 10).

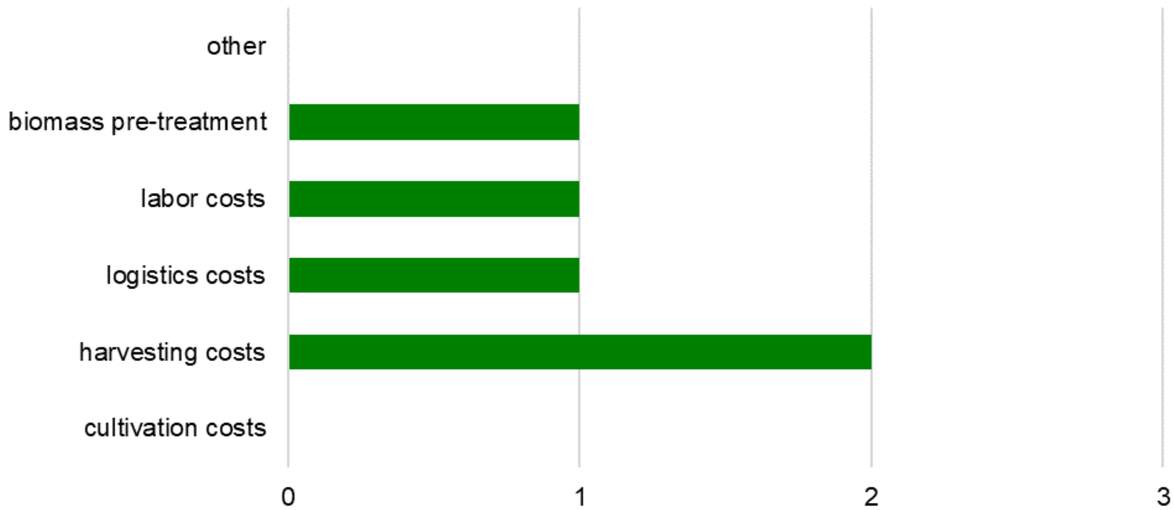


Figure 10. Feedstock price regulators according to the respondents.

Harvesting costs have been mentioned two times, while logistics, labor and pre-treatment costs have been quoted also. Of course, the answers of the respondents depend on their activities, meaning that the Italian straw and the Greek olive providers, that are farmers, focused on the agricultural work and the relevant costs. The Spanish supplier that commercializes pellets from vineyard prunings takes into consideration also the pre-treatment costs. The costs related to agricultural (i.e. cultivation, harvesting, labor, etc.) are steady costs while pre-treatment costs are inversely proportional to logistics costs. Their balance is the key towards the biomass costs reduction and the establishment of sustainable supply chains.

2.4.2 Refineries

Leaders of the refining industry in Greece[4], Spain[5], Czech Republic[6], and Netherlands[7] represented the Target Group of Refineries.

[4] https://www.helpe.gr/
[5] https://www.repsol.com/en/index.cshtml
[6] https://www.unipetrol.cz/en/Pages/default.aspx
[7] https://www.q8.com/

The production activities of all the respondents are mainly focused on the typical fossil-derived liquid fuels (i.e. gasoline, diesel, jet fuel, marine fuel). Regarding biofuels, Ethyl Tertiary-Butyl Ether (ETBE) and Hydrotreated Vegetable Oils (HVO/HEFA) were highlighted. ETBE is produced from bioethanol and isobutylene in a catalytic reaction. ETBE provides improvements when blended into conventional gasoline as oxygenate and octane booster, while its bio-based percentage (bioethanol) incorporates renewable energy in gasoline [123]. HVO/HEFA fuels, commonly referred to as renewable diesel (HVO) and jet fuel (HEFA), are produced via hydroprocessing of waste fats, oils, and greases (FOGs). HVO/HEFA offers a number of benefits over Fatty Acid Methyl Esters (FAME/Biodiesel), such as reduced NOx emissions, better storage stability, and better cold flow properties. Hence, HVO can typically be used in all diesel engines. HEFA is the only market-proven biofuel technology for aviation so far, and is used in blends with conventional jet fuel up to 50% (Chapter 1).

Concerning the bio-based percentage in the final refinery products, it seems that it is not a refinery's objective itself, but rather a fuel trader's matter, and varies from one EU member to another according to the national legislation. The context of the major directive (RED III) is generally adopted from all state members. However, each country according to its individualities (e.g. size, financial situation, facilities, etc.) differentiates in terms of obligations and long term goals [124]. The Fuel Quality Directive (FQD) regulates the products specifications by restricting blending potential; for example max 10% (bio)ethanol in gasoline, maximum 7% FAME (v/v) in diesel.

Another issue set in the questionnaires was the involvement of biomass-derived sources into existing petroleum refineries in terms of co-processing of biomass-derived feedstock with petroleum fraction. Petroleum refineries already have a highly-sophisticated infrastructure to produce fuels and base chemicals and, consequently, would not require additional intensive investments for processing renewable similar feedstock [125]. The utilization of conventional vegetable oils and Used Cooking Oils (UCOs) was quoted for the production of HVO/HEFA while some of the respondents characterized this information confidential and denied to answer. This could be an indication that co-processing of different renewable streams with petroleum fraction is under active investigation for the refining industry. The financial advantages, the potential slight infrastructure modifications as well as the biogenic content compliance with the regulations are factors that surely demand strategic decisions.

The opinion of the refineries experts was requested regarding the main technical challenges towards biofuels increasing involvement and establishment. The answers were divided into two parts; the technical difficulties of co-processing renewable feeds and the biofuels specifications that are in dispute. For the first part (co-processing), some feedstock contaminants as well as the higher costs for renewable feedstock are common bottlenecks for refining industries that are called to involve co-processing in their activities. The contaminants in some renewable feeds and products formed during co-processing pose operational problems in the industrial units and ultimately limit the maximum amount that can be fed to the units for co-processing. For the second part, which refers to the technical specifications of the produced biofuels, their weak cold properties have been highlighted from every respondent as a major issue especially for potential aviation use. Other critical technical parameters that were mentioned concerning biofuels performance and blending efficiency are the oxidation stability, the polarity, and their density (Figure 11).

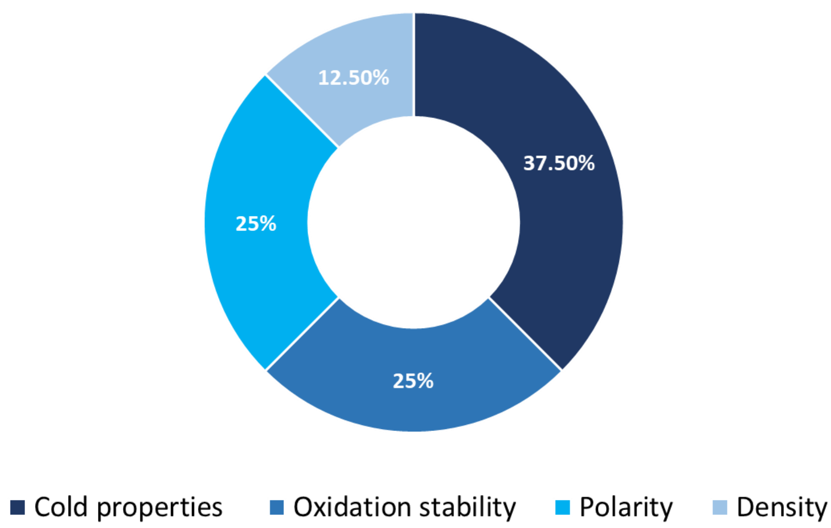


Figure 11. Biofuels main technical challenges according to the respondents.

The term cold properties mainly refers to cloud point, pour point, and cold filtering plugging point (CFPP) of the fuel, which are parameters that describe the flow behaviour of a liquid fuel in low temperature environments. These parameters are very important for the assessment of aviation fuels, since the outdoor temperature during a flight is several decades below zero. During cold conditions, inferior cold flow properties can lead to particles crystallization and blockage of the fuel system. The low-temperature operability of any fuel is a critical parameter that will enable biofuels with superior cold flow properties to extend their blending percentage and subsequently their market penetration. The term oxidation stability refers to the tendency of the fuel to degrade by oxidation, while the term polarity refers to fuel affinity for water.

The technical challenges for biofuels establishment are not the same for every sector. There is a big difference in the degree of difficulty for a road/marine biofuel to reach the market compared to an aviation biofuel. In the first case, it is sufficient only for the final blend to comply with the regulations even if the bio-based component itself does not meet all the specifications in order to be used as a drop-in fuel. However, in the case of aviation, the blending specifications are justifiably stricter and it is not enough only the final blending to be compatible with the international standards, but the biofuel itself must almost fully comply with the synthetic jet fuel specifications, as indicated in ASTM D7566, and already be a high quality fuel.

Finally, it has to be mentioned that among the answers there was one respondent that expressed general scepticism about biofuels. It represents a trend in the petroleum industry that is still wary of biofuels. The main reasons for this are the financial/technical challenges to introduce extensive co-processing and the inability of refiners to recover additional costs, as the product markets are very competitive. The trust between biofuels and the refining industry should be built gradually with parallel favorable policies and ‘drop-in’ technologies (compatible with the existing refineries infrastructure) that encourage renewable feeds or/and co-processing.

2.4.3 Fuel traders

The sole representative of the Fuel traders Target Group was GoodFuels[8]. Fuel traders are responsible for the supply of the refinery products into the market. Their expertise lies on the recognition of that set of fuel specifications that is able to ensure effective market penetration. The bio-based fuels that seem to take part in GoodFuels’ activities are HVO and FAME. GoodFuels is a market leader in sustainable biofuels, especially for marine use. Nevertheless, in both aviation

[8] https://www.goodfuels.com/

and marine sectors, some common aspects will navigate the potential market penetration of a candidate alternative fuel (Figure 12).

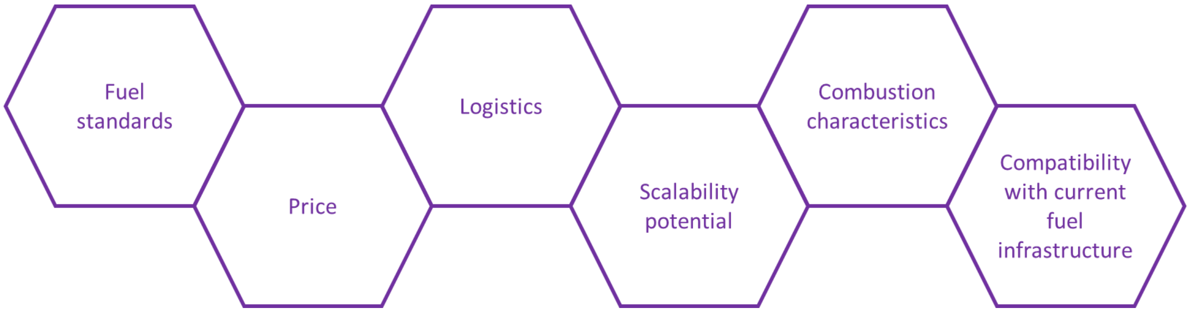


Figure 12. Set of biofuels specifications for a sustainable market penetration.

Already from the refineries-oriented survey, it was understood that the blending ability of the refinery products in order to achieve the targeted bio-based percentages in the traded fuels, according to the directives and the respective national legislation, is a critical issue. The characterization of the blending ability of the fuels as 'utmost important', from the side of fuel traders as well, confirms that claim. The lining up with the RED III sustainability criteria has been mentioned also from the fuel traders, validating the RED directive as the dominant variable in biofuels involvement and utilization. Finally, it has been underlined the need of biofuels supply chains to be certified by an internationally standard sustainability system (e.g. ISCC or RSB).

2.4.4 Final end-users

The term Final end-users mainly refers to aviation airlines and ship owners. Nevertheless, organizations and companies (e.g. marine classification, airport management) that cooperate directly with them and fulfill a part of their obligations should not be excluded from the survey. In total, five (5) questionnaires were collected from this Target Group; three (3) shipping companies (DANAOS[9], ANEK[10], and Seajets[11]), one (1) aviation airline[12] (Aegean Airlines), and an airport management company[13] (Aena).

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[9] https://www.danaosshipping.gr/
[10] https://www.anek.gr/
[11] https://www.seajets.com/el
[12] https://el.aegeanair.com/
[13] https://www.aena.es/en/corporative/about-aena/company-profile.html

Concerning the main type of fuels that are currently involved in the marine sector, the common marine distillate (i.e. Marine Gas Oil) and residual fuels (i.e. Heavy Fuel Oil) have been quoted as well as their subcategories (e.g. Intermediate Fuel Oil, Low Sulfur Fuel Oil, etc.). Moreover, the potentials of LNG (Liquefied Natural Gas) and LPG (Liquefied Petroleum Gas) are mentioned. Various parameters related to the fuel price, the quality, the regulations as well as the local restrictions seem to play a role towards the fuel selection for marine stakeholders. The compliance with the rules that governing shipping nowadays along with the fuel costs and the fuel compatibility with each company's engines are presented to be the dominant regulators for marine fuel selection. Other parameters that have been mentioned from the respondents are the availability, the energy density, combustion quality, and local port requirements (Figure 13).

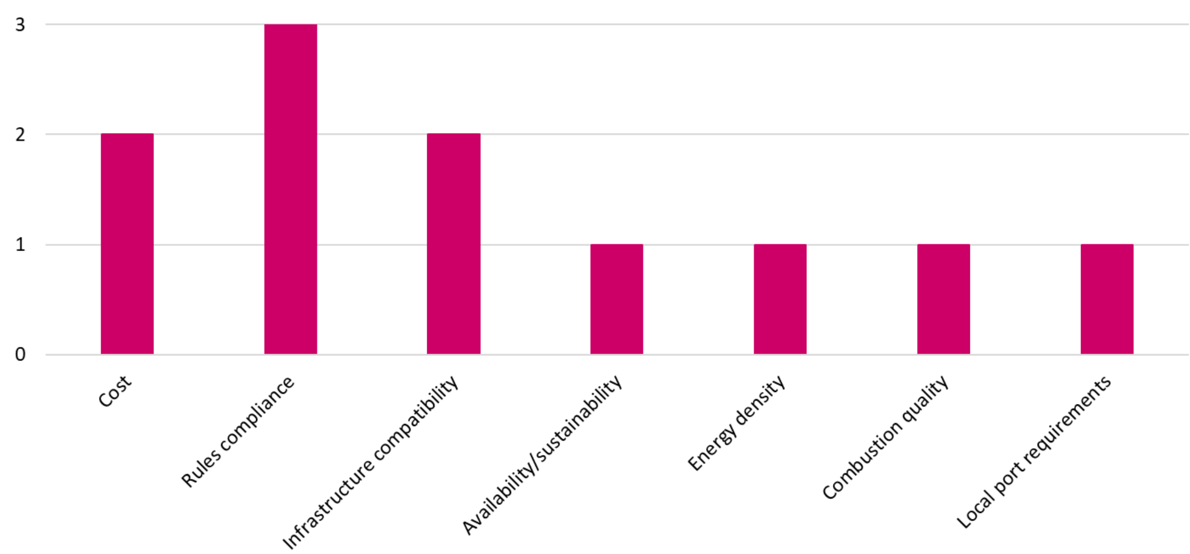

Figure 13. Main criteria for marine fuel selection according to the respondents.

It can be conceived that marine fuel selection is a matter of different (quantitative, qualitative, legislative, etc.) individual factors and therefore shipping companies seem to have a relative flexibility concerning their fuel strategy. In aviation, on the other hand, the fuel standards are the same high for every aviation fuel and therefore the interest for their selection is limited on the fuel cost, the source of origin, the location of the plant, and the compliance with the regulation framework. For jet fuel the whole production pathway must be qualified and meet strict sustainability criteria, and not only the final product. The respondents were also asked about potential fuel improvements that could lead them to investigate alternative options for their fuel. From the marine sector, the answers included the energy/price ratio, the compliance with new regulations, the emissions reduction and the fuel stability, while aviation sector focused on the reduction of WtW (Well-to-Wheels) emissions (aviation fuel quality is the same). The mentioned responses for both sectors are gathered and presented according to their rates in Figure 14.

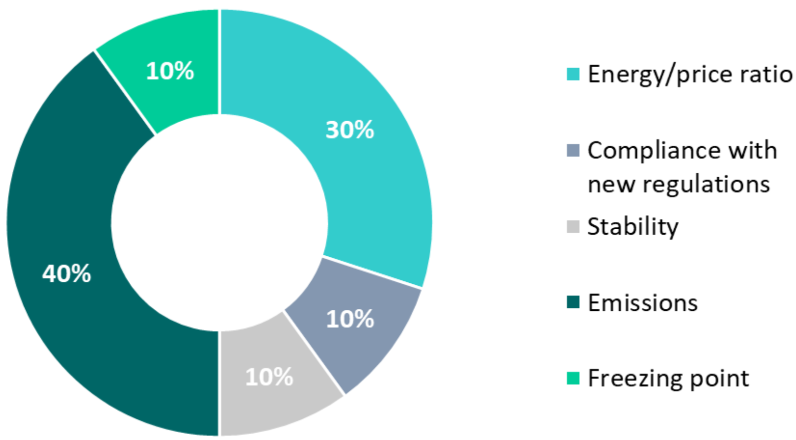

Figure 14. Fuel improvement priorities according to the respondents.

New fuels and potentially new fuel specifications might demand mild retrofitting of the existing infrastructure. Consequently, it is interesting to investigate up to which grade the end-users stakeholders would be interested or negotiable to partial retrofitting of their infrastructure. The respondents set an holistic (operational, tactical, environmental) assessment as prerequisite for such an initiative. However, all the respondents replied in a remarkably positive mood and expressed their willingness to perform modifications in their infrastructure, if the new involved fuels come up with strong benefits and improvements in factors that they recognize as ‘weak’ in their current fuel selection.

Finally, it is remarked that the limited SAFs (Sustainable Aviation Fuels) production in the EU along with the high prices that they exhibit compared to conventional Jet-A1, make it difficult for aviation biofuels to compete. In general, after taking into account the input from all the relevant Target Groups (Refineries, Fuel traders, Final end-users), there is a common alignment related to the uniqueness of aviation sector. One the one hand, it seems a favorable field for advanced biofuels to flourish since SAFs have been adopted as the spearhead towards the decarbonization of the sector. On the other hand, biofuels production for aviation is a quite challenging task that should follow strict requirements and high-quality standards all along the value chain.

2.4.5 Policy makers

The Hellenic Ministry of Environment & Energy[14] represented the Target Group of Policy makers. At this point, the current involvement of biofuels in Greece is limited up to 7% v/v biodiesel in diesel and 3.5% v/v bioethanol in gasoline. The revised National Energy and Climate Plan (NECP), aligned with the RED indications, aims to support the production of advanced biofuels and renewable fuels of non-biological origin (RFNBOs). There is currently no production of advanced biofuels nor RFNBOs in Greece. However, the contribution of advanced biofuels is planned to reach 2.4% of transport fuels by 2030 and 17% by 2040, while RFNBOs to reach 1% by 2030 and 23% by 2040.

The new ReFuelEU Aviation and FuelEU Maritime regulations set specific targets for the introduction of renewable fuels in aviation and maritime, respectively. The assessment of the Ministry is that the forthcoming transportation fuel policies will need some time to be incorporated in the Greek fuel network, but they recognize the very important role of liquid biofuels towards the energy transition of these two sectors. Concerning the strategy for promoting advanced liquid biofuels, targeted support and funding at national level as well as public-private partnerships will hopefully improve the availability and financial sustainability of relevant fuels and accelerate their deployment.

2.5 Conclusions

Five (5) Target Groups have been selected to represent the key stakeholders towards the deployment of advanced biofuels:

- A – Feedstock suppliers
- B – Refineries
- C – Fuel traders
- D – Final end-users
- E – Policy makers

A questionnaire survey was performed, aiming to obtain an industrial insight regarding the main market needs and expectations. In total, fourteen (14) filled questionnaires, at least one from each

[14] https://ypen.gov.gr/

group, were secured. Some key facts have been elected for each Target Group according to the responses, and are presented in Table 4.

Table 4. Stakeholders (Target Groups) specifications according to the survey.

Target Group	Main challenges	Critical aspects
Feedstock suppliers	A balance between pre-treatment and logistic costs in order to reduce the final feedstock price	Seasonality impact, storage facilities, agricultural work costs (e.g. harvesting)
Refineries	For drop-in biofuels: cold-flow properties, oxidation stability, polarity, energy density For co-processing: feedstock contaminants & feedstock prices	Aviation biofuels must comply almost entirely with conventional jet fuel specifications, since the blending regulations for aviation sector are stricter than other transportation
Fuel traders	Blending ability of traded fuels Supply chains must be certified by a sustainability system (e.g. ISCC, RSB)	Fuel standards, price, logistics, scalability potential, combustion characteristics and compatibility with current infrastructure
Final end-users	Emissions reduction, energy/price ratio, fuel stability, adaptability to new regulations	For aviation fuel selection, there are not qualitative factors since the fuel standards are the same high for every aviation fuel Advanced biofuels in Europe struggle to compete due to their limited production and high cost
Policy makers	Time needed for fuel policies to be incorporated in each national legislation framework and fuel network Targeted support and funding at national level	Advanced biofuels and e-fuels are high on the agenda towards energy transition in aviation and maritime sector

Chapter 3

Insight into indirect gasification technologies and screening of biogenic residues around Europe

3.1 Indirect gasification technologies

3.1.1 Introduction

As discussed in Chapter 1, Air Transport Association (IATA) has elected biofuels as the most efficient strategy, at least short term, to reduce the environmental impact of the sector with the existing fuel systems (engines, fuel distribution network). At the same time, the EU's biofuels policy, as documented in the latest directives (i.e. RED II, ReFuelEU Aviation), underlines the promotion of residue-based biofuels (or so-called advanced biofuels).

Lignocellulosic biomass conversion into liquid biofuels through thermochemical routes is considered as a favorable option that offers several advantages. The main challenge for these pathways is to develop advanced technologies with reduced energy consumption. The low energy density (due to high oxygen content) and the corrosive nature of pyrolysis bio-oil or the high costs (catalysts, high pressures) of liquefaction have established biomass gasification as the most efficient technology for lignocellulosic biomass conversion [7, 126]. The resulting synthesis gas (syngas) can be converted via multiple routes into synthetic transport fuels. For the majority of these routes, high quality syngas (nitrogen-free) is an important prerequisite for the subsequent efficient syngas processing.

Towards this direction, indirect biomass gasification systems have become an attractive option for syngas production, due to their extended fuel flexibility as well as the avoidance of costly, energy demanding oxygen production units (e.g. Air Separation Unit). The most dominant representative technologies of indirect gasification are Dual Fluidized Bed Gasification (DFBG) and Chemical Looping Gasification (CLG). The major difference between the two similar technologies is that in opposition to DFBG, where the required heat for gasification is provided by partial char combustion, in CLG the required lattice oxygen is introduced by a solid oxygen carrier (OC) that is circulated between the two reactors [127].

DFBG is a semi-commercially proven technology [128]. The technological functionality that the Güssing plant (8 MWth) proved, led to the development of other large-scale DFBG applications like Oberwart (9 MWth), Senden (15 MWth), and the Gothenburg – GoBiGas plant (32 MWth). CLG has just been demonstrated at pilot scale [129, 130]. The synergy of CSIC (Spain), Chalmers

(Sweden), and TU Darmstadt (Germany), within the framework of the CLARA project [10], led to the successful pilot CLG operation in the facilities of the latter (1 – 1.5 MWth). (Figure 15)

The main objective of the present study is to investigate the operational characteristics of two promising indirect gasification technologies in order to evaluate their technical specifications and financial parameters, their commercialization potential as well as their appropriateness for Biomass-to-Liquid (BtL) applications. The stated claims are supported by pilot tests and upscaling simulation results.

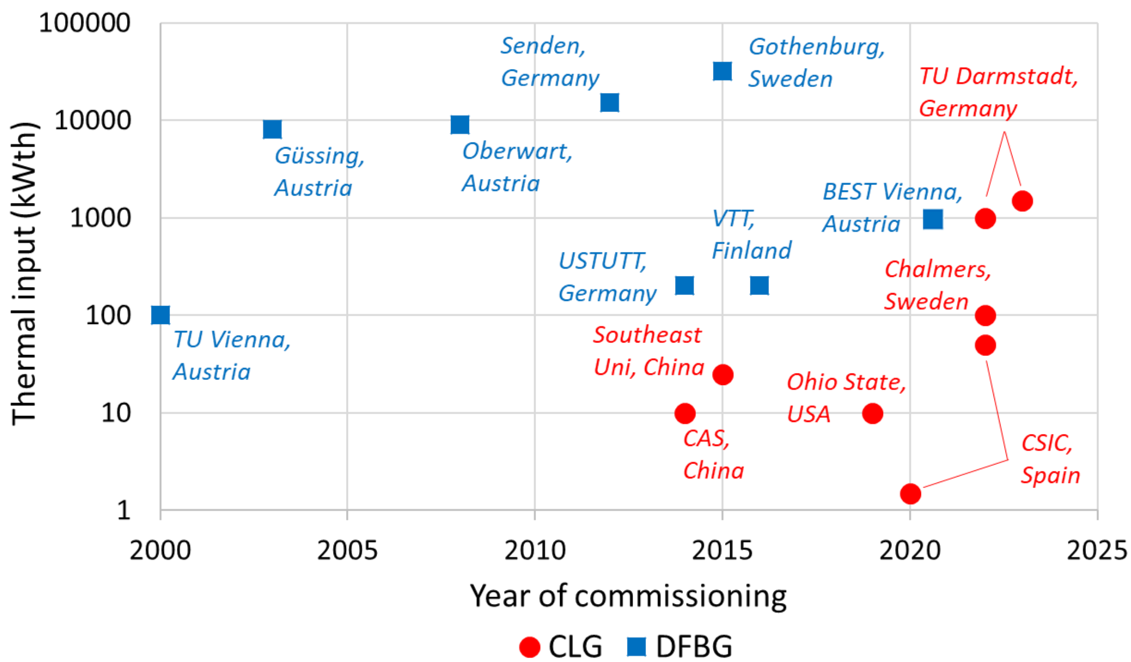

Figure 15. Major DFBG and CLG applications to date.

3.1.2 Materials and methods

Within the framework of the BioSFerA [9] and CLARA [10] projects, VTT and TU Darmstadt (TUDA) provided experimental data from pilot DFBG (200 kWth) and CLG operation (1.5 MWth), respectively. These data were utilized for the proper model development and validation of the two gasification processes. The rationale is to form reliable models for both technologies that will be able to serve comparative full-scale simulations and upscaling considerations.

In order to secure the consistency of the comparative analysis, operational points with similar feedstock (forest residues) (Table 5) were selected for the pilot model validation as well as the subsequent full-scale simulations.

Table 5. Feedstock properties for forest residues involved in the pilot tests.

Biomass Feed	Forest residues (DFBG)	Forest residues (CLG)
Proximate analysis (%)		
Moisture	7.40	4.40
Fixed Carbon (d.b)	19.60	17.40
Volatile Matter (d.b)	77.80	80.30
Ash (d.b.)	2.60	2.30
Ultimate analysis (% d.b.)		
Ash	2.60	2.30
Carbon	52.50	51.15
Hydrogen	6.10	6.07
Nitrogen	0.30	0.44
Chlorine	0.01	0.01
Sulphur	0.02	0.02
Oxygen	38.47	40.01
Net Calorific Value a.r. (LHV) (MJ/kg)	18.10	18.30

Two critical performance indicators for the evaluation of every gasification system are introduced:

- Cold Gas Efficiency (CGE) is the fraction of the chemical energy in the initial feedstock that is transferred to syngas in the gasifier
- Carbon Conversion (CC) is the fraction of carbon in the initial feedstock that is transferred to syngas in the gasifier

3.1.2.1 DFBG – Process description and model validation at pilot scale

The DFBG system consists of two interconnected reactors at ambient pressure, the Fuel Reactor - FR (gasifier) where gasification takes place, and the Air Reactor – AR (combustor) where partial combustion of the char or additional fuel combustion takes place in order to secure the heat requirements of the gasifier. In particular, the produced char, other residues (i.e. ash) and part of the bed material are transported to the combustor where they react with the oxidizing medium (air) to produce heat. The (hotter) bed material returns to the gasifier, serving as an external heat source for the endothermic steam gasification reactions, leading to higher carbon conversion rate and thermal efficiency. The operating principle of the DFBG technology is illustrated in Figure 16.

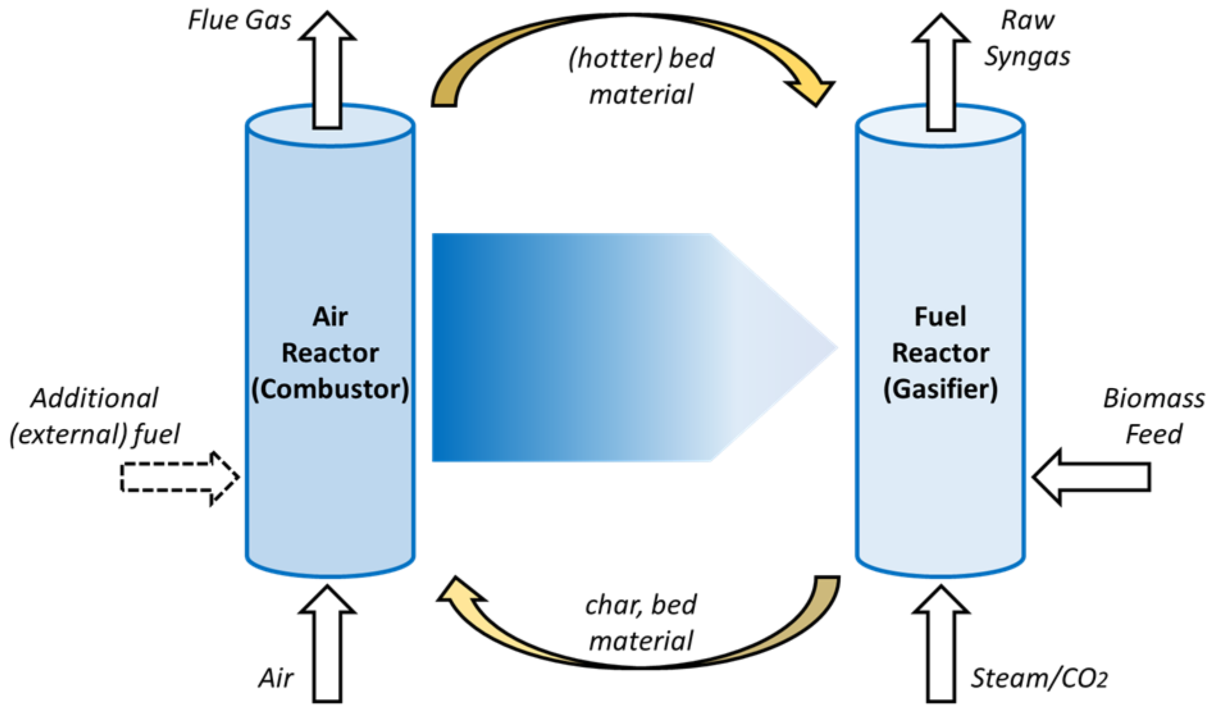

Figure 16. DFBG operating principle.

The governing reactions in the FR are the steam gasification reaction (1), the water-gas shift (WGS) reaction (2), and the homogeneous gas reactions that form hydrocarbons (3-5). Char combustion (6) is performed in the AR:

$$C + H_2O \rightarrow CO + H_2 \quad (1)$$

$$CO + H_2O \rightarrow H_2 + CO_2 \quad (2)$$

$$CO + 3H_2 \rightarrow CH_4 + H_2O \quad (3)$$

$$2CO + 4H_2 \rightarrow C_2H_4 + 2H_2O \quad (4)$$

$$6CO + 9H_2 \rightarrow C_6H_6 + 6H_2O \quad (5)$$

$$C + O_2 \rightarrow CO_2 \quad (6)$$

A selected operational point from the experimental trials of VTT [131] was used for the DFBG model validation. The VTT pilot DFBG configuration consists of two CFBs (Circulating Fluidized Beds) and can support a thermal input up to 200 kWth. The focus is given on the main syngas species (CO, H_2, CO_2, CH_4) of the two outlet gas streams (i.e. syngas from FR & flue gas from AR).

A good agreement is achieved between the model results and the experimental measurements (Figure 17). The previous experience of large-scale DFBG applications was also evident during the VTT's experimental trial, since stable operation was secured for a total of 400 hours and notable performance indicators were attainable. The obtained syngas composition corresponds to a CGE around 77%, while the CC in the gasifier accounts for 75%.

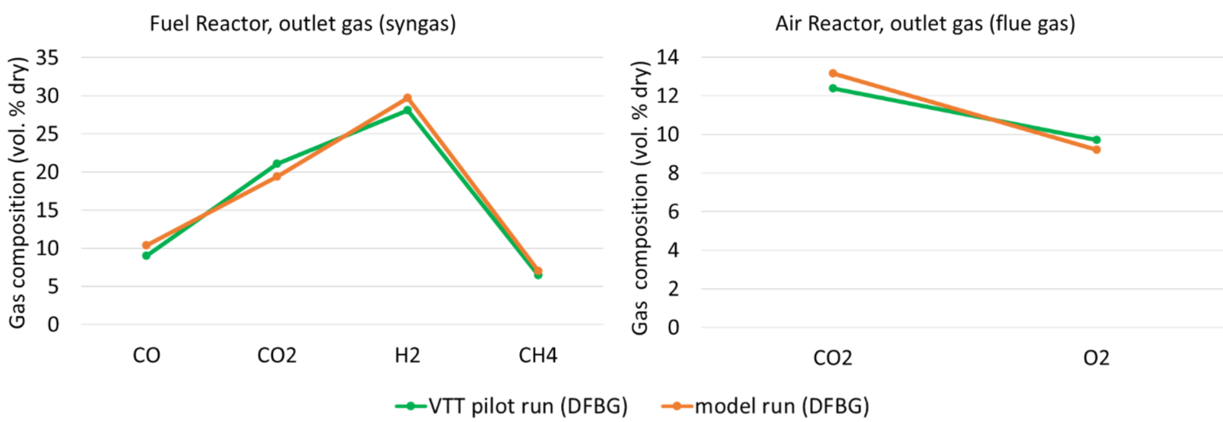

Figure 17. DFBG model validation at pilot scale (200 kWth).

3.1.2.2 CLG – Process description and model validation at pilot scale

The reactor system of the CLG process typically consists of two coupled fluidized bed reactors operated at ambient pressure, the FR (gasifier) where gasification takes place and the AR (combustor) where oxidation of the oxygen carrier takes place. Thus, a solid oxygen carrier that is circulated between the two reactors provides the oxygen required for the endothermic gasification reaction. Metal oxides (e.g. ilmenite) are typically used as oxygen carrier [132, 133]. The oxygen carrier particles leaving the FR with the syngas are separated from the gas (by means of a cyclone) and transferred to the air reactor (fluidized with air), where the reduced form of the oxygen carrier (Me_xO_{y-1}) is re-oxidized to Me_xO_y by the oxygen contained in air. The oxygen carrier particles leaving the AR with the depleted air are separated (by means of a cyclone) and transferred back to the FR. Unconverted char leaving the FR may also be transferred to the air reactor and combusted there (carbon 'slip'). However, the ambition in CLG systems is to minimize the carbon 'slip' and keep the AR as clean as possible from fuel components. The operating principle of the CLG technology is illustrated in Figure 18.

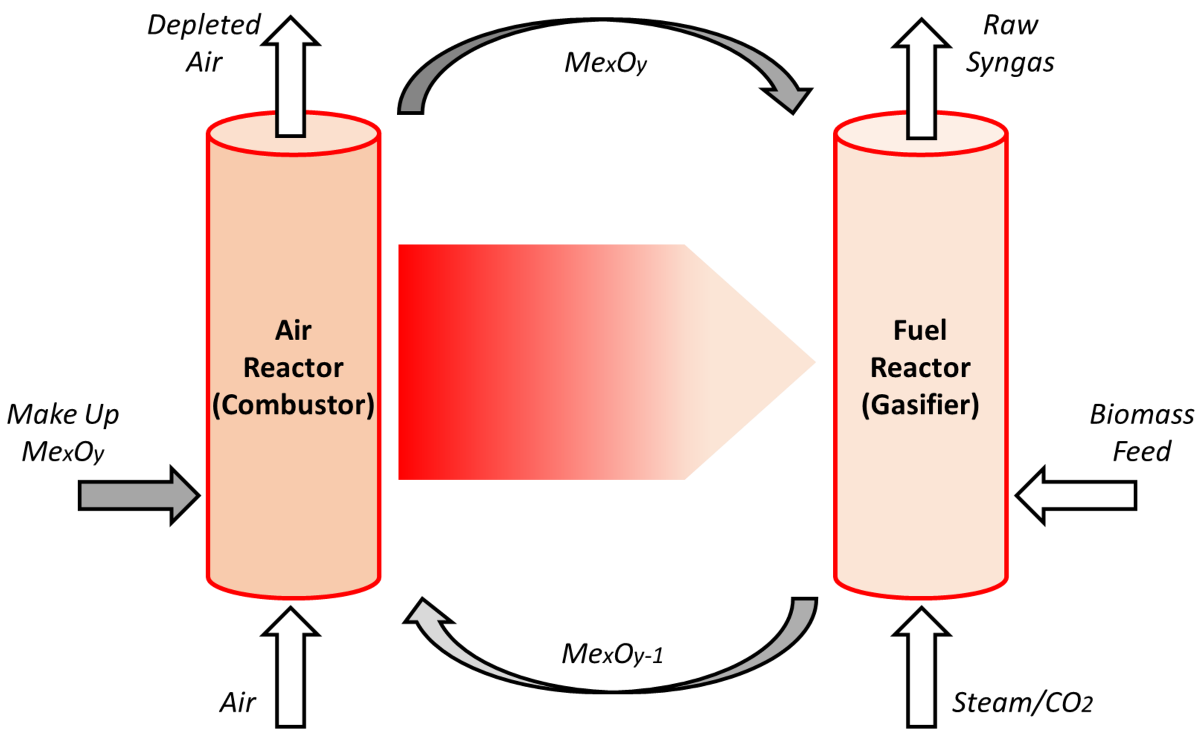

Figure 18. CLG operating principle.

To the mentioned governing reactions (1-5) in the FR, the OC reduction reactions must be added for the case of CLG (7-9). In the AR, apart from the combustion of unconverted char from FR (6), the re-oxidation of the oxygen carrier has to be considered (10) [134, 135].

$$Me_xO_y + CO \longrightarrow Me_xO_{y-1} + CO_2 \quad (7)$$

$$Me_xO_y + H_2 \longrightarrow Me_xO_{y-1} + H_2O \quad (8)$$

$$Me_xO_y + CH_4 \longrightarrow 4Me_xO_{y-1} + 2H_2O + CO_2 \quad (9)$$

$$Me_xO_{y-1} + 0.5O_2 \longrightarrow Me_xO_y \quad (10)$$

A selected operational point from the experimental trials of TU Darmstadt [130] was used for the CLG model validation. The TUDA pilot CLG configuration consists of two CFBs and can support a thermal input up to 1.5 MWth. The successful pilot test campaign, performed by TU Darmstadt within CLARA project is the largest CLG application up to now, and thus is considered as a breakthrough regarding the maturation of the technology.

A good agreement is attained between the model results and the experimental measurements (Figure 19). The inherent major heat losses (~25% of the total thermal input) of the TUDA pilot CLG plant (high surface-to-volume ratio of the pilot plant) as well as other plant-specific restrictions led to lower process efficiencies than those obtainable in an industrial (optimized) unit. The latter reflects on the relatively high CO_2 content (~50%) in the produced syngas. In particular, a CGE around 48% is obtained in the 1 MWth unit, while the CC in the gasifier is measured at 85%. Hence, the carbon 'slip' in the AR accounts for 15% and this is the reason why some CO_2 is also present in the outlet gas of the AR (depleted air).

In general, stable CLG operation was accomplished for more than 100 hours during TUDA's pilot test campaigns, revealing valuable technical insight towards the upscale of the technology and underlining that efficient CLG operation is possible in industrial scale.

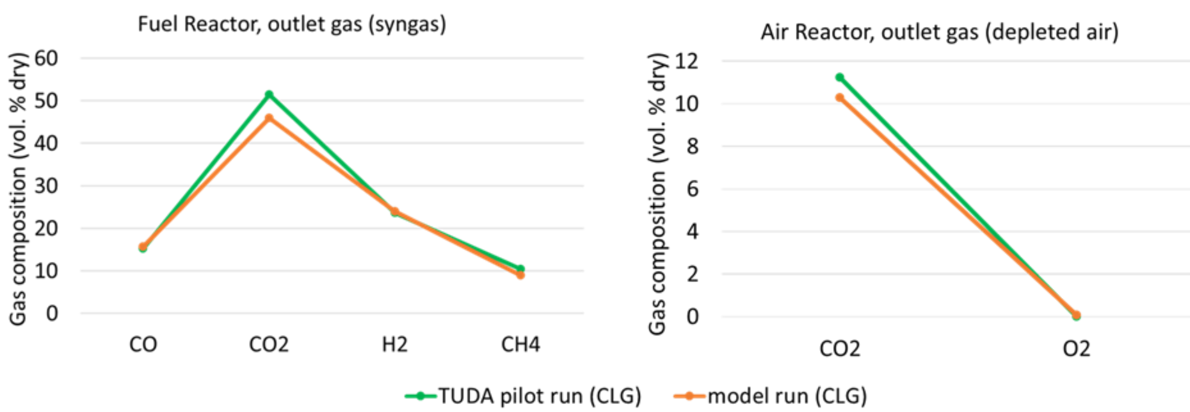

Figure 19. CLG model validation at pilot scale (1.5 MWth).

3.1.3 Results and discussion

Using the validated Aspen Plus™ pilot models as a basis, upscaling considerations are performed and full-scale simulations (200 MWth) are carried out for both processes. The target is to identify the operational characteristics for both gasification technologies in a potential industrial (optimized) setup and evaluate their appropriateness for commercial BtL applications.

Autothermal system operation (both reactors are in heat balance) is considered for the full-scale simulations of both technologies. Inherent heat losses equal to 1% (2 MWth) of the total thermal input are set for both cases as well. The main input parameters for the full-scale process simulations are presented in Table 6.

Table 6. Main input parameters for the full-scale process simulations.

Parameter	**DFBG**	**CLG**
Thermal input (MWth)	200	200
Feedstock inlet in FR (kg/s)	11.05	10.93
Steam/Biomass ratio (kg/kg)	0.70	0.60
Air inlet in AR (kg/s)	18.60	19.30
OC flow in FR (kg/s)	-	506
Air pre-heating temperature in AR (°C)	400	400
Steam pre-heating temperature in FR (°C)	350	350
AR Temperature (°C)	900	1000
FR Temperature (°C)	800	900

3.1.3.1 Full-scale process simulations of DFBG technology

The stream results, as obtained from the full-scale DFBG simulations, are presented in Table 7. The relatively large steam flow required for DFBG technology leads to extended WGS effect and subsequent dominance of H_2 over CO in the produced syngas. The remarkable content of light hydrocarbons along with the non-negligible tars production indicate the need of catalytic reforming downstream of the gasifier in order to avoid tar-related operational problems and enhance the H_2, CO syngas content.

Table 7. Stream results for the industrial DFBG technology.

Component (vol. %)	FR, syngas	AR, flue gas
H_2O	39.15	-
CO	9.95	-
H_2	27.90	-
CO_2	14.77	16.90
CH_4	5.56	-
O_2	-	4.10
N_2	-	79.00
C_2H_4	1.83	-
C_6H_6, other tars	0.50	-
H_2S, COS	188 ppm	-
NH_3, HCl	0.20	-

The energy and carbon balances of the process have been calculated (Figure 20). A CGE around 81.4% is achieved. Thermal exploitation of the two hot streams of the DFBG unit (syngas, flue gas) is envisaged for the pre-heating demands of air and steam, while the estimated (useful) excess heat percentage accounts for 17.6% of the total thermal input. Moreover, as already mentioned, 1% heat losses are set for both reactors combined (AR 0.6% and FR 0.4%). Focusing on the carbon balance, a CC factor equal to 75.5% is calculated for the case of autothermal industrial DFBG operation. Thus, 24.5% of the initial carbon inlet is directed to the AR for combustion and ends up as CO_2 in the flue gas formed.

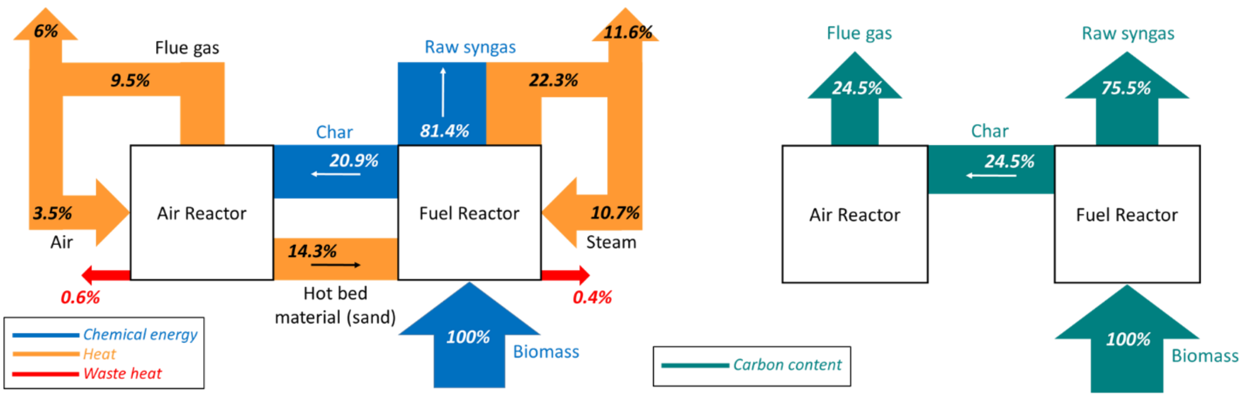

Figure 20. Estimated energy balance (left) and carbon balance (right) for the industrial DFBG technology.

3.1.3.2 Full-scale process simulations of CLG technology

The stream results, as obtained from the full-scale CLG simulations, are presented in Table 8. Due to the higher operating temperature of the FR, a lower concentration of tars is observed. However, the remarkable content of light hydrocarbons, also in the case of CLG, implies the necessity of catalytic reforming prior any subsequent syngas handling (e.g. fuel synthesis).

Table 8. Stream results for the industrial CLG technology.

Component (vol. %)	FR, syngas	AR, depleted air
H_2O	35.93	-
CO	15.16	-
H_2	23.08	-
CO_2	17.48	9.01
CH_4	5.84	-
O_2	-	0.83
N_2	-	90.16
C_2H_4	2.14	-
C_6H_6, other tars	0.10	-
H_2S, COS	145 ppm	-
NH_3, HCl	0.26	-

The energy and carbon balances for the CLG case are illustrated in Figure 21. A CGE around 80.2% is calculated. The oxygen/energy transfer between the two reactors is accomplished via the OC oxidation/reduction scheme. The heat integration strategy that was presented for the DFBG configuration, is also applied for the CLG (pre-heating of steam and air via syngas and depleted air, respectively). The estimated excess heat percentage accounts for 18.8% of the total thermal input. Despite the increased carbon conversion in the gasifier (CC ~ 89.1%) compared to the DFBG technology, a small portion (10.9%) of carbon 'slips' with the OC in the AR and is oxidized.

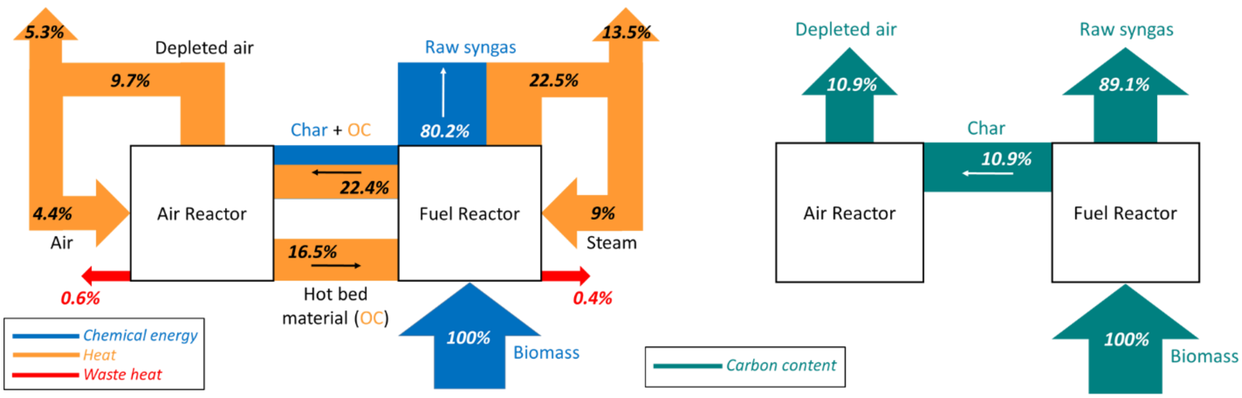

Figure 21. Estimated energy balance (left) and carbon balance (right) for the industrial CLG technology.

3.1.3.3 Comparative analysis and design considerations for applicability in BtL schemes

The full-scale simulations and the resulting energy and carbon balances confirmed the effectiveness as well as the similarity of DFBG and CLG processes. Figure 22 highlights the determined key performance indicators (CGE, CC, useful excess heat). It is observed that both technologies, in their potential commercial and optimized version, are capable of providing a high quality syngas (CGE > 80%) and optimal heat integration (useful excess heat ~ 20%). Their main differentiation lies on the ability (operational characteristic) of CLG to achieve higher carbon conversions in the gasifier (CC) and subsequently higher carbon capture/utilization potential. With respect to GHG emissions, the potential for negative CO_2 emissions in parallel with biofuel production is greater for CLG-driven plants than for the respective DFBG-driven pathways (BtL concepts).

The identified advantage (higher CC) of the CLG technology is based on the efficient and stable oxygen transfer via OC. While the CapEx (Capital Expenditures) requirements are estimated more or less the same for both technologies (i.e. feedstock feeding system, FR, AR, cyclones & interconnecting ducts, ash removal and handling), the additional OpEx (Operational Expenditures) for the OC make-up are present only in CLG applications. Thus, the OC stability in CLG operation is not only a matter of great technical importance, but also a critical factor in terms of financial sustainability of the process (the higher the OC stability, the lower the required OC make-up rates and relevant operational costs). Within the TUDA CLG pilot tests, encouraging make-up rates equal to 0.15-0.25% of the OC circulation rates were required. In potential commercial applications, when using ilmenite with a perfectly tailored particle size distribution, even lower OC make-up rates (0.05-0.1%) could be attainable, ensuring that OC related costs will account for less than 5% (low influence) of the annual OpEx of a BtL plant.

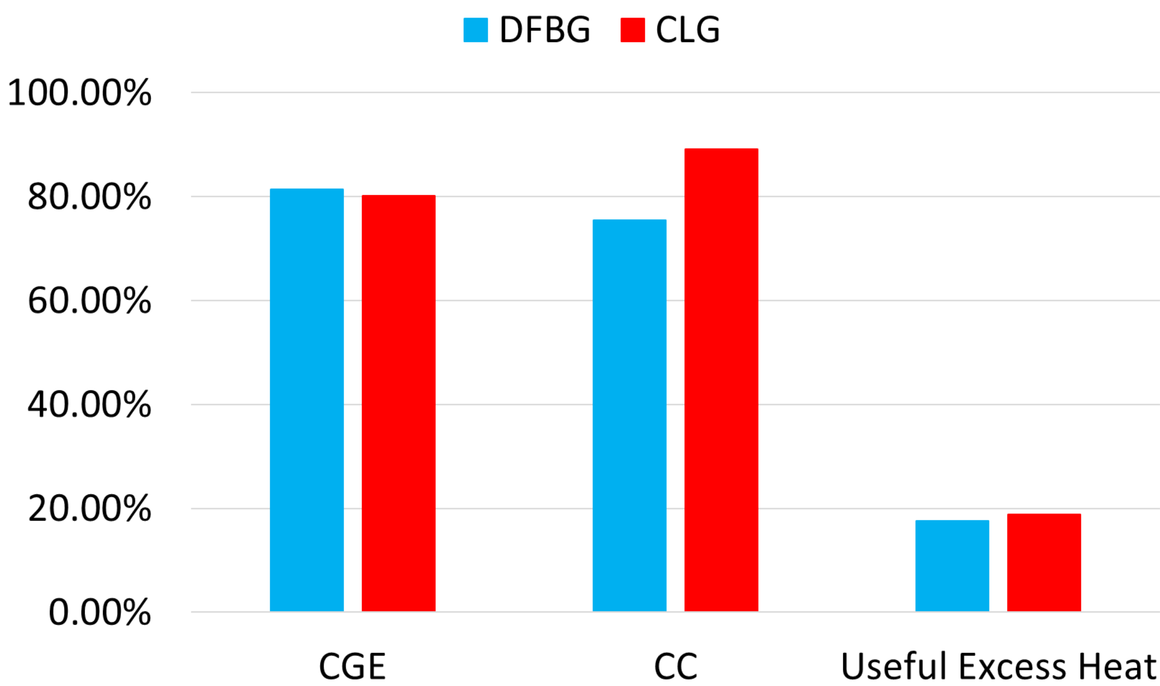

Figure 22. Comparative assessment of key performance indicators.

To sum up, both examined indirect gasification processes (DFBG, CLG) come up with great performance indicators and seem able to outperform the conventional gasification technologies in terms of feedstock flexibility, syngas quality, and heat integration for BtL applications. While DFBG is already a semi-commercially proven and efficient technology, CLG can be considered as a slightly improved variant of the DFBG technology that enables higher carbon capture/utilization with affordable additional costs. The latter should be secured with the continuous maturation of CLG technology, since it has just been tested at pilot scale.

3.1.4 Conclusions

This study aims to investigate the operational characteristics of two promising indirect gasification technologies, DFBG & CLG. DFBG is a semi-commercially proven technology, while CLG has just been demonstrated at pilot scale. The major difference between the two similar technologies is that in opposition to DFBG, where the required heat for gasification is provided by partial char combustion, in CLG the required lattice oxygen is introduced by a solid oxygen carrier (OC) that is circulated between the two reactors. The main purpose of the present study is to provide a comparative insight and evaluate their suitability for commercial Biomass-to-Liquid (BtL) applications. The stated claims are supported by pilot tests and upscaling simulations results.

In particular, within the framework of the BioSFerA and CLARA projects, VTT and TU Darmstadt (TUDA) provided experimental data from pilot DFBG (200 kWth) and CLG operation (1.5 MWth), respectively. These data were utilized for the proper model development and validation of these two gasification schemes. Using the validated Aspen Plus^{TM} pilot models as a basis, upscaling considerations were performed and full-scale simulations (200 MWth) in a potential industrial (optimized) setup were carried out for both processes. Both technologies are capable of providing a high quality syngas (cold gas efficiency > 80%) and optimal heat integration. Their main performance differentiation lies on the ability of CLG to achieve higher carbon conversions in the gasifier and subsequently higher carbon capture/utilization potential (potential negative CO_2 emissions for CLG-driven BtL concepts).

In general, there are claims that the next decades might be dominated by technologies handling advanced feedstock (i.e. biogenic residues). The examined indirect gasification processes seem ideal for future BtL applications. No insurmountable barriers towards their scaling up were detected. On the one hand, DFBG can be considered a sufficiently mature (tested up to 32 MWth) and solid technology that is able to support large-scale gasification-based biorefineries. On the other hand, the favorable aspects of the emerging CLG technology (just tested up to 1.5 MWth) should be exploited in large-scale applications as well, only after further maturation of the technology that will decisively mitigate any technical (e.g. agglomeration) and financial (OC make-up costs) risks.

3.2 Screening of biogenic residues around Europe

3.2.1 Introduction

Agriculture and forestry residues are the main providers of biogenic residues that can be exploited for energy use (e.g. gasification). Biogenic residues may be carbon sources of lower quality than the sugar-, starch-, and oil plants used for conventional liquid biofuels, but nevertheless do not come in conflict with food production and tend to avoid land use restrictions. Using biogenic residues has the advantage of being in line with the EU's biofuels policy documented in the RED III directive, mentioning the promotion of residue based biofuels (advanced biofuels) [136].

Feedstock supply chains often represent the lion's share in bioenergy deployment costs, and especially when also considering seasonal aspects for feedstock sourcing and pricing, major obstacles regarding the economic feasibility and upscaling potential may arise. Thus, the securement of a sustainable and cost-effective feedstock supply chain is a high priority towards the implementation of large-scale Biomass-to-Liquid (BtL) projects [137].

The objective of the present study is the screening of biogenic residues all around Europe and the identification of appropriate feedstock types in terms of capacity, technical characteristics, and market price. In particular, a classification of possibly relevant biogenic residues and biogenic carbon carriers is performed, their capacity around Europe is investigated with the aid of S2Biom toolset [138], and after combining their technical and market specifications, some types of biogenic feedstock are elected.

3.2.2 Feedstock screening and classification

3.2.2.1 Biomass categorization

The feedstock screening was largely relied on S2Biom platform. S2Biom project aimed to contribute towards the sustainable delivery of non-food biomass feedstock at local, regional, and pan European level through developing strategies and roadmaps that are supported by a proper toolset with updated harmonized datasets for EU28, Western Balkans, Moldova, Turkey, and Ukraine. These datasets comprise the sustainable supply of lignocellulosic biomass from forestry, actual energy cropping, agricultural residues and secondary residues from wood and food industry as well as from waste. Projections regarding the biomass technical potential (i.e. given the state-of-the-art technologies and practices) for 2030 are available. The S2Biom database was based on different methods and guidelines developed within previous relevant projects, such as BEE [139] or EUROPRUNING [140].

Following these guidelines, S2Biom project generated a classification regarding the available residual biomass around Europe, which is adopted and presented in Table 9.

Table 9. Overview of the potential residual biomass categories.

Category	Subcategory	Type
Primary residues from forests	Logging residues from final fellings & thinnings	Logging residues from final fellings from conifer and non-conifer trees
		Logging residues from thinnings from conifer and non-conifer trees
	Stumps from final fellings & thinnings	Stumps from final fellings from conifer and non-conifer trees
Secondary residues from wood industries	Sawmill residues	Sawdust (conifers/non-conifers)
		Other residues
	Other wood processing industry residues	Residues from industries producing semi-finished wood based panels
		Residues from further wood processing
	Secondary residues from pulp and paper industry	Bark
		Black liquor
Agricultural residues	Straw/stubbles	Cereals straw
		Maize stover
		Sunflower straw
		Rice straw
		Oil seed rape straw
		Sugar beet leaves
	Woody pruning & orchards residues	Residues from olive trees plantations
		Residues from vineyards
		Residues from fruit tree plantations
		Residues from citrus tree plantations
		Residues from nuts plantations
Secondary residues from industry utilizing agricultural products	By-products and residues from food and fruit processing industry	Olive-stones
		Rice husk
		Cereal bran
		Pressed grapes dregs
		Other food processing residues
Municipal waste	Biodegradable municipal waste	Bio-waste separately and jointly collected
Waste from wood	Post-consumer wood	Hazardous/non-hazardous post- consumer wood

3.2.2.2 Technical parameters

The biomass feedstock has physical and compositional differences: heating value, moisture, ash content, bulk density or chemical composition. For example, low ash and moisture feedstock contents mean higher heating values and are subsequently preferred from the technical point of view since they lead to higher process efficiencies. With high biomass moisture content, the overall calorific value of the produced gas decreases due to the energy required to evaporate the additional water before combustion and gasification takes place. Biomass should be preheated or dried up to moisture content between 10-20% or lower, before it enters the gasifier. Circulating and bubbling fluidized bed reactor types both work optimally within the moisture range of 10-15%, even if they are functional also in higher water concentrations [141].

Moreover, particle size distribution and bulk densities should be considered, especially when talking about gasifier feeding system and its fluidized conditions. Smaller particle sizes exhibit higher total gas yields, lower char/ tar yields and more homogeneous product composition in overall. Furthermore, feedstock with smaller particles have higher porosity and larger specific surface area, which results in higher chemical reaction rates [142]. In general, the feedstock physical properties, like moisture content and bulk density, can be improved by means of pretreatment (i.e. drying, chopping, chipping, pelletizing, etc.), since these kinds of processes don't affect chemical composition. Pre-processing is required to avoid feeding problems in the bench- and pilot scale tests. Pre-processing requirements are lower in a commercial scale unit, and therefore the costs related to pelletizing can be avoided.

Another crucial issue concerning the technical feedstock characteristics, is its inorganic content [143, 144]. Many of the problems in thermochemical processes are related to its quantity and behavior. The compositional differences in the inorganic matter influence destiny of elements in the gasification process and the behavior of the produced ashes. A high concentration of alkali metals (Na, K) leads to a low melting/sintering point of ash. The sintered ash limits the maximum gasification temperature and taking into consideration that in low gasification temperatures excessive tar formation can be observed, it can be realized that melted ash and ash handling in general can be proved a critical problem. The ash fusion temperature gives an indication of the extent of ash agglomeration and clinkering within the gasifier. Therefore, the selected fuels for the gasification process should preferably have low ash content and more specifically, below 5%. Low gasification temperature also leads into formation of larger amounts of inert char.

Other parameters that should be taken into attention are the sulfur, nitrogen and chlorine feedstock content. Sulfur content must be considered as a key element, not only because of its interactions with other elements in the gasifier bed, but also by its H_2S-release to the product gas. HCN production would demand special treatment as well. In general, the contaminants concentrations (H_2S, NH_3, HCl, HCN, etc.) in the produced gas largely define the gas cleaning strategy (and related costs), and subsequently the suitability (or not) of a solid feedstock for BtL applications.

The main technical parameters that should be considered for biogenic feedstock selection are presented in Table 10.

Table 10. Main technical parameters for biogenic feedstock selection.

Technical criteria
Heating value
Moisture content
Elemental composition (gasification behavior)
Ash content & composition (e.g. alkali metals)
Sulfur, Chlorine, Nitrogen content
Bulk density & particle size distribution

3.2.2.3 Market parameters

Wood-based fuels represent the main source of bioenergy. Major share of wood fuels is derived from the by-products of the forest industry, including bark, sawdust, and other industrial wood residues.

In the forestry sector, residue bark from coniferous species, like spruce and pine, is considered as the most promising source, while in the agricultural sector wheat straw leads the potential and represents one of the most important lignocellulose residues in EU. The power plants that have used straw are generally able to pay lower prices than for wood feedstock (< 20 EUR/MWh) [145].

Concerning the raw biomass processing, pelletizing is the most widely used process for the production of high density, solid energy carriers from biomass. The main advantages of the biomass pellets, compared to the raw biomass, are their higher energy density, homogeneous quality, improved storage properties and better applicability for different uses like gasification. A typical energy content is 16.5 MJ/kg with a mass density of 650 kg/m^3. The production costs of wood pellets depend on the feedstock source and on the requirements of drying, but can be estimated to vary in the range of 20-40 EUR/MWh [146]. Wood chips can be also used for energy purposes. They source either from recovered/waste wood or from harvesting residues such as branches, tops, thinning or other inferior wood not suitable for pulp and paper production. Although typical energy content and density (12.5 MJ/kg & 220 kg/m^3) are lower than for wood pellets, international trade is still feasible especially for shorter trade distances.

The main market parameters that should be considered for biogenic feedstock selection are presented in Table 11:

Table 11. Main market parameters for biogenic feedstock selection.

Market criteria
Availability & sustainable sourcing
Transport costs, storability, and storage costs
Seasonality impact
Pre-treatment requirements
Compatibility with the Energy Policies (i.e. RED)

3.2.3 Key feedstock types and potential capacities in Europe

An attempt has been made to distinguish some promising types of feedstock from the main residual biomass categories (i.e. forestry residues, agricultural residues). The predictive potential (for 2030) of biogenic residues in Europe indicates that there is a suitable ground in terms of capacity in order sustainable supply chains to be built and efficient full-scale gasification plants that could potentially benefit from. The administrative level used for the feedstock screening was the NUTS 1 level. The NUTS classification (Nomenclature of territorial units for statistics) [147] (Figure 23) is a hierarchical system for dividing the economic territory of the EU serving:

- the collection, development and harmonization of European regional statistics
- socio-economic analyses of the regions
  - NUTS 1: major socio-economic regions
  - NUTS 2: basic regions for the application of regional policies
  - NUTS 3: small regions for specific diagnoses
- framing of EU regional policies

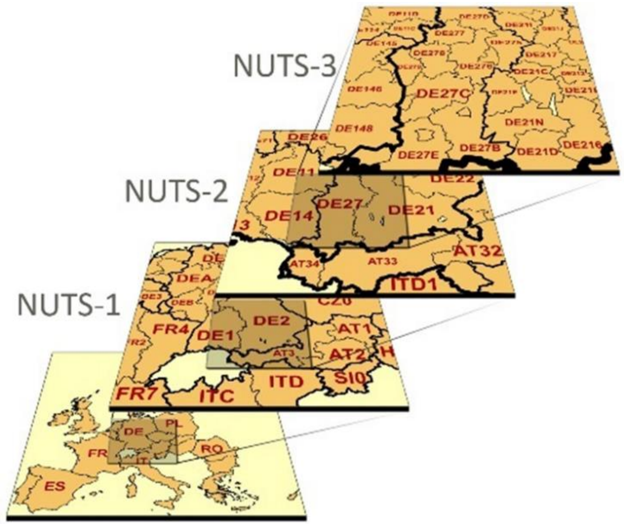

Figure 23. NUTS classification system. [147]

3.2.3.1 Woody prunings

The focus for estimating the biomass potential from permanent crops will be on the pruning material and not on the trees and stumps that can be removed at the end of a plantation lifetime. Pruning is a normal practice to enhance and maintain the production of the main fruit; thus is a cyclical activity delivering a stable amount of biomass every year. Permanent crops in Europe are usually arranged in classes: olive, vineyard, fruits, citrus, nuts (dry fruits) and others. However, some countries are specialized in the production of fruits, olives and grapes, mostly in the Mediterranean area and mild climatic areas. In Spain, Italy, and Greece, olive and vineyard are the prevailing crops, offering a greater sustainability potential in comparison with the other permanent crops (Figure 24, Figure 25). Moreover, according to previous results from European projects, like the uP_running [148] and AGROinLOG [149], the prunings from these two permanent crops hold another notable advantage compared to the most of fruit tree prunings, which lies on the fact that they do not present high concentrations of sulfur and other metals that can put in danger the steady process operation.

Samples of olive and vineyard prunings were collected from Greece and Spain, respectively. A series of analyses were carried out for the characterization of the samples in order to determine the key material properties (by means of proximate and ultimate analysis) and initially evaluate its gasification potential (Appendix, Section A-2, Table A1).

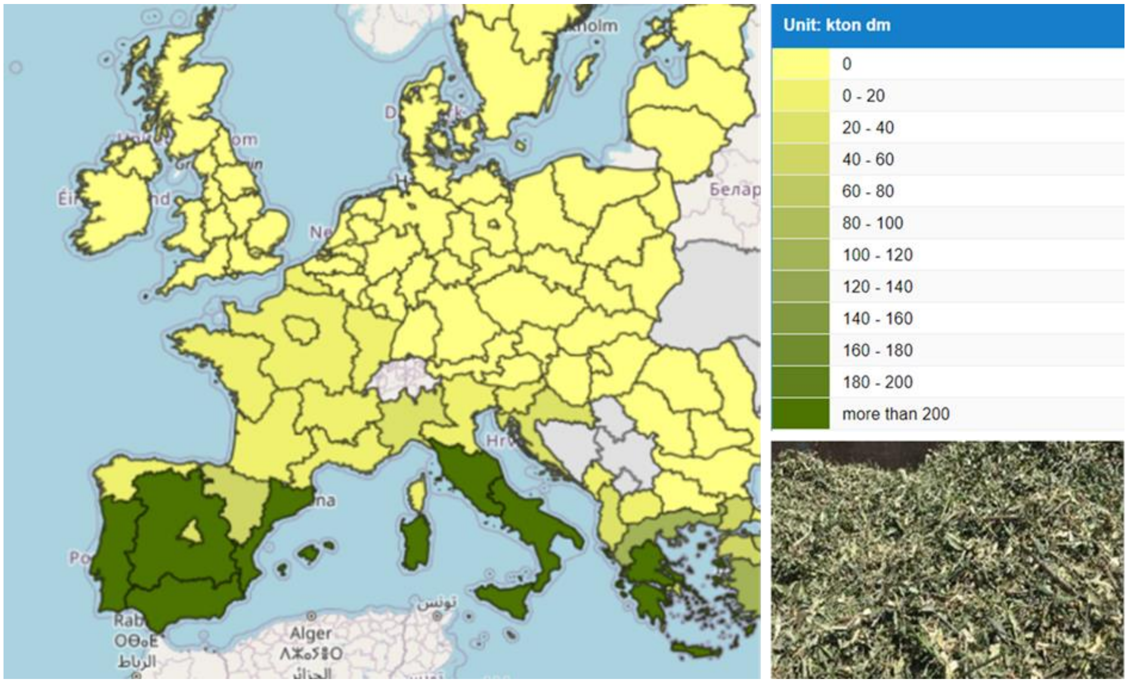

Figure 24. Annual (residual) biomass potential from the olive tree plantations around Europe (2030 - NUTS1) [138].

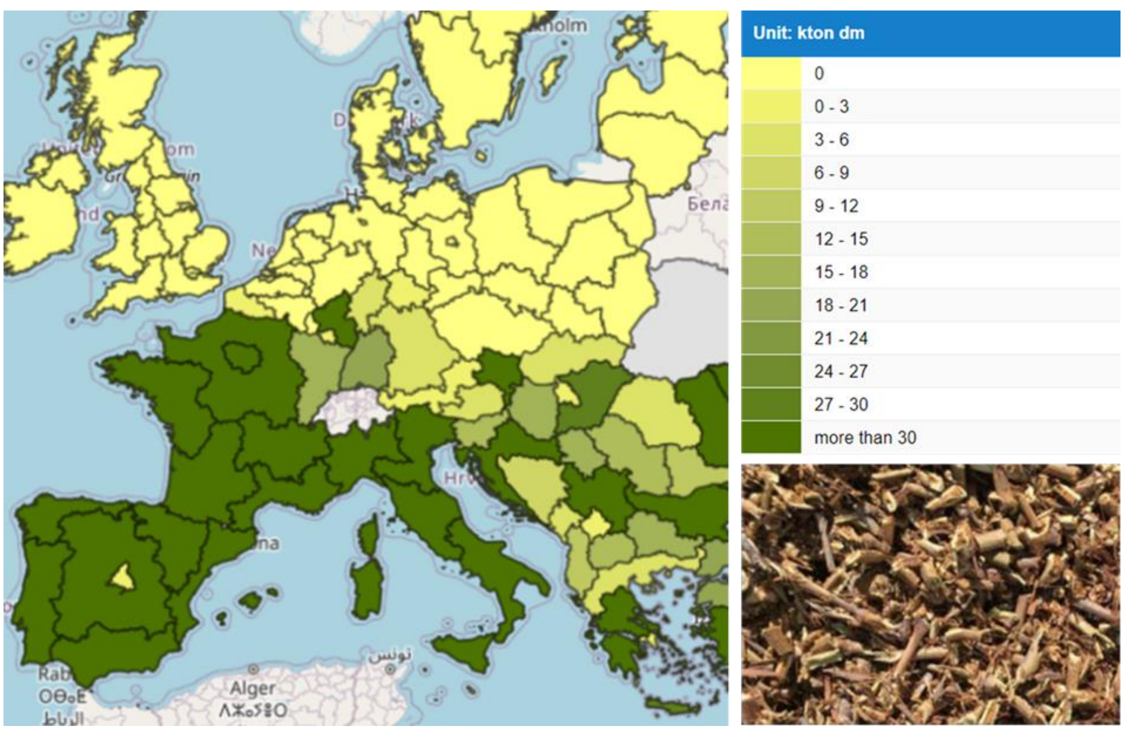

Figure 25. Annual (residual) biomass potential from the vineyards around Europe (2030 - NUTS1) [138].

3.2.3.2 Straw/stubbles

Wheat, barley, oat, and rye are the most popular cereal crops that are cultivated in over 100 countries in the world. France, Germany, Ukraine, and some other central European countries are the leading producers of cereals in Europe, and subsequently the countries where the largest straw capacities are generated (Figure 26). Straw is a term used for all harvestable residues after wheat and barley grain have been collected by grain harvesting, and includes major parts of the stem and leaves. For off-field utilization, straw is collected in packs or bales, which are produced by self-propelled baling machines. If straw is not collected, it can be ploughed into the field or left as a mulch layer that covers the top soil [150]. Currently cereal straw is used as feedstuff, as fertilizer, in the pulp and paper industry, for production of nanomaterials and for production of biofuels. One of the main reasons that cereal straw presents a wide range of uses is its physical, chemical and thermochemical properties [151]. At the same wavelength is also the sunflower husk, which in pellet form is quite competitive with the pellet from the cereal straw. Sunflower derived residues can be found in decent quantities especially in Ukraine, while France is following [152]. A sample of Italian cereal straw was secured, the main properties of which can be found in the Appendix (Section A-2, Table A1).

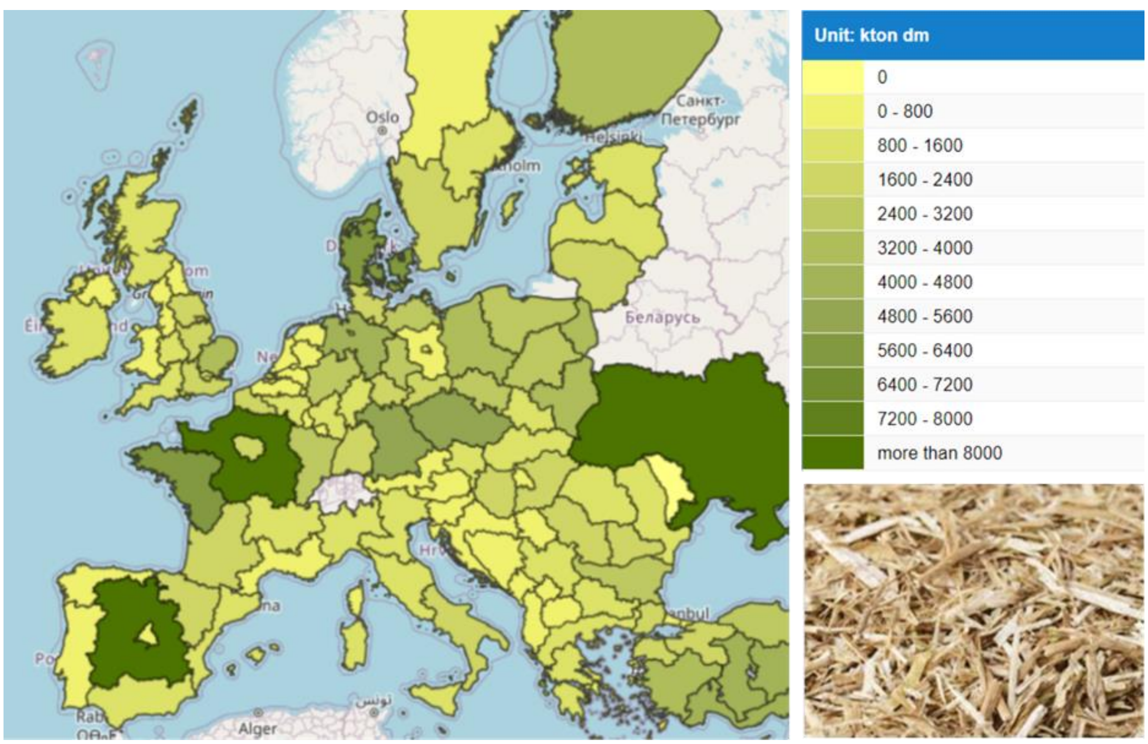

Figure 26. Annual (residual) biomass potential of cereal straw around Europe (2030 – NUTS1) [138].

3.2.3.3 Forestry/wood residues

Forests are a natural and abundant source of bioenergy, from which vast amounts of wood-based fuels are produced annually either as primary residues derived from silvicultural and harvesting operations or as by-products of the forest industry [153]. Logging residues belong to the primary forestry residues and represent a remarkable share of wood-based fuels that are used for energy generation. Logging residues consist of treetops, branches, needles/leaves, and non-merchantable stem wood. However, the major share of wood-based fuels consists of bark, sawdust and other industrial wood residues. Wood waste is mostly the result of wood processing industries like sawmills, plywood, panels, and other wood supplies that may generate significant amount of by-products. Indicatively, wood bark is generated as a by-product of the wood processing industry, and is usually used to fuel boilers in forestry plants. Sawdust is generated during the production processes of sawmills and can be used in a variety of ways (e.g. pellets) [154]. The largest amount of logging residues (including their secondary residues like bark and sawdust) is concentrated in Nordic countries (Figure 27, Figure 28). Samples of forestry residues (logging chips & crushed bark) from Finland were secured and characterized (Appendix, Section A-2, Table A1).

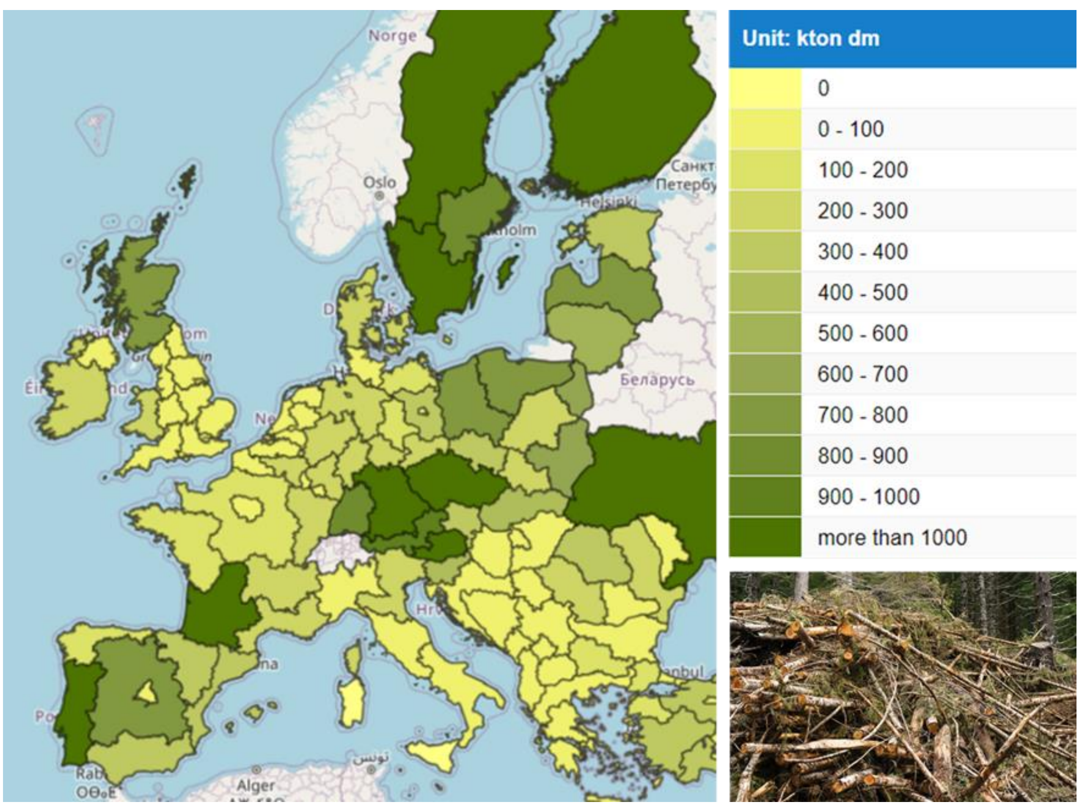

Figure 27. Annual potential from logging residues of conifer trees around Europe (2030 – NUTS1) [138].

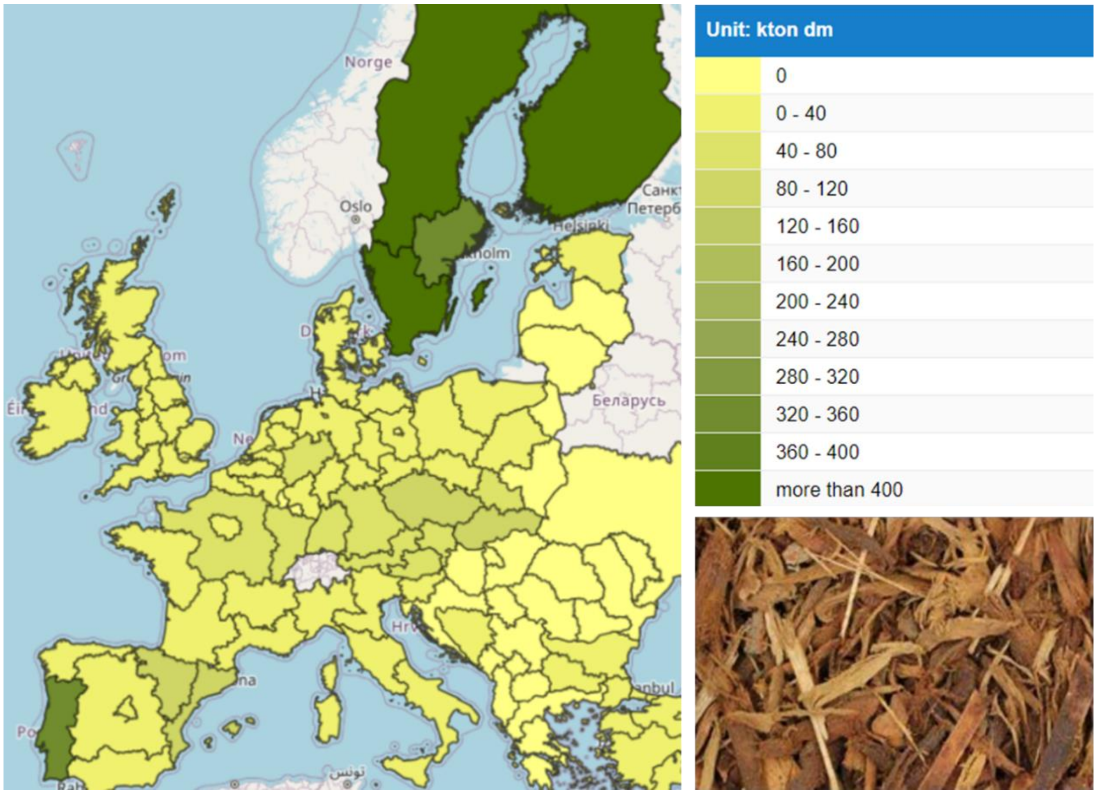

Figure 28. Annual potential from bark residues around Europe (2030 – NUTS1) [138].

3.2.4 Summary

The EU biofuels policy, as outlined in the RED III directive, mentions the promotion of residue-based biofuels (advanced biofuels). The primary sources of biogenic residues that can be utilized for energy production (such as gasification) are forestry and agricultural residues.

With the assistance of the S2Biom toolset, a classification of relevant biogenic residues was carried out and their projected capacity (for 2030) throughout Europe was examined. Using literature data as well as available logistics models for agro-biomass, the most important technical and market specifications were identified. Certain types of feedstock that could potentially fulfill the key requirements for the implementation of large-scale BtL applications (i.e. capacity, market scalability, technical performance) are highlighted:

- Woody prunings (e.g. olive, vineyard)
- Straw/stubbles (e.g. cereal straw)
- Primary forestry residues (e.g. logging) and secondary wood residues (e.g. bark, sawdust)

The Mediterranean countries exhibit accumulations of both olive tree and vineyard prunings. A fact quite expectable, since Spain, Italy, and Greece consist the top three olive producers worldwide, while they are also well versed in the wine industry. France, Germany, Ukraine, and some other nations in central Europe are the top cereal providers in Europe, and at the same time the regions with the largest straw potential. Nordic countries are offered ideally for forest valorization. Primary forestry residues as well as residues from the wider wood industry are sourcing in a potentially sustainable way.

Finally, it should be noted that co-processing and blending (if technically feasible) of some of the mentioned biogenic residues has the potential to both generate new supply chains and improve the sustainability of the ones that are now in place through Europe. Feedstock-flexible plants can tackle seasonality challenges and significantly decrease the associated feedstock and logistics costs.

Chapter 4

Introduction of a novel gasification-driven Biomass-to-Liquid (BtL) scheme – Design considerations

4.1 Introduction

An alternative Biomass-to-Liquid (BtL) route for the production of drop-in aviation and maritime fuels is introduced. The proposed concept aims to establish a combined thermochemical-biochemical pathway for the treatment of biogenic residues that minimizes the shortcomings of the existing technologies and takes advantage of their strong aspects in order to produce elevated yields of the desired fuels with limited energy consumption. The suggested process chain can be divided into three distinct parts: the thermochemical, the biological, and the thermocatalytic. Concerning the first (thermochemical) part, a Dual Fluidized Bed Gasification (DFBG) unit is considered for the syngas production from biogenic residues followed by a catalytic tar reformer, while for the second (biological) part, a double-stage syngas-to-acetate-to-triglycerides (TAGs) fermentation unit is involved accompanied by a lipids extraction and purification system. The last (thermocatalytic) part refers to the hydrotreatment unit, where the obtained TAGs are converted into drop-in liquid fuels. The described BtL concept is illustrated in Figure 29.

The European Horizon 2020 project BioSFerA [9] has undertaken the realization and implementation of the mentioned integrated concept at pilot scale. DFBG is a semi-commercially proven technology that has already been tested with a wide variety of feedstock types, such as wood pellets/chips, bark, straw, sewage sludge, etc. [155]. However, so far, no previous research had examined the connection of a DFBG unit with a double-stage fermentation system at such level. Only bench-scale experiments had demonstrated the potential of a two-stage bioprocess for the conversion of syngas to acetate, and finally lipids [156]. To date, no known study has focused on the hydrotreatment of this type of microbial oil deriving from yeast, although there is a large variety of alternative oils (e.g. vegetable oils, fats or UCOs) that have already been hydroprocessed for the production of liquid fuels.

In this study, a conceptual design based on the aforementioned process chain is developed and presented. Heat and mass balances are calculated for the integrated scheme via full-scale process simulations in Aspen Plus^{TM} assuming a thermal input of 200 MWth with crushed bark as feedstock. Three different operational scenarios have been examined and assessed mainly through overall performance indicators; carbon utilization (CU), energetic fuel efficiency (EFE), liquid fuels mass yield and overall energetic efficiency. Design considerations and their impact on process efficiency were performed for the assumed scenarios, including parameters such as internal/external hydrogen securement via Pressure Swing Adsorption (PSA)/water electrolysis, oxy-/air- acetate fermentation as well as autothermal/allothermal operation of the catalytic reformer. The development of this preliminary process design is based on available literature data and relevant experimental studies of the main individual sub-processes. The main objective of the present study is to define the key process specifications and evaluate the potential of the proposed concept compared to other competitive technologies. The investigated scenarios and the obtained primary conclusions can act as a benchmark for the further development and optimization of the integrated concept.

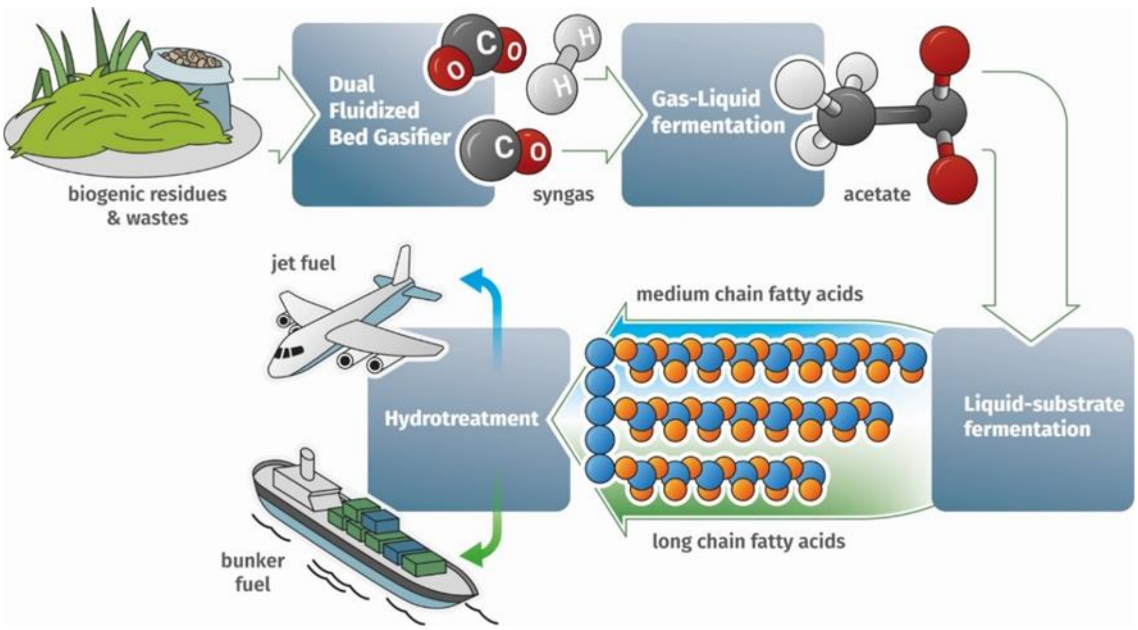

Figure 29. The examined BtL concept from start-to-end [157].

4.2 Materials and methods

4.2.1 Concept description

4.2.1.1 Feedstock selection and handling

Thanks to the DFBG technology, the process can be driven feedstock-flexible using a broad and variable portfolio of biogenic residues. Section 3.2 (Chapter 3) provided an extended feedstock screening and proposed some promising types of residual biomass including agricultural residues (woody prunings, straw), forestry residues (logging, bark), and other industrial wood residues (sawdust). The feedstock selection should also consider the pre-treatment requirements towards the optimization of the supply chain economics. Some mild (e.g. drying, chipping) or more intense (e.g. torrefaction, pelletizing) pre-treatment activities may be needed for some feedstock types prior gasification, although the pre-treatment requirements for the selected DFBG technology are expected to be rather limited in commercial scale [131].

4.2.1.2 Dual Fluidized Bed Gasification (DFBG) and Gas Cleaning

The conversion of the biomass feedstock into syngas is carried out with the DFBG technology. The DFBG operating principle was discussed in Chapter 3. The produced high quality (nitrogen-free) syngas is filtered at the gasifier exit, and subsequently is catalytically reformed. The reformer is heated by partial combustion with oxygen or air, and the reforming reactions consume steam and/or CO_2. The primary function of the catalytic reformer may be to convert tars and hydrocarbon gases to H_2 and CO, but it can also be modified to attain several targets related to the syngas purification requirements for the subsequent fermentation process. Depending on the gas cleaning needs, different catalyst loadings and reactor design can be applied. For example, HCN contents can be reduced to 1-10 ppm by using calcium-based bed materials in the gasifier followed by a reformer that is also active for NH_3 decomposition. Beyond that, depending on the purity level target, additional scrubbers and adsorbents can be implemented for the efficient removal of other syngas contaminants (e.g. H_2S, HCl, COS) prior the fermentation unit [131].

4.2.1.3 Double-stage fermentation (syngas → acetic acid → TAGs)

In the first step of the biological part of the process, syngas is converted into acetic acid under anaerobic conditions. Several anaerobic bacteria (*Clostridium*, *Acetobacterium*, *Eubacterium*) have shown their ability to ferment single carbon gases such as CO and CO_2 plus H_2 into chemicals, usually acetate, through the acetyl-CoA pathway. These bacteria are named acetogens. The acetyl-CoA pathway (Wood-Ljungdahl pathway) can utilize both CO and H_2 as a source of electrons and CO and CO_2 as a source of carbon [158]. Two critical factors, that highly influence the fermentation kinetics and consequently the acetate productivity, are the gas solubility and the ratios of CO_2/CO/H_2; especially CO and H_2 present low solubility in water. By recirculating the off-gas back to the fermenter, the unconverted syngas components can be recovered and recycled. At the same time, the broth containing the produced acetic acid in low concentration is extracted in a continuous way, and the liquid volume is kept constant by adding fresh culture medium. Increasing the pressure improves the gas solubility, and consequently the acetate production yield. A cell recycling system (hollow fiber membrane) is also required to retain the cells while extracting the liquid effluent from the fermenter.

The second fermentation step refers to the production of TAGs through an aerobic fermentation process. The production of lipids from acetate has been described in different microbial species. So far, the most efficient microorganisms in carrying out this conversion are the so-called oleaginous yeasts, as *Yarrowia lipolytica* and *Cutaneotrichosporon oleaginosus*. In order to obtain strains that exhibit high lipid concentration, yield and acetate conversion, a metabolic engineering strategy of *Y. lipolytica* can be adopted. The produced intracellular microbial oil mainly consists of fatty acids like oleate, stearate, and palmitate [159]. During the continuous acetate fermentation process, the dilute acetic acid effluent stream from the syngas fermentation enters the aerobic fermenter, where the targeted TAGs are produced in the presence of oxygen, additional nutrients, salts, and the oleaginous yeast (*Y. lipolytica*). A cell recycle system (hollow fiber membrane) can be installed to recirculate the cellular biomass in the bioreactor while extracting the effluent. During the continuous feed of the diluted acetic acid into the reactor, metabolic reactions take place and lipids are formed as intracellular products. At the same time, a gaseous CO_2-rich stream is formed and leaves the reactor from the top.

A simplified illustration of the double-stage fermentation scheme, containing both the anaerobic syngas fermentation and the aerobic acetic acid fermentation, is presented in Figure 30.

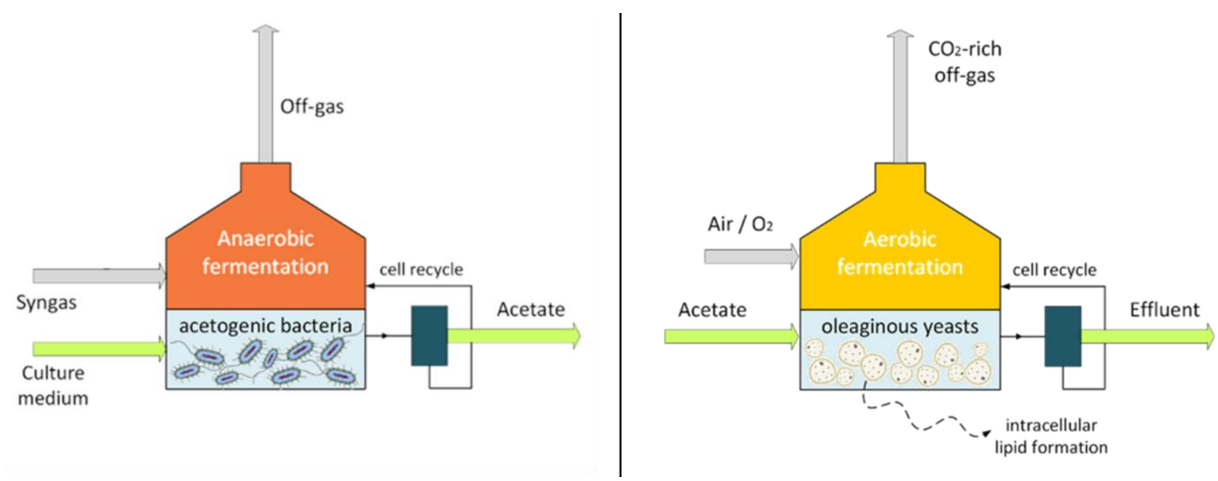

Figure 30. Syngas fermentation (left) and acetate fermentation (right) in a continuous mode.

4.2.1.4 Triglycerides (TAGs) purification

Lipids extraction from the oleaginous yeasts is an important step before hydrotreatment and the final liquid biofuel formation. As oleaginous yeasts store lipids in intracellular form, an extraction technique is required to obtain TAGs. Mechanical disruption (e.g. high-pressure homogenization) requires energy inputs such as shear forces, electrical pulses, waves or heat. Mechanical processes generally provide high product recovery yields with good management and scalability, but they are energy intensive. Steam explosion is an innovative method with reduced environmental impact, lower costs and energy demand, compared to other techniques that are widely used. In steam explosion, raw material is exposed to steam at 180-240 °C for several minutes and then is subjected to depressurization under ambient conditions. This generates an explosion that causes cell-wall disruption [160]. In a context in which heat flows are available as downstream of other processes, and so steam could be generated at low cost, steam explosion should be considered as a potential technology for the recovery of intracellular products reaching high yields. Then, microfiltration/centrifugation have been positively evaluated for their ability to separate oil from the broth deriving from steam explosion.

4.2.1.5 Microbial oil hydrotreatment

The final stage of the value chain includes the upgrading of microbial oil into drop-in aviation and marine biofuel. The core of the thermocatalytic part of the concept is the hydrotreatment unit where the consecutive hydrogenation, deoxygenation, isomerization and fractionation procedures of the purified TAGs take place. Common catalysts for this process are Pt, Ni or other metals based on Al_2O_3. In particular, the saturated fatty acids are converted to straight long-chain alkanes by hydrodeoxygenation and decarboxylation, co-producing propane, methane, water, CO, and CO_2. The deoxygenated straight chain paraffins are selectively hydrocracked or isomerized yielding highly branched alkanes. The resulted organic product is a mixture of straight and branched C_nH_{2n+2} that can be suitably used as drop-in liquid fuel. Fractionation is necessary to separate the jet from marine fraction.

4.2.2 Model overview

The proposed BtL value chain is separated in three (3) main parts; the thermochemical, the biological, and the thermocatalytic part. The thermochemical part refers to the DFBG unit and the following syngas conditioning that secures a smooth transition to the biological part (double-stage fermentation and lipids purification). The thermocatalytic part refers to the TAGs hydrotreatment in order the final liquid fuels to emerge. Two additional units, that could potentially interact with the BtL value chain and determine the plant operation mode, were investigated. The first one is a RES-based water electrolysis unit that covers the hydrogen and oxygen requirements of the plant, while the second one is a Heat Recovery Steam Generator (HRSG) unit for the efficient heat recovery and steam generation from the high-temperature thermochemical part. A block flow representation of the concept is provided in Figure 31.

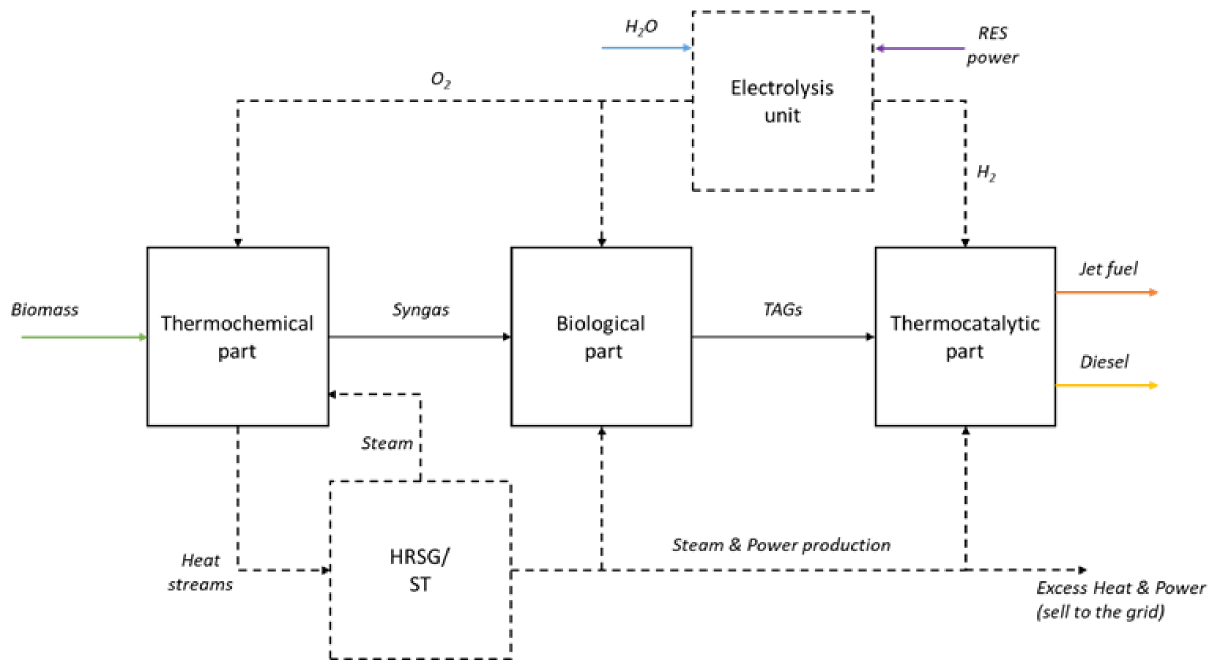

Figure 31. Block flow diagram of the BtL plant and potential operation modes.

The process model was developed in the commercial software Aspen Plus^{TM}. The simulations were performed at full-scale (200 MWth) and crushed bark was selected as feedstock. The main specifications of the feedstock used in the process simulations are presented in Table 12.

Table 12. Feedstock properties for crushed bark involved in the process simulations.

Mass flow a.r. (kg/s)				11.24		
Net Calorific Value LHV a.r. (MJ/kg)				17.79		
Proximate Analysis (%)						
Moisture		Fixed Carbon		Volatile Matter		Ash
8.4		18.5		77.8		3.7
Ultimate Analysis (%)						
Ash	Carbon	Hydrogen	Nitrogen	Chlorine	Sulfur	Oxygen
3.7	51.5	5.8	0.3	-	0.06	38.64

An important aspect for the correct operation and integration of the individual units in the simulation environment is the definition of the appropriate property methods for the efficient estimation of the thermos-physical properties of the components and streams. The IDEAL property method was selected for the thermochemical part, while the Predictive Soave-Redlich-Kwong (PRSK) method was used for the biological and thermocatalytic parts. For the development of the HRSG model, IAPWS-95 property method was used for the water side, and IDEAL property method for the flue gases side. A heat to power conversion efficiency equal to 45% is applied in case of coupling the HRSG with a Steam Turbine (ST). An average electricity demand of 180 MJ/kg of produced hydrogen (electrolyzer efficiency 70-80%) is set for the water electrolysis unit [161].

Concerning the thermochemical part, equilibrium models have been used for the implementation of the gasification and the reforming reactions. For kinetically and hydrodynamically controlled phenomena that cannot be predicted with the rules of chemical equilibrium (e.g. unconverted solid carbon, formation of gaseous hydrocarbons) fitting of selected parameters with experimental data was followed. The selected parameters and the fitting of the model were based on previous steam DFBG pilot tests with crushed bark [131, 162]. For the DFBG unit, a gasifier operating with steam at 780°C and an oxidizer operating with air at 880°C were considered. Char is the main fuel source of the oxidizer, but also off-gases from other sub-units of the integrated BtL scheme can be used as supplementary fuel. Filtration of syngas takes place at gasifier outlet, while the filter ashes are also directed to the oxidizer. A mixture of sand and limestone was used to represent the bed material. For the catalytic reformer, there are two design options. On the one hand, there is the autothermal reforming (ATR) where the reformer operates under autothermal conditions with the addition of oxygen or air as oxidation media and steam or CO_2 as reforming agent. On the other hand, there is the steam methane reformer (SMR) that is heated externally with the assistance of an air-heated combustor where purge gases are burnt in order to cover the energy requirements of the steam reforming reactions.

The core of the biological part of the process model is the two fermenters where syngas and acetic acid fermentation take place, respectively. For the syngas fermentation stage, *Moorella thermoacetica* was used as the reference acetogenic bacterium, and thus an anaerobic reactor operating at 55°C was considered since the optimal temperature range for these strains is 55–60°C

[163]. The operating pressure of the reactor was considered to be 5 bar in order to achieve higher solubility of the reacting gases in the liquid phase. Syngas derived from the reforming and purification units enters the anaerobic fermenter where it is partially converted into acetic acid. A minor syngas percentage is also consumed for the growth of the acetogenic bacteria. The aerobic fermenter, where the acetic acid fermentation takes place, operates at 30°C under atmospheric pressure. The acetic acid extracted by the first fermenter reacts with oxygen for the production of TAGs and non-lipid biomass (yeast growth). Triolein ($C_{57}H_{104}O_6$), tripalmitin ($C_{51}H_{98}O_6$), trilinolein ($C_{57}H_{98}O_6$), and tristearin ($C_{57}H_{110}O_6$) were selected as the representative TAGs produced during this phase.

For the thermocatalytic part, the decomposition of the produced TAGs is taken initially into account to simulate the fatty acid distribution that consists of palmitic acid ($C_{16}H_{32}O_2$), oleic acid ($C_{18}H_{34}O_2$), stearic acid ($C_{18}H_{36}O_2$), and linoleic acid ($C_{18}H_{32}O_2$). Then, an equilibrium reactor is employed for the simulation of the hydrotreating reactor involving hydrogenation and deoxygenation reactions. The reactor is set at 370 °C and 100 bar, while a hydrogen/TAGs ratio equal to 0.05 is assumed. The product yield is determined by the equilibrium state of the occurred reactions in it [164-166]. The produced liquid alkanes are separated from the gas phase (unreacted hydrogen, light hydrocarbons) and directed to the isomerization/fractionation section to retrieve the drop-in biofuels. The formed light gases are sent back to the DFBG unit to be used as supplementary fuel for the oxidizer.

4.2.3 Process configurations and examined scenarios

The process has heat, electricity, steam, air/oxygen, and hydrogen requirements. The overall plant efficiency, its operation mode and its full spectrum of capabilities are highly dependent on the effective securement and integration of all these parameters in the BtL scheme. The oxygen-driven components (i.e. autothermal reformer, aerobic fermenter) have been identified as key aspects concerning the overall process design.

An oxy-blown autothermal reformer (ATR) covers the heat requirements for the reforming reactions with partial oxidation of syngas. The high-quality syngas along with the relatively low content of light hydrocarbons derived from the DFBG unit make the energy degradation of the gas that takes place with its partial oxidation affordable, since the gas that leaves the reformer is a nitrogen-free gas, which still maintains a high energetic content that can be used entirely for the liquid fuels production. An ATR can be operated also with air instead of oxygen, but the extended presence of nitrogen in the reformed gas may cause problems in the biological part and its handling in general. On the other hand, an allothermal steam reformer (SMR) can be operated with external heating from a combustor that utilizes air. The impact of WGS reaction in this case, due to the excess steam in the reformer and absence of oxidation, may be stronger creating a local energetic upgrade of the reformed syngas, but the external heat requirements are larger and remarkable part of the syngas should be used for combustion instead of fermentation. The latter is rather inefficient from the overall BtL point of view. The two different possible operation modes of the catalytic reformer are illustrated in Figure 32.

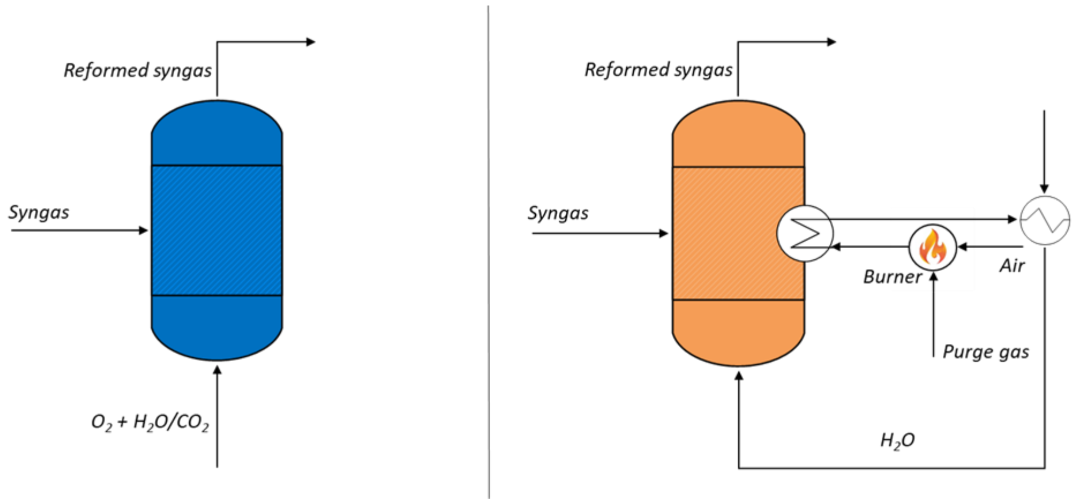

Figure 32. Autothermal (left) and allothermal (right) operation of the catalytic reformer.

Another procedure that has oxygen requirements is the aerobic fermentation of acetic acid. The process may be oxy-driven or air-driven. The difference is that fermentation with pure oxygen will lead to the formation of a quite pure CO_2 stream in the fermenter outlet and consequently strengthen the carbon capture and storage/utilization (CCS & CCU) ability of the plant.

There are also hydrogen requirements in the process chain and in particular in the hydrotreatment unit. The lower hydrogen requirements compared to the oxygen requirements of the plant, means that potential oxygen securement via water electrolysis would be accompanied with excess of pure hydrogen. The establishment of an electrolysis unit to cover primarily oxygen demands instead of hydrogen seems rather unreasonable and inefficient for any plant. However, in this way two off-gases (i.e. pure CO_2 from oxy-fermentation of acetic acid & pure H_2 from the water electrolysis) are formed and are capable of upgrading the plant either via their re-utilization in the biological part (i.e. gas fermentation) or via other catalytic routes of fuel synthesis. On the other hand, if there is not electrolysis implementation, then the required hydrogen for the hydrotreatment section can be obtained internally from syngas via PSA. Finally, the steam requirements of the plant can be covered with the HRSG section that utilizes the waste heat from the DFBG unit and produces steam. A Steam Turbine (ST) system for power production could be applied also in the end of the HRSG unit in case of excess heat in high temperatures. After considering all the above-mentioned points, the following scenarios have been developed and simulated:

1st scenario

In this case study, the establishment of an electrolysis unit is assumed for hydrogen production. This means that pure oxygen can be available also for the autothermal reformer as well as for the aerobic fermentation of acetate. The produced syngas is utilized entirely for the final fuels production, meaning that the efficiency of the BtL plant is high and it can be further enhanced from the emerging pure streams of H_2 and CO_2. Of course, since water electrolysis is a rather expensive choice, it can be considered only in the case of low-cost RES electricity. Otherwise, this scenario refers to a scheme with high electricity demands. (Figure 33)

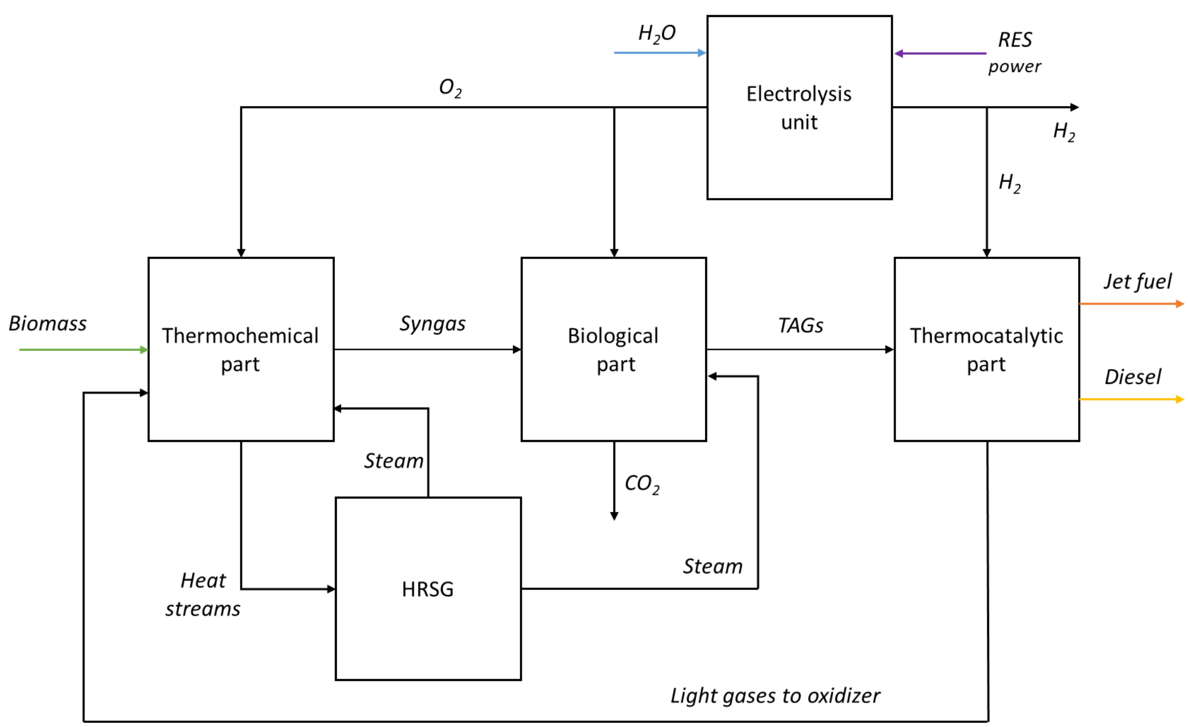

Figure 33. The block flow diagram of the 1st operation mode for the BtL plant (1st scenario).

2nd scenario

In this case study, electrolysis unit is not involved. Pure industrial oxygen can be purchased externally for oxy-autothermal reforming or oxy-fermentation of acetate. Otherwise, autothermal reforming with limited air can be applied and respectively air fermentation that will lead to a N_2/CO_2 mixture in the fermenter gas outlet. The chemical energy of the produced syngas is utilized once again almost entirely for the biofuels production, apart from a small portion of hydrogen that is extracted via PSA from the recirculating off-gases of the anaerobic fermenter in order to secure the hydrotreatment hydrogen requirements. (Figure 34)

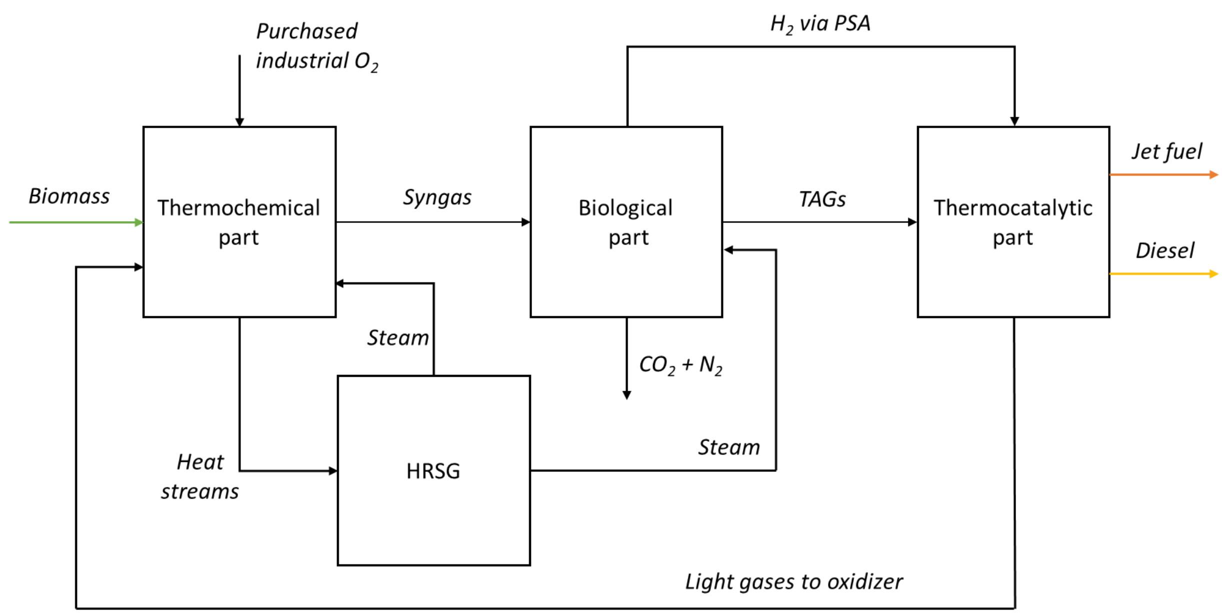

Figure 34. The block flow diagram of the 2nd operation mode for the BtL plant (2nd scenario).

3rd scenario

In this case study, no use of pure oxygen is considered neither in the reformer nor in the aerobic fermenter. The technology of SMR is applied, which imposes an assisting combustor that utilizes air and part of the syngas to provide the appropriate heat to the reformer. This is achieved by extracting a portion of the recirculating off-gases of the anaerobic fermenter and sending them to the SMR combustor. The hydrogen requirements are covered again by the same stream via PSA and therefore the syngas ‘losses’ in terms of fuel production are expected remarkable and the BtL plant’s efficiency low. However, the flue gases stemming from the SMR combustor in this case is an additional hot source that can be thermally exploited. The primary objective is the steam generation for the reforming, but its further thermal utilization could boost a potential power generation of the plant with the addition of a ST. (Figure 35)

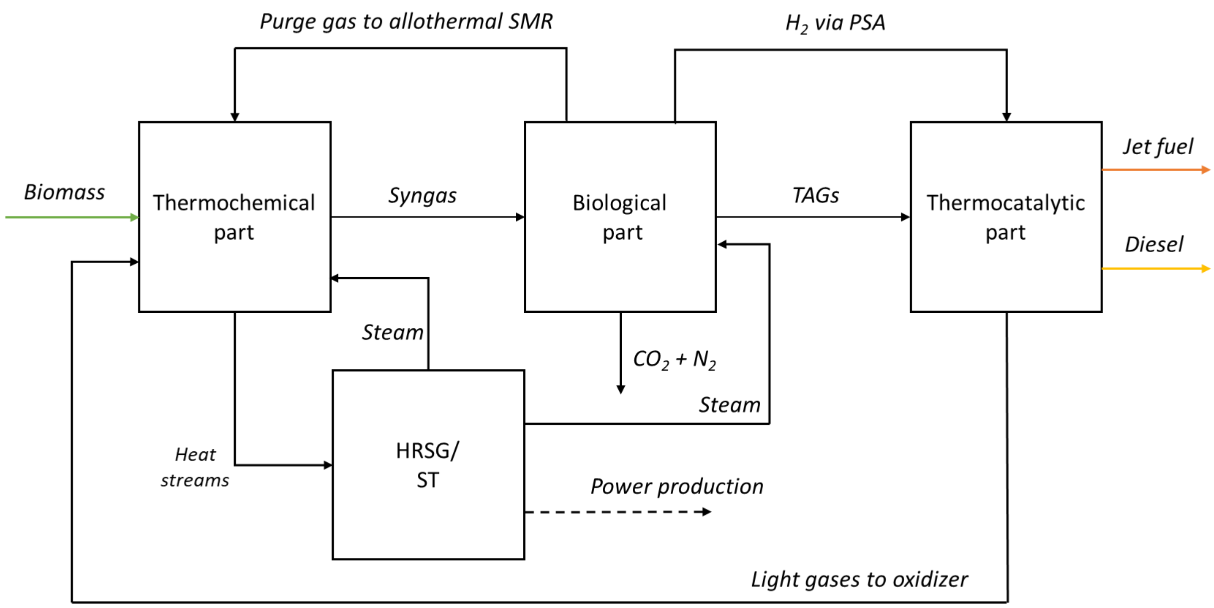

Figure 35. The block flow diagram of the 3rd operation mode for the BtL plant (3rd scenario).

The overview of the examined scenarios is presented in Table 13 in a more concise form.

Table 13. Integration scenarios and potential operation modes for the BtL concept.

	1st scenario	**2nd scenario**	**3rd scenario**
Water electrolysis unit	✓		
Oxy-autothermal reformer	✓	✓	
Allothermal reformer			✓
Acetate oxy-fermentation	✓		
Acetate air-fermentation		✓	✓
Pressure Swing Adsorption		✓	✓
Heat Recovery Steam Generator	✓	✓	✓
Steam Turbine			✓

4.3 Results and discussion

The heat and mass balances are calculated for each case study and indicators for the overall plant performance are assessed. The following performance indicators are introduced:

- Carbon Utilization (CU) is the fraction of carbon in initial feedstock that is converted to the final liquid fuels

- Energetic Fuel Efficiency (EFE) is the fraction of chemical energy in the initial feedstock that is transferred to the final liquid fuels
- Liquid fuels mass yield ($yield_{liquid}$) is the mass flow ratio of liquid fuels to solid feedstock (crushed bark)
- Energetic Efficiency (η_E) is the energy ratio of the sum of chemical energy of liquid fuels plus electricity produced, to the sum of chemical energy in the initial feedstock plus electricity consumed

4.3.1 Carbon balance

In the 1st case study, a water electrolysis unit feeds the BtL plant with oxygen and hydrogen, while the HRSG unit exploits the thermal load of the hot gases to cover the process steam requirements (i.e. gasification, reforming, lipids purification). In case all the oxygen requirements are covered from the electrolyzer, excess of hydrogen and a quite pure stream of CO_2 are obtained. The CU of the BtL plant has been calculated equal to 26.44%. A high carbon content (43.37%) is found among the outlet gas streams of the biological part, mainly through the CO_2-rich stream that leaves the aerobic fermenter (36.94%) and secondly through the purge gas (bleed stream) extracted from the recirculation gases of the anaerobic fermenter (6.43%). Further utilization of this CO_2-rich stream along with the hydrogen excess sourcing from the electrolyzer could potentially increase the CU of the BtL plant and reach values greater than 37%. The rest carbon 'expenses' of the process are the flue gases leaving the oxidizer (24.23%), the carbon utilized for the cellular biomass formation in both fermenters (5.22%) as well as the low organic content of wastewaters (0.74%). (Figure 36)

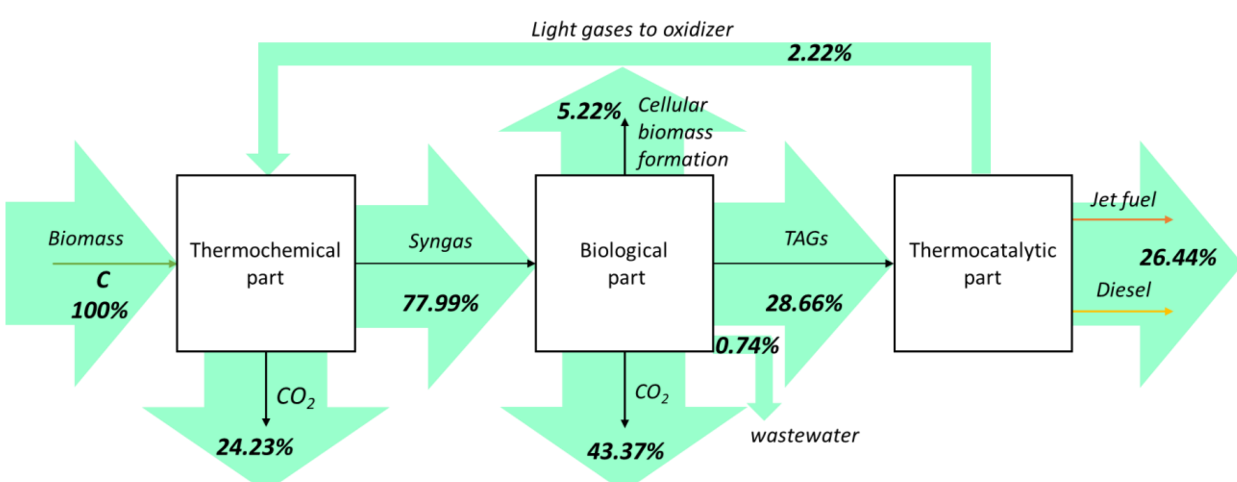

Figure 36. Estimated carbon balance of the 1st operation mode.

In the absence of an electrolysis unit in the context of the 2nd case study, autothermal reforming is performed with the assistance of externally purchased industrial oxygen, while the hydrogen requirements of the hydrotreatment unit are covered via PSA with extraction from the off-gases of the anaerobic fermenter. Industrial oxygen could be purchased also for the aerobic fermentation in order to achieve high CO_2 purity in the off-gases, but this would lead to remarkably higher operational costs. The internal H_2 securement, that can be considered as a small syngas 'loss' for the BtL plant, affects the efficiency of the syngas fermentation and is translated to slightly lower syngas conversion to acetate and consequently lower liquid fuels production and carbon conversion to biofuels. In particular, the obtained CU for the 2nd scenario is measured at 25.19%. Since the plant's hydrogen requirements are not extended, PSA technology might be preferable in terms of pure hydrogen generation in comparison with the establishment of a whole electrolysis unit. (Figure 37)

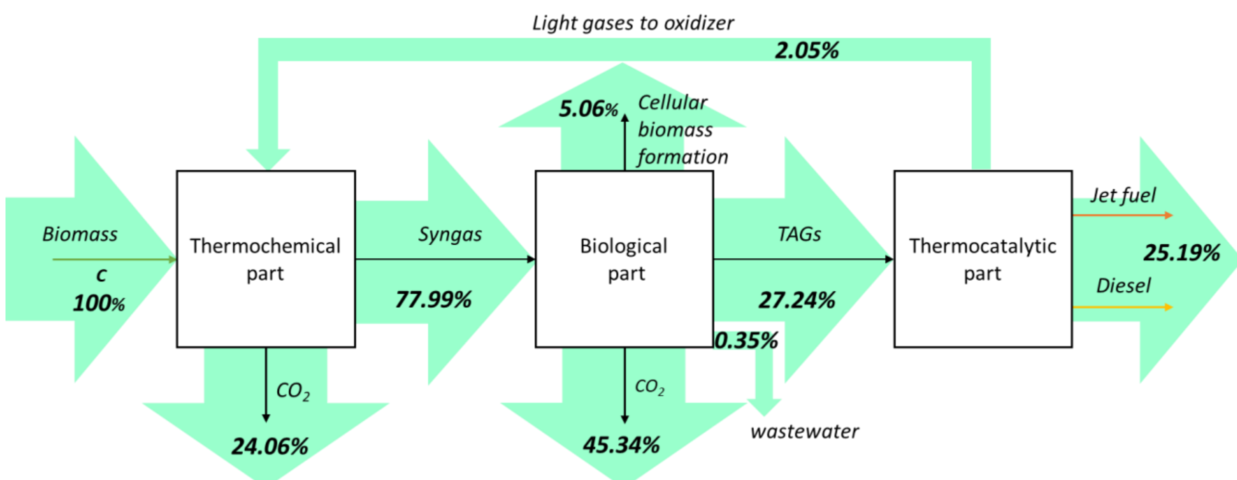

Figure 37. Estimated carbon balance of the 2nd operation mode.

In the integrated concept of the 3rd case study, there is not any pure oxygen involvement since the reforming (i.e. allothermal) as well as the aerobic fermentation procedures are performed with air utilization. The required heat input for the allothermal reformer is secured with partial gas extraction from the recirculating gases of the anaerobic fermenter. The same goes for hydrogen, which is extracted via PSA from the same stream. The reformer operates at 900 °C and the assisting combustor at 950 °C. The obtained CU for this case study is equal to 22.86%. A remarkable carbon content (20.52%) is transferred to the supporting combustor of SMR and ends up as an additional CO_2 emission from the thermochemical part. Therefore, in terms of carbon, an increase in the carbon content that is released from the thermochemical unit is observed due to the presence of two flue gas sources now (i.e. DFBG oxidizer & SMR combustor). The allothermal operation of the reformer seems to have a notable negative impact on the overall performance of the BtL plant, since a non-negligible amount of syngas ends up as flue gas in the SMR combustor instead of acetate and subsequently liquid fuel. (Figure 38)

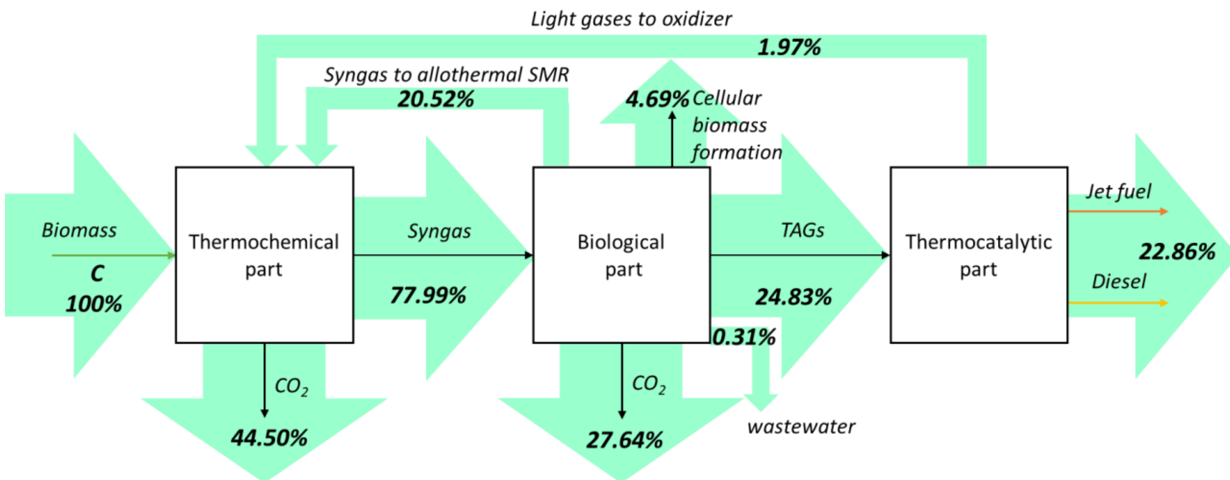

Figure 38. Estimated carbon balance of the 3rd operation mode.

The CU factors of the investigated scenarios are relevant with the calculated liquid fuels mass yields that are presented in Table 14. The highest liquid fuel yields are obtained for the 1st scenario where the supply of pure hydrogen and oxygen can potentially boost the liquid fuels production, while the 2nd scenario achieves competitive numbers without the energy consuming electrolysis addition. The 3rd scenario, due to the remarkable syngas losses in the allothermal reforming, presents the lowest fuel yields.

Table 14. Liquid fuels mass yield for the investigated scenarios.

Scenario	1	2	3
crushed bark (kg/s)	11.24	11.24	11.24
liquid fuel (kg/s)	1.65 (2.11*)	1.57	1.42
$yield_{liquid}$ (kg/kg)	0.147 (0.188*)	0.140	0.126

*these numbers refer to further exploitation of the CO_2 and H_2 streams that can be obtained in the 1st scenario.

4.3.2 Energy balance

The heating value of the obtained raw mixture of jet/diesel paraffins, which is considered as the final product of the present simulation study, was measured in the range of 44-45 MJ/kg (LHV-based) in every case.

The EFE for the 1st scenario is measured at 37%. Heat recovery for steam generation and the oxidizer's air pre-heating is performed from the hot streams of the DFBG unit (15.35%). The main energy losses are observed in the biological synthesis of TAGs via double-stage fermentation (42.25%), while the losses from the syngas cooling to the operating temperatures of the biological part (7.5%) and the hydrotreatment unit (1.5%) are lower. The electrolysis power consumptions only for the hydrogen requirements of the hydrotreatment unit have been considered as well. The redirection and the re-utilization of the quite pure CO_2 stream sourcing from potential oxy-fermentation of acetate will enhance the CU as well as the EFE of the plant in a remarkable way (i.e. CU>37% & EFE>45%). However, a prerequisite of this strategy is the extended electrolysis operation (i.e. higher power consumptions) for pure oxygen supply. (Figure 39)

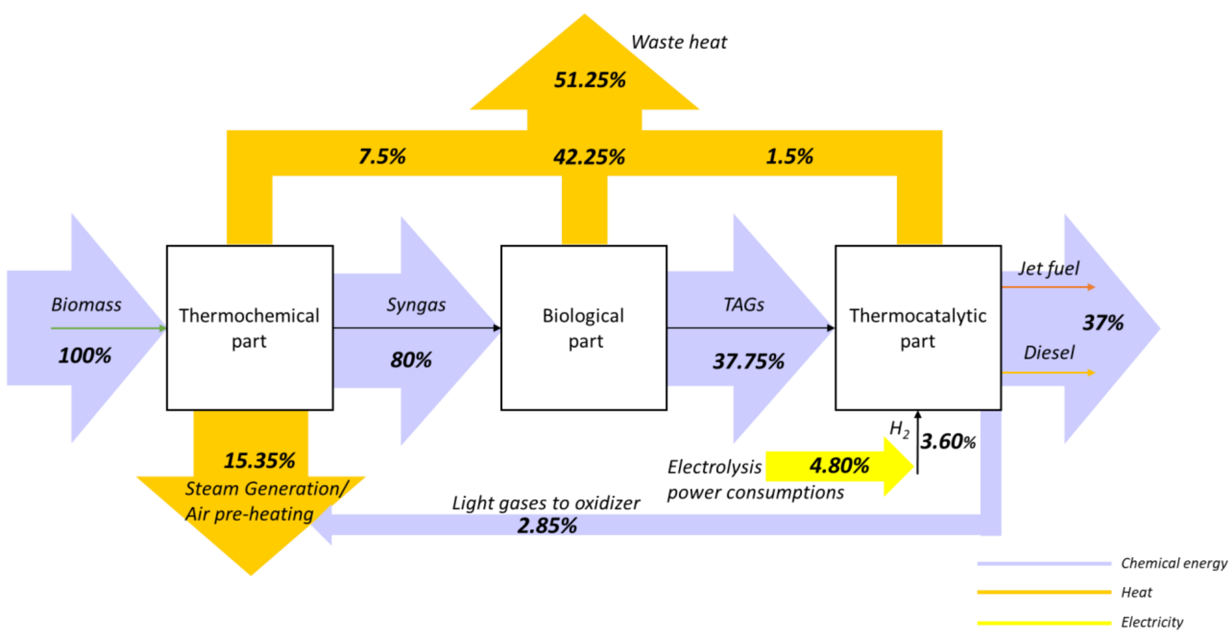

Figure 39. Estimated energy balance of the 1st operation mode.

Within the 2nd scenario, the impact of the internal hydrogen extraction in the energy balance of the process can be observed. An EFE equal to 35% is obtained. The lower acetate production leads to lower energy content of the produced TAGs. The observed decrease in CU & EFE of the BtL plant can be characterized as affordable. The involvement of the PSA technology and the internal securement of the limited hydrogen needs of the process seem to have a controllable effect on the process performance. The avoidance of an electrolysis unit would drastically reduce the capital and operational costs of the plant. However, the main shortcoming of a scheme without the capability of pure oxygen is that the off-gases of the aerobic fermenter will be a mixture of CO_2 and N_2 and therefore their carbon re-utilization will be difficult. (Figure 40)

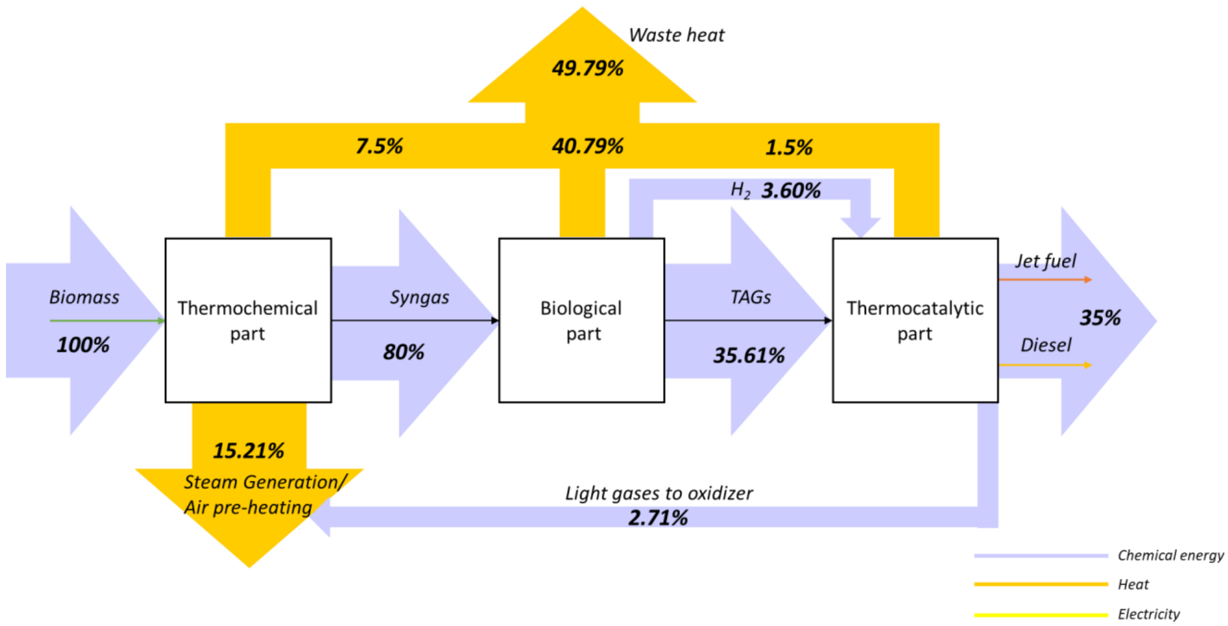

Figure 40. Estimated energy balance of the 2nd operation mode.

The decreased fuels production of the BtL plant in the 3rd scenario is also reflected in the EFE that is calculated at 31.5%. The purge gas that is transferred to the reforming combustor contains a remarkable energy content (25%) that does not participate in the CU or EFE enhancement. However, the flue gases of the SMR combustor is a hot stream that updates the heat recovery and steam generation capability of the plant. For this reason, this is the only case study that the addition of a Steam Turbine could make sense in terms of power production (>10% of thermal input). It has to be mentioned that this is the only case that seems to have the potential to offer power-independence of the plant via a polygeneration scheme of power, heat and fuel production. (Figure 41).

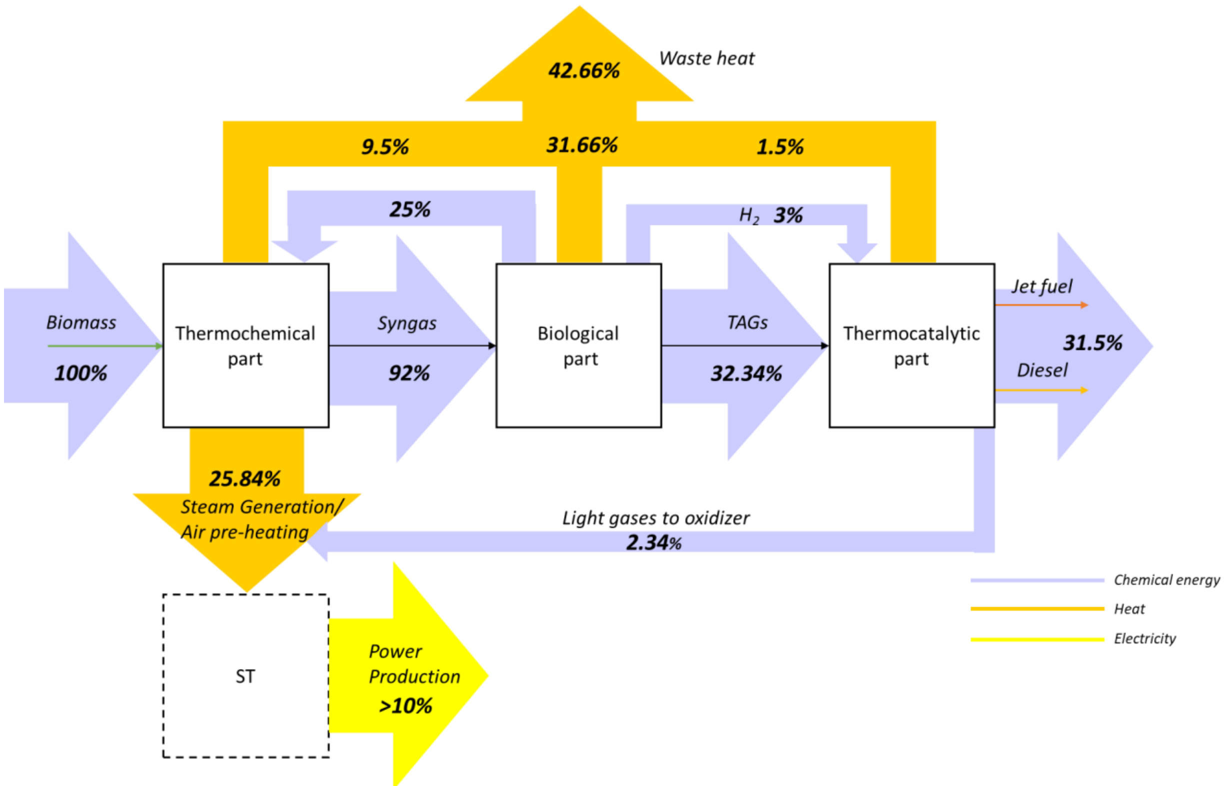

Figure 41. Estimated energy balance of the 3rd operation mode.

Aiming to obtain a performance overview of the concept in terms of energy quantity and quality distribution in the examined scenarios, the corresponding energetic efficiencies (η_E) have been calculated (Table 15):

Table 15. Overall energetic efficiency for the investigated scenarios.

Scenario	1	2	3
Fuels energy content (MW)	74 (90*)	70.5	63
Feed thermal input (MW)	200	200	200
Electricity produced (MWel)	0	0	21
Electricity consumed (MWel)	16 (102*)	5	5.5
Energetic efficiency, η_E (%)	34.2 (29.8*)	34.4	40.8

*these numbers refer to further exploitation of the CO_2 and H_2 streams that can be obtained in the 1st scenario.

The 3rd scenario may present the higher overall energetic efficiency (~40%) due to its polygeneration scheme, but on the other hand it is the scenario with the lowest performance indicators concerning liquid fuels production (EFE & CU). On the contrary, the 1st and the 2nd scenarios come up with lower and similar overall energy efficiency (~34%) since power production is not envisaged in these cases, but present higher liquid fuels productivity factors (EFE & CU). Another important aspect that has already been mentioned, and is proven from the performed energetic analysis, is the inefficiency of potential extended electrolysis to cover pure oxygen demand further than the hydrogen requirements of the hydrotreatment unit. In other words, the higher the electrolysis involvement in the 1st scenario, the lower the overall system performance in terms of energy quality (~30%) despite the increased fuels productivity.

4.3.3 Overview of the examined scenarios

A short description of the three (3) scenarios along with the identified pros/cons as well as the calculated key performance indicators are included in Table 16.

Table 16. Advantages, disadvantages, and main performance indicators of the examined BtL scenarios.

Scenario No	**1**	**2**	**3**
Short description – key aspects	water electrolysis, oxy-autothermal reformer, oxy-fermentation of acetate, HRSG	oxy-autothermal reformer, air-fermentation of acetate, PSA, HRSG	allothermal reformer, air-fermentation of acetate, PSA, HRSG, ST
Advantages	- High BtL efficiency - Pure oxygen production - Potential reutilization of pure H_2 & CO_2 streams	- High BtL efficiency - Low power consumptions - Water electrolysis avoidance	- No pure oxygen requirements - High potential of power independence
Disadvantages	- Extended power consumptions	- Potential purchase of industrial oxygen	- Low BtL efficiency
CU	26.44% (37*)	25.19%	22.86%
EFE	37% (45*)	35%	31.5%

*these numbers refer to further exploitation of the CO_2 and H_2 streams that can be obtained in the 1st scenario.

Taking for granted that the priority of a BtL concept is the high liquid fuels productivity, the competitiveness of the 2nd scenario in all aspects by avoiding the establishment of an electrolysis unit, turn the combination of internal H_2 extraction via PSA (for hydrotreatment) and the potential limited purchase of industrial O_2 (for reforming) as an attractive possibility in terms of cost and performance. Moreover, the external purchase of O_2 is rather an operational option rather than an inherent drawback of the 2nd scenario since air-reforming can be functional as well despite the unwilling N_2 presence. A thorough techno-economic analysis, that is expected to be a follow-up work of the present study, will serve the optimization of the proposed concept and along with dedicated lab and pilot tests will verify its potential.

4.3.4 Comparison with other certified biofuel pathways

The comparative assessment of the examined concept against other certified biofuels production pathways in terms of liquid fuels productivity is aimed within this section. Thus, the focus is given on the corresponding performance indicators such as EFE, CU and liquid fuels mass yield. In particular, the established technologies of HEFA/HVO, the Fischer-Tropsch Synthesis (FTS) and the Alcohol-to-Jet (AtJ) are selected for comparison.

HEFA/HVO fuels are produced by the hydrogenation of vegetable oils, animal fats or waste oils. The HEFA technology is currently the most mature one, with HEFA fuels being the only alternative already used commercially. However, HEFA is a feedstock-constrained pathway that usually raises skepticism related to food vs. fuel or land use change (Chapter 1). Fischer-Tropsch liquids are produced through bio-based gasification with FT synthesis using lignocellulosic biomass as feedstock. This technology is now just approaching commercialization and has received growing attention since it offers potentially carbon-neutral fuels directly usable in the transport sector. AtJ is a pathway that produces fuels from sugary, starchy, and lignocellulosic biomass, such as sugarcane, corn grain and switchgrass, via fermentation of sugars to ethanol or other alcohols. AtJ technology is also at the pre-commercial level. An estimation of the performance range of the mentioned technologies has been carried out by utilizing data from previous related studies reported in the literature [62, 167-169], and are contained in Table 17 and Figure 42 along with the corresponding performance indicators extracted by the present study.

Table 17. Certified biofuel pathways and preliminary comparison with the proposed concept.

Pathway	Feedstock	$\text{yield}_{\text{liquid}}$ (kg/kg)	EFE (%)	CU (%)	Ref.
HEFA/HVO	vegetable/ animal oils & fats	0.50-0.70	60-70	70-80	[167, 168]
FTS	lignocellulose	0.16-0.21	35-46	25-30	[62, 169]
ATJ	lignocellulose/ starch-rich crops/ sugars	0.11-0.24	26-48	22-32	[62, 168]
This study (1st scenario)	lignocellulose (crushed bark)	0.147 (0.188*)	37 (45*)	26.44 (37*)	-
This study (2nd scenario)	lignocellulose (crushed bark)	0.140	35	25.19	-
This study (3rd scenario)	lignocellulose (crushed bark)	0.126	31.5	22.86	-

*these numbers refer to further exploitation of the CO_2 and H_2 streams that can be obtained in the 1st scenario.

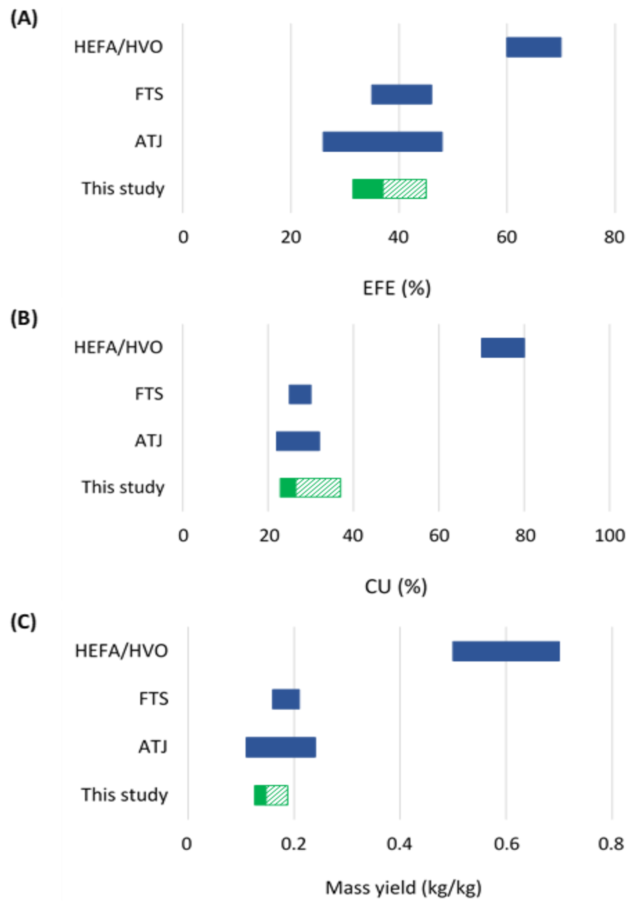

Figure 42. Preliminary comparison of the proposed concept with certified biofuel pathways in terms of EFE (A), CU (B), and liquid fuels mass yield.

The proposed BtL pathway is able to achieve competitive values in terms of liquid fuels productivity (EFE, CU, yield) in comparison with already certified technologies that exploit similar feedstock (i.e. FTS, AtJ). However, the aimed favorable position of the suggested concept lies on its ability to reach decent efficiency levels by avoiding the strict specifications of FTS that usually require costly and energy demanding equipment or the several unit operations (pre-treatment, hydrolysis, fermentation, dehydration, oligomerization) of the AtJ route that raise the total production costs. HEFA/HVO technology, as expected, presents high efficiency numbers in the selected performance indicators due to the more straightforward chemical structure of the involved feedstock (i.e. oils) compared to the other routes. However, apart from the feedstock constraints related limited availability, it should not be ignored that the HEFA/HVO feedstock is significantly more expensive than the advanced feedstock used in the BtL technologies (i.e. lignocellulose, energy crops).

4.4 Conclusions

Within this Chapter, a basic definition of a novel integrated thermochemical-biochemical BtL process has been performed. The extended feedstock flexibility, the limited gas cleaning requirements as well as the low-pressure and mild operating temperatures of the biological part, turn the proposed pathway into a promising BtL technology. An overall process model was developed and process simulations were performed at full-scale (200 MWth) for the BtL plant with crushed bark as feedstock. Design parameters like PSA/water electrolysis, oxy-/air- acetate fermentation or autothermal/allothermal reformer operation were investigated and their compatibility with the system was assessed via dedicated operational scenarios. The Heat & Mass balances for the examined configurations were solved and evaluated via overall performance indicators (i.e. CU & EFE).

Values between 22 and 27 % and between 31 and 37 % were obtained for the CU and EFE, respectively. Re-utilization of the CO_2 stream deriving from the oxy-fermentation of acetate could enhance the CU and EFE of the plant reaching values of 37% and 45%, respectively. The major carbon and energy losses were observed in the biological part. The optimization of the double-stage syngas fermentation (recirculation rates, gas solubility, optimum parameters, etc.) is expected to reduce these losses and enhance the overall performance of the plant. The limited H_2 requirements of the plant cannot probably justify the presence of such an energy-consuming unit like the electrolyzer, while internal H_2 extraction via PSA seems the most efficient option in terms of cost-performance balance. The scheme with the allothermal SMR seems inappropriate for this concept, since notable decrease in the performance indicators of the BtL plant is observed. A primary placement of the suggested concept among other certified biofuel pathways (i.e. HEFA/HVO, FTS, AtJ) was attempted. Competitive performance indicators were achieved compared to technologies that refer to similar feedstock. Of course, the concept of the present study is subject to optimization and a subsequent techno-economic assessment is expected to properly define its encouraging potential.

The investigated scenarios and the obtained primary conclusions can act as a benchmark for the further development and optimization of the integrated concept. The more in-depth techno-economic assessment of the BtL value chain is a necessary follow-up work towards the scalability evaluation of the technology.

Chapter 5

Techno-economic assessment of jet fuel production via gasification

5.1 Introduction

The aviation industry is considered a constantly and rapidly expanding sector despite the shock to air travel that the COVID-19 pandemic delivered. The International Air Transport Association (IATA) claims that the request for air connectivity will continue to grow. Indicatively, the recovery of international air traffic, following its COVID-19 low point in 2020, accelerated in 2021 and 2022, while in the first quarter of 2023 reached 81.6% of 2019 levels which were the highest ever measured (more than 4 billion passengers and 64 million tons of cargo). The increasing demands of air traffic lead to increasing demands of aviation fuels (jet fuels). The extensive use of petroleum-derived jet fuels has turned the aviation sector one of the biggest sources of transport GHG emissions, second only to road transport, and responsible for around 4% of the total current GHG emissions. The Paris Agreement's objectives related to climate change put aviation, along with other sectors, under great pressure and environmental inspection [170, 171].

At the 77th Annual General Meeting of IATA in 2021, IATA member airlines agreed to commit to net-zero carbon emissions by 2050 to limit the aviation industry's contribution to the global warming. IATA has identified the production of sustainable aviation fuels (SAFs) as the most promising strategy to reduce the environmental impact of the sector. SAFs refer to completely interchangeable substitutes (drop-in) for conventional petroleum-derived jet fuel (i.e. Jet A or Jet A-1) that are produced from sustainable resources (e.g. biogenic feedstock, renewable hydrogen + CO_2). The fact that no adaptations are required for the existing fuel systems (i.e. engines, fuel distribution network) establishes SAFs as the key driver in realizing secure and decisive decarbonization of the aviation field. Around 65% of the mitigation needed for net-zero carbon emissions in 2050 is expected to come from SAFs. Indicatively, in 2022, the global SAFs production reached around 300 million liters (200% increase compared to 2021), and airlines purchased all available quantities of SAF. Hydrogen aviation or electrification require deep and comprehensive changes in the industry and can only be considered as long-term alternatives [17, 172].

Hydroprocessed esters and fatty acids (HEFA), Fischer-Tropsch (FT), Alcohol-to-Jet (AtJ), and Power-to-Liquid (e-jet) are the identified leading SAF technologies towards the targeted fuel transition of the aviation sector. The latest EU proposal 'ReFuelEU Aviation' [6] highlights the key role of HEFA, FT, AtJ, and e-fuels in the emerging jet fuel market. So far, only specific SAFs have secured ASTM certification for commercial use (via blending), while HEFA is currently the only market proven pathway. E-jet pathways currently struggle to present affordable production costs, but projections for rapid reductions in hydrogen and green electricity prices form a promising future. HEFA jet fuel produced from waste fats, oils, and greases (FOGs) is the most cost-competitive option and is expected to remain the most efficient pathway, at least through to 2030. However, the limited supply of feedstock and lack of cultivation areas turn HEFA into a feedstock-constrained pathway that is unable on its own to support the needs of a large-scale fuel transition. Therefore, there are reasonable claims that the next two decades will be dominated by technologies handling advanced feedstock (e.g. biogenic residues/wastes) such as FT and AtJ. The main challenge related to these technologies is the reduction of the production costs since the current Biomass-to-Liquid (BtL) pathways usually involve intense capital and operational expenses (Chapter 1) [5, 20, 173].

The low energy density (due to high oxygen content) and the corrosive nature of pyrolysis bio-oil or the high costs (catalysts, high pressures) of liquefaction have established biomass gasification as the most cost-effective and efficient technology for residual biomass to bio-energy (Chapter 3) [7, 8, 126]. Nowadays, FT and AtJ are justifiably the dominant emerging gasification-driven BtL technologies, but the strict specifications of FT (i.e. extended gas-cleaning requirements, high temperatures/pressures) or the several unit operations (i.e. fermentation, dehydration, oligomerization) of AtJ usually lead to high production costs. In this study, an alternative gasification-driven BtL concept for the production of drop-in aviation fuels is introduced and evaluated. In particular, a fuel synthesis scheme based on the double-stage fermentation of the produced syngas is examined instead of the conventional FT or AtJ (via ethanol) synthesis, aiming to the establishment of a competitive BtL technology characterized by mild operating temperatures, low pressures, and potentially reduced costs.

The suggested process chain can be divided into three distinct parts: the thermochemical, the biological, and the thermocatalytic. Concerning the first (thermochemical) part, a Dual Fluidized Bed Gasification (DFBG) unit is considered for the syngas production from biogenic residues followed by a catalytic tar reformer, while for the second (biological) part a double-stage syngas-to-acetate-to-triglycerides (TAGs) fermentation unit is involved accompanied by a lipids extraction and purification system. The last (thermocatalytic) part refers to the hydrotreatment unit where the obtained TAGs are upgraded into drop-in liquid fuels. The European Horizon 2020 project BioSFerA [9] has undertaken the realization, optimization, implementation at pilot scale, and scaling up evaluation of the described concept. Extensive conceptualization and design considerations of the novel BtL scheme have been performed (Chapter 4), while the beneficial environmental impact of the whole process reflects on 50-80% GHG emission reductions compared to conventional (fossil) routes [174].

The objective of the present study is the comprehensive techno-economic evaluation of this innovative 200 MWth BtL plant, whose performance has been simulated with reasonable upscaling considerations and models validated at pilot scale. Appropriate business scenarios are developed and the main capital and operational costs of the concept are estimated. Moreover, sensitivity analysis on multiple operational aspects is performed for the identification of the main cost-drivers of the process. Finally, the financial competitiveness of the technology compared to the current dominant SAF pathways is assessed.

5.2 Materials and methods

5.2.1 Process description

This section provides an overview of the examined BtL process. The concept has been initially defined in Chapter 4, where multiple design considerations were thoroughly examined. The technical maturation of the technology via performed experimental activities throughout the value chain during the BioSFerA project [9] enables an updated and more valid integration scheme.

The main operating principles and conditions of each sub-process are presented along with the elected block flow of the integrated BtL concept, while a more detailed Process Flowsheet Diagram (PFD) with the key stream results can be found in the Appendix (Section A-3, Figure A1, Table A2, Table A3, Table A4).

5.2.1.1 Thermochemical part

The conversion of the biomass feedstock into syngas is carried out with the Dual Fluidized Bed Gasification (DFBG) technology. The DFBG system consists of two interconnected CFB (Circulating Fluidized Bed) reactors, the gasifier (fuel reactor) and the oxidizer (air reactor). The steam that enters the gasifier is generated via thermal utilization of hot syngas, while the flue gases from the oxidizer are used for the pre-heating of the air that enters the air reactor. Both hot streams (i.e. syngas & flue gas) may be available for further thermal exploitation in a Heat Recovery Steam Generator (HRSG).

The gasification reactions take place in the gasifier, while the produced char, other residues (i.e. ash), and part of the bed material are transported to the oxidizer where they react with the oxidizing medium (i.e. air) to produce heat. The (hotter) bed material returns to the gasifier, serving as the heating medium for the endothermic steam gasification reactions. The produced raw syngas is filtered at the exit temperature of the gasifier and subsequently is catalytically reformed. The autothermal reformer (ATR) is heated by partial syngas combustion with air, and in addition, the reforming reactions consume steam and/or CO_2. The primary function of the catalytic reformer may be to convert tars and hydrocarbon gases to H_2 and CO, but it can also be modified to attain several targets relating to the syngas purification requirements for the subsequent fermentation process. For example, the reformer can be designed to largely decompose ammonia (NH_3) or hydrogen cyanide (HCN), and especially the latter which has turned out to be a major contaminant causing inhibition of the fermentation bacteria. The latest pilot trials [175] regarding the minimization of gas cleaning steps prior the biological part revealed that an alkaline scrubber provides sufficient removal of targeted contaminants (mainly H_2S & HCN) and secures the desired syngas fermentation efficiency. (Figure 43)

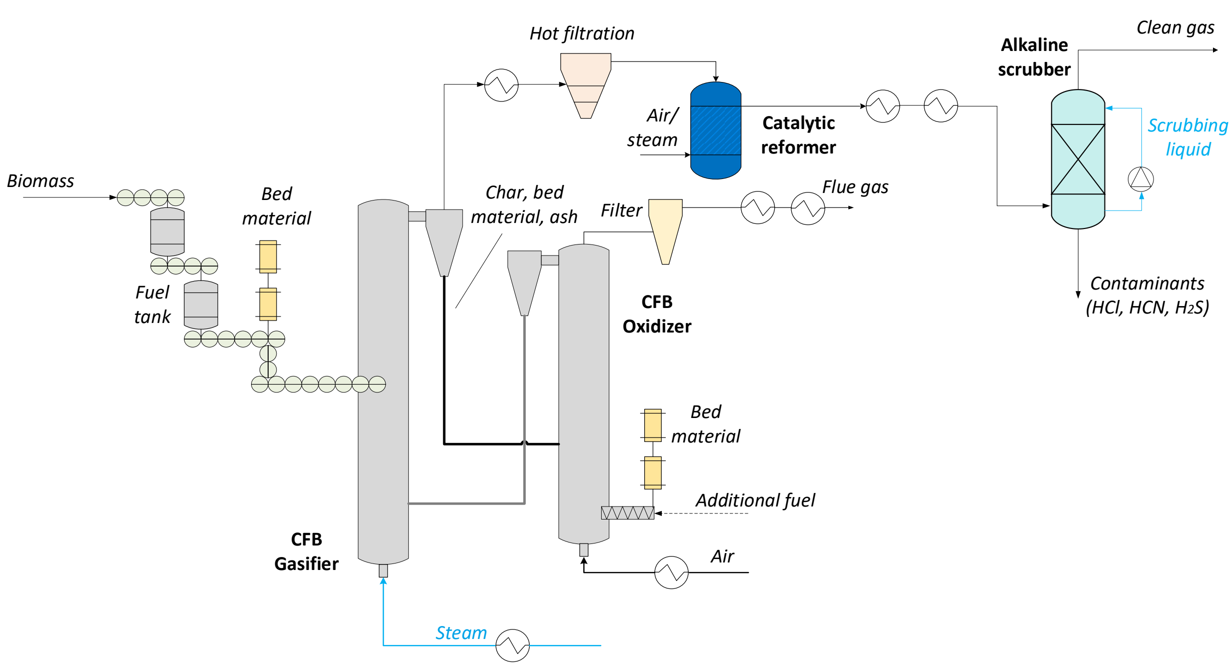

Figure 43. Configuration of the thermochemical part.

The main operating conditions for the thermochemical part are presented in Table 18.

Table 18. Operating conditions of the thermochemical part.

Parameter	Input
Pressure (bar)	1.5
Gasifier temperature (°C)	780
Oxidizer temperature (°C)	880
Steam-to-biomass ratio (kg/kg dry, ash free)	0.7
Steam pre-heating temperature (°C)	350
Air pre-heating temperature (°C)	400
Reformer (ATR) temperature (°C)	900
Steam-to-carbon ratio (ATR) (mol/mol)	1.5
Alkaline scrubber temperature (°C)	35

5.2.1.2 Biological part

In the first step of the biological part of the process, the interaction of syngas with the acetogenic bacteria under anaerobic conditions leads to acetic acid (acetate) production. For the syngas fermentation stage, after the extended experimental testing, *Moorella thermoacetica DSM 2955* was selected as the most efficient acetate producer strain [176]. The operating temperature is set around 55 °C, since the optimal temperature range for these strains is 55-60 °C [177]. The operating pressure of the reactor was considered to be 5 bar in order to achieve higher solubility of the reacting gases. Two critical factors, that highly influence the fermentation kinetics and consequently the acetate productivity, are the gas solubility and the ratios of CO_2/CO/H_2. The unconverted syngas components (off-gas) can be either recycled back to the fermenter or utilized elsewhere in the plant (see section 5.2.1.4). The broth containing the produced acetate in low concentration is extracted in continuous way, and the liquid volume is kept constant by adding fresh culture medium. A cell recycling system (hollow fiber membrane) is required to keep the cells in the fermenter while extracting the liquid effluent.

The second fermentation step refers to the production of triglycerides (TAGs) via aerobic fermentation of the diluted acetic acid stream (liquid fermentation). Taking into account the relevant experimental trials, *Yarrowia lipolytica* is the yeast strain that has been selected to be involved in the liquid substrate fermentation of acetate [178, 179]. The diluted acetate effluent stream from the syngas fermentation enters the aerobic fermenter, where the targeted TAGs are formed as intracellular products in the presence of oxygen, additional nutrients, salts and the oleaginous yeast (*Y. lipolytica*). A cell recycle system (hollow fiber membrane) can be installed to recirculate the cellular biomass in the bioreactor while extracting the spent effluent. At the same time, a gaseous CO_2-rich stream is produced and leaves the bioreactor from the top. (Figure 44)

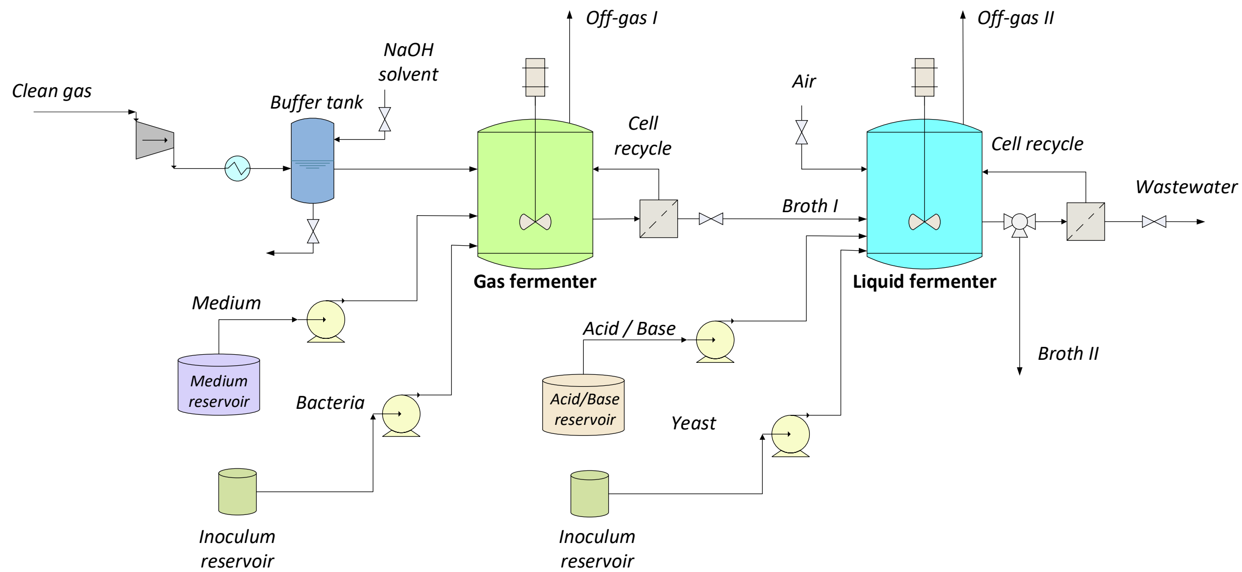

Figure 44. Configuration of the double-stage fermentation.

Lipids extraction from the oleaginous yeasts is an important step before hydrotreatment. As oleaginous yeasts present in the fermentation broth store lipids in intracellular forms, extraction is required to obtain the TAGs. Cell disruption alongside lipid extraction steps are critical for large-scale biofuel production in terms of cost adequacy. Mechanical disruption requires energy inputs such as shear forces, electrical pulses, waves or heat. Mechanical processes generally provide high products recovery yields with good management and scalability, but they are energy intensive. For the suggested concept, based on the insights gained in relevant experimental activities [180], a scalable DSP (downstream processing) train based on steam explosion, microfiltration, and centrifugation was defined for the efficient lipids recovery from the fermentation broth. In steam explosion, raw material exposed to steam at 150-240 °C for several minutes and then subjected to depressurization to ambient conditions. This generates an explosion that causes cell-wall disruption. Low pressure and temperature (about 5 bar and 150 °C) seem preferable for steam explosion in order to avoid TAGs disruption. Microfiltration/centrifugation have been positively evaluated for their ability to separate oil from the broth deriving from steam explosion. Finally, it has to be noticed that difficulties associated with the formation of emulsions can moderate the TAGs recovery effectiveness. (Figure 45)

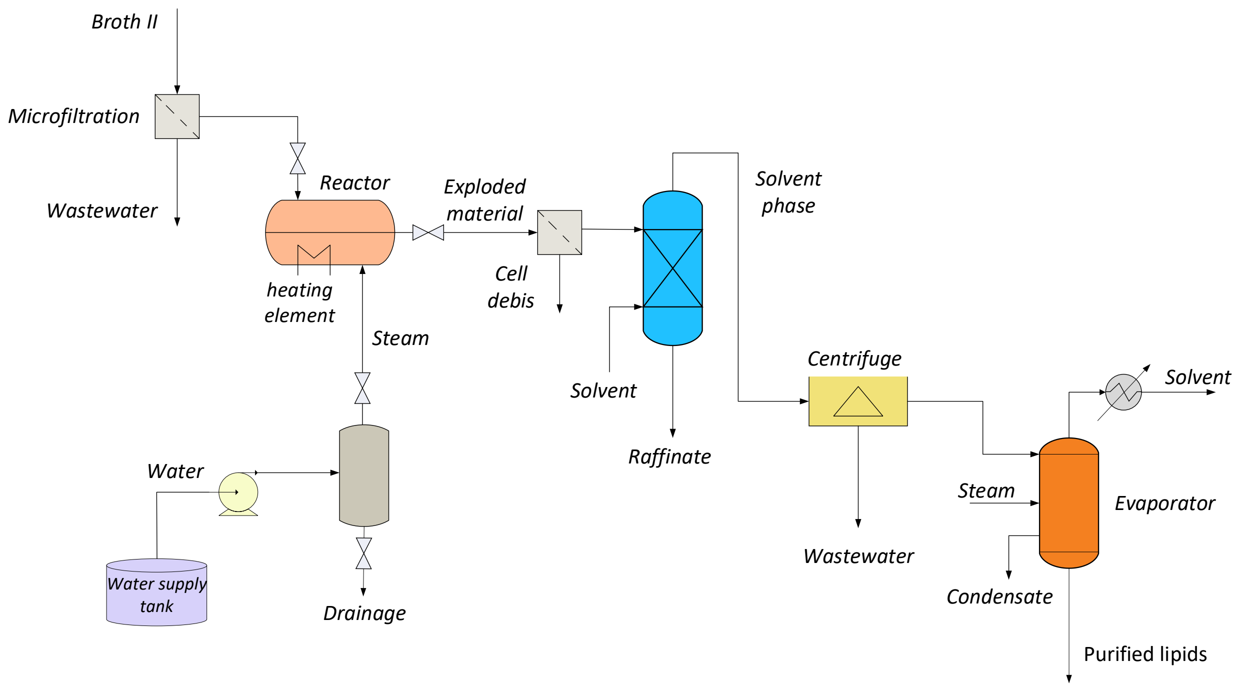

Figure 45. Configuration of the elected DSP train for lipids recovery.

The main operating conditions for the biological part are presented in Table 19.

Table 19. Operating conditions of the biological part.

Parameter	Input
Gas Fermentation Pressure (bar)	5
Gas Fermentation Temperature (°C)	55
Liquid Fermentation Pressure (bar)	1
Liquid Fermentation Temperature (°C)	28
Steam Pressure for Steam Explosion (bar)	5
Steam Temperature for Steam Explosion (°C)	150

5.2.1.3 Thermocatalytic part

The final section of the suggested value chain includes the upgrading of microbial oil (TAGs) into drop-in aviation biofuel. The core of the thermocatalytic part of the concept is the hydrotreatment unit where the consecutive hydrogenation, deoxygenation, isomerization, and fractionation procedures of the purified TAGs take place. Common catalysts for this process are Pt, Ni or other metals based on Al_2O_3. In particular, the saturated fatty acids are converted to straight long-chain alkanes by hydrodeoxygenation and decarboxylation, co-producing propane, methane, water, CO, and CO_2. The deoxygenated straight chain paraffins are selectively hydrocracked or isomerized yielding highly branched alkanes. The resulted organic product is a mixture of straight and branched C_nH_{2n+2} that can be suitably used as drop-in liquid fuel. (Figure 46)

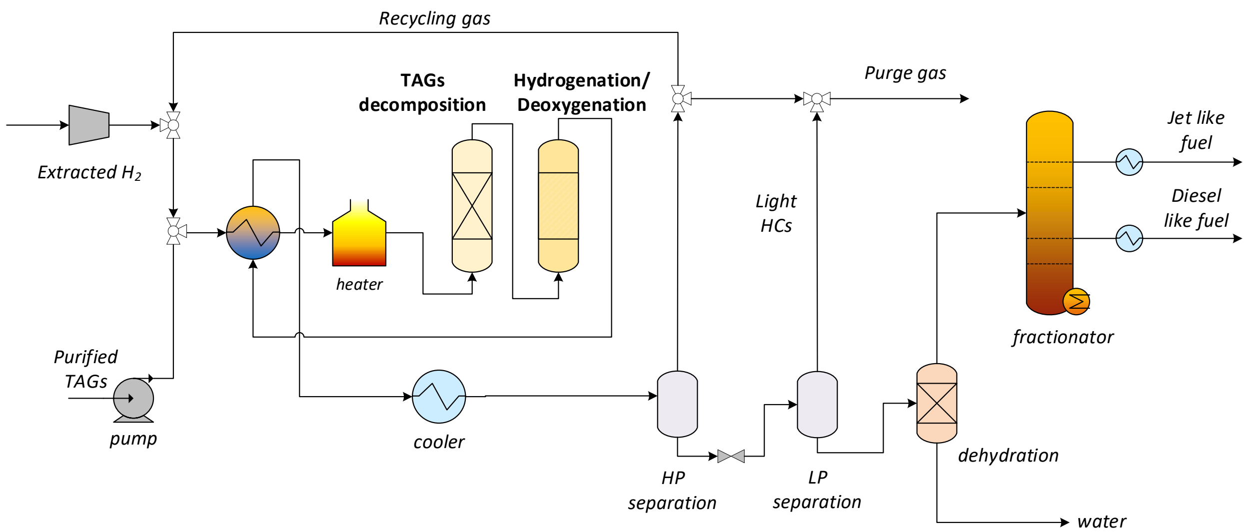

Figure 46. Configuration of the hydrotreatment unit.

The main operating conditions for the thermocatalytic part are presented in Table 20.

Table 20. Operating conditions of the thermocatalytic part.

Parameter	Input
Reactor pressure (bar)	100
Reactor temperature (°C)	370
Hydrogen-to-TAGs ratio (kg/kg)	0.05

5.2.1.4 Integrated Biomass-to-Liquid (BtL) process chain

Taking into account the extensive conceptualization and design considerations that are available at Chapter 4 as well as the findings from the experimental activities of each sub-process, the integrated process chain was elected targeting to the greatest possible performance and cost efficiency. The optimized configuration of the integrated BtL concept is illustrated in Figure 47.

The major aspects of the integrated concept are:

- Utilization of the off-gas (unreacted gas) of the anaerobic fermentation (gas fermentation) in the oxidizer of the DFBG unit → higher gasification efficiency, avoidance of technical barriers related to internal gas recycle in the bioreactor (i.e. inerts/contaminants accumulation)

- Internal hydrogen extraction (and supply to the hydrotreatment unit) from the off-gas of the anaerobic fermentation via PSA (Pressure Swing Adsorption) → avoidance of such an energy/cost-consuming unit like an electrolyzer
- Air-driven autothermal reforming of syngas hydrocarbons instead of oxygen-driven, since in the absence of gas recycle in the bioreactor, some nitrogen content in the reformed gas would not be a critical problem → avoidance of operational costs related to external purchase of industrial oxygen

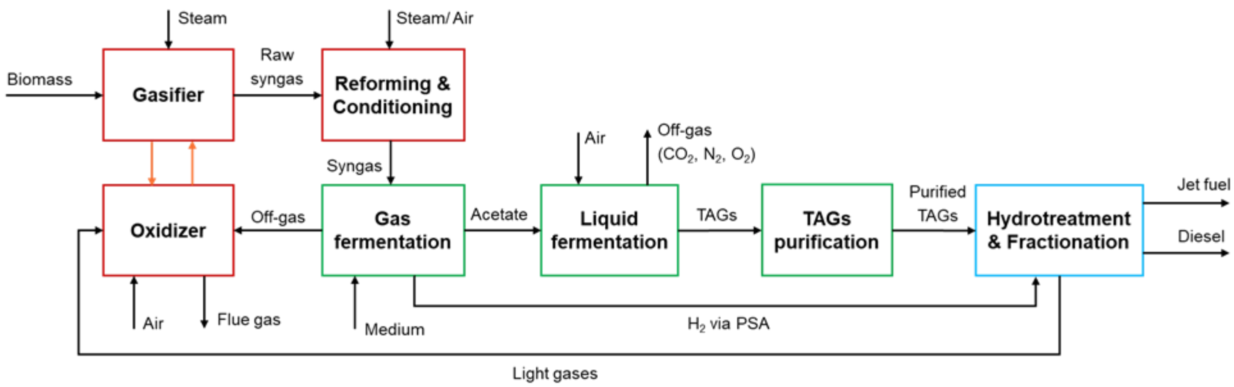

Figure 47. Block flow diagram of the integrated BtL concept.

5.2.2 Model validation

The process model was developed in the commercial software Aspen Plus^{TM}. The simulations were performed at full-scale (200 MWth) and the selected feedstock was crushed bark, the main specifications of which have already been provided in Chapter 4 (Table 12). Every available experimental activity was taken into account for the validation of the process. The aim is to enhance the fidelity of the model and the effectiveness of the concept design.

5.2.2.1 Dual Fluidized Bed Gasification (DFBG)

The actual DFBG pilot runs (200 kWth) performed by VTT [131] as well as the upscaling considerations and full-scale simulations (100 MWth) performed by Sumitomo SHI FW [181] were utilized in order to assess the reliability of the 200 MWth DFBG model that serves the scope of the present study. Thus, Figure 48 presents the correlation between the actual pilot tests (200 kWth) by VTT, the 100 MWth simulations by SHI FW, and the 200 MWth simulations of this study. The focus is given on the main syngas species (H_2, CO, CO_2, CH_4). In all cases, autothermal DFBG operation was considered (no external fuel, 1% inherent heat losses).

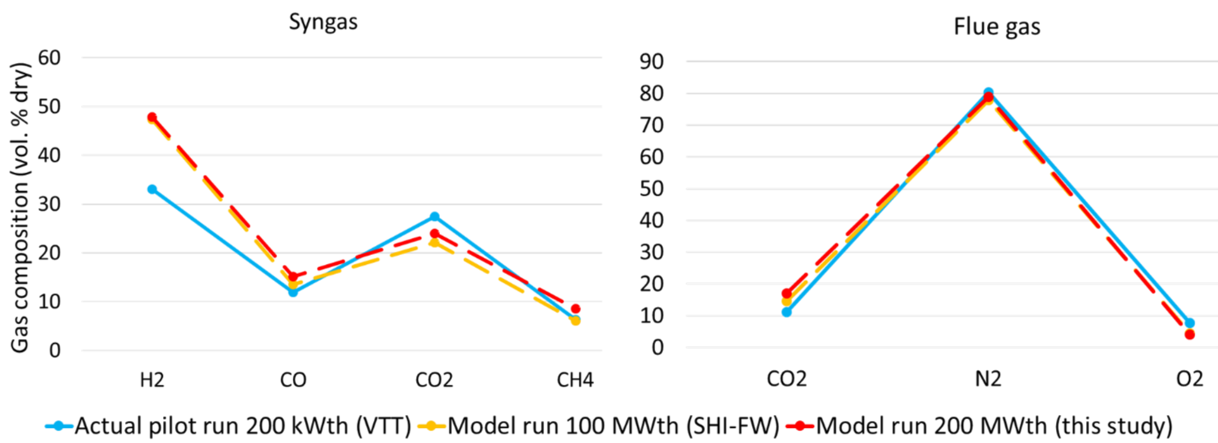

Figure 48. Validation of the 200 MWth DFBG model.

The 200 MWth 'syngas curve' (red) matches well with the corresponding 100 MWth syngas composition (orange) simulated by SHI FW. The discrepancies between the simulated commercial applications and the actual pilot runs (blue) are mainly due to the increased nitrogen content (~20%) of the produced gas during the pilot tests. Due to the inherent constraints of a pilot configuration, some air is introduced in the gasifier during the DFBG pilot tests in order to ensure stable performance. This leads to increased percentage of N_2 in the produced gas. On the contrary, the share of purge nitrogen in potential commercial applications is smaller and the produced syngas is of higher quality (nitrogen-free). As expected, the flue gases composition is almost identical for all three cases.

In summary, the 200 MWth DFBG model seems to be in good agreement with the SHI FW predictions (100 MWth) regarding the operation of a commercial DFBG system, and both large-scale simulation results follow in a logical way the actual experimental results (pilot tests). Thus, it can be considered as a reliable tool for the full-scale process simulations of the concept.

5.2.2.2 Syngas fermentation (anaerobic gas fermentation)

The optimization of the gas fermentation model was based on data extracted from relevant experimental activities [175, 177] as well as on literature studies for similar industrial processes (e.g. gas fermentation for ethanol production).

To represent the growth of the acetogenic bacteria (*Moorella thermoacetica)* taking place in the reactor, reactions (11) & (12) were added. The elemental formula for the bacteria was considered to be $CH_{1.75}O_{0.5}N_{0.25}$ [182]. The acetic acid production was simulated by reactions (13) & (14).

Based on literature and the conducted fermentation tests that indicate negligible generation of by-products from *M. thermoacetica*, no by-product formation was considered in the model.

$$2CO + 0.25NH_3 + 0.5H_2O \rightarrow CH_{1.75}O_{0.5}N_{0.25} + CO_2 \quad (11)$$

$$CO_2 + 2H_2 + 0.25NH_3 \rightarrow CH_{1.75}O_{0.5}N_{0.25} + 1.5H_2O \quad (12)$$

$$4CO + 2H_2O \rightarrow CH_3COOH + 2CO_2 \quad (13)$$

$$2CO_2 + 4H_2 \rightarrow CH_3COOH + 2H_2O \quad (14)$$

A high gas utilization was assumed since in large-scale reactors, the increased surface area, the enhanced mixing, the reduced concentration gradients and the optimal process design allow for efficient gas transfer. Specifically, after reviewing literature on gas fermentation for ethanol production [183, 184], a 90% utilization percentage for CO and an 80% utilization percentage for H_2 were selected. Moreover, the low quantity of unreacted syngas (off-gas) eliminates the need for installing a gas recycle system. Instead, it was decided to exploit the off-gas of the fermenter for the enhancement of the DFBG efficiency (see section 5.2.1.4).

The applied conversion rates of the utilized gas are presented in Table 21. Non-utilized (unreacted) gas leaves the fermenter from the top.

Table 21. Conversion rates for syngas fermentation.

Parameter	Input
Conversion of CO in Reaction (11)	5%
Conversion of H_2 in Reaction (12)	5%
Conversion of CO in Reaction (13)	95%
Conversion of H_2 in Reaction (14)	95%

5.2.2.3 Acetic acid fermentation (aerobic liquid fermentation)

A similar approach for the optimization of the liquid fermentation model was adopted, wherein data was collected from the performed liquid fermentation tests [179, 185] as well as from relevant literature studies on microbial oil production. The fermentation broth from the gas fermenter containing 30 g/L acetic acid is sent directly to the liquid fermenter. The results obtained from the tests indicated that the oleaginous yeast can grow effectively on the broth deriving from the gas fermenter, without the necessity of any purification steps. The liquid fermentation was divided into two phases: the growth phase and the lipid production phase. Reaction (15) was added for biomass formation (growth). The elemental formula for the yeast was considered to be $CH_{1.66}O_{0.54}N_{0.14}$. Reactions (16) – (19) describe the intracellular lipid production phase. Triolein ($C_{57}H_{104}O_6$), tripalmitin ($C_{51}H_{98}O_6$), trilinolein ($C_{57}H_{98}O_6$), and tristearin ($C_{57}H_{110}O_6$) were selected as the representative TAGs produced during this phase.

$$CH_3COOH + 0.908O_2 + 0.147NH_3 \rightarrow 1.05CH_{1.66}O_{0.54}N_{0.14} + 0.95CO_2 + 1.349H_2O \quad (15)$$

$$59CH_3COOH + 38O_2 \rightarrow C_{57}H_{104}O_6 + 61CO_2 + 66H_2O \quad (16)$$

$$50.11CH_3COOH + 27.72O_2 \rightarrow C_{51}H_{98}O_6 + 49.22CO_2 + 51.22H_2O \quad (17)$$

$$62CH_3COOH + 45.5O_2 \rightarrow C_{57}H_{98}O_6 + 67CO_2 + 75H_2O \quad (18)$$

$$56CH_3COOH + 30.5O_2 \rightarrow C_{57}H_{110}O_6 + 55CO_2 + 57H_2O \quad (19)$$

The applied conversion rates of the acetic acid are presented in Table 22. The TAGs representation and conversion rates have been set in a way to be consistent with the fatty acid distribution observed during available experimental tests [179] (Figure 49). The airflow rate for the two phases was regulated by the oxygen concentration in the off-gases, as measured during the tests.

Table 22. Conversion rates for acetate fermentation.

Parameter	Input
Conversion of CH_3COOH in Reaction (15)	10.0%
Conversion of CH_3COOH in Reaction (16)	42.8%
Conversion of CH_3COOH in Reaction (17)	21.1%
Conversion of CH_3COOH in Reaction (18)	12.6%
Conversion of CH_3COOH in Reaction (19)	13.5%

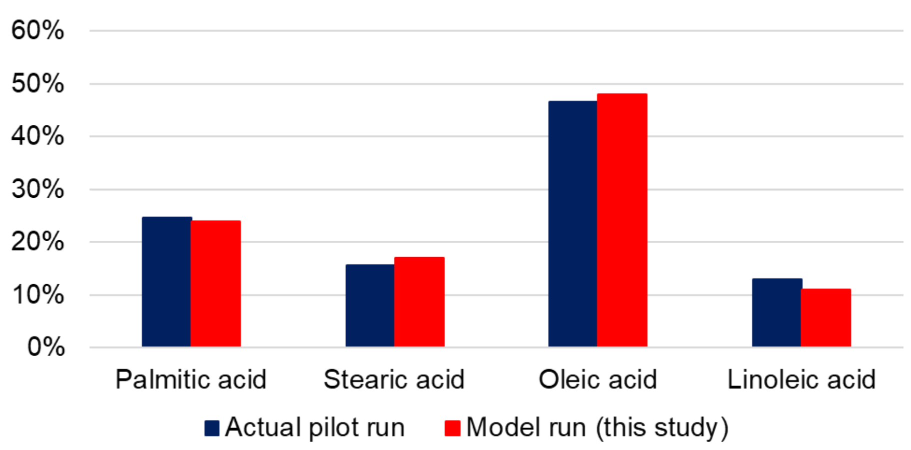

Figure 49. Validation of the liquid fermentation model via experimentally measured fatty acid distribution.

In summary, the simulation results of the two-step fermentation process (gas fermentation & liquid fermentation) were compared and found to be consistent with the results obtained from the continuous fermentation tests. This fact indicates the reliability of the biological model that serves the full-scale simulations of the present study.

5.2.2.4 TAGs hydrotreatment

For the validation of the hydrotreatment part, the model was updated and enriched with data obtained from the performed experimental activities [186] and data extracted from literature.

The obtained liquid products are jet and diesel fractions. Appropriate catalytic system selection was assumed for maximization of the jet fraction (80% jet - 20% diesel wt. %). The paraffinic composition of the two fuel fractions (as detailed in the Appendix, Table A4, streams 20 & 21) was based on relevant literature studies focusing on the production of jet-like and diesel-like fuels from hydrotreated oils [187, 188]. The simulated jet and diesel fuels resulted in Lower Heating Values (LHVs) of 44.4 MJ/kg and 43.8 MJ/kg, respectively. Table 23 provides information on the properties of jet fuel stream deriving from fractionation of the hydrotreated oil, as calculated in Aspen Plus™, along with the respective specifications for commercial Jet A-1.

Table 23. Properties of the simulated jet fuel (deriving from fractionation) and Jet A-1 specifications (ASTM D1655)

Parameter	Unit	Simulated Jet	Jet A-1 spec
LHV	MJ/kg	44.4	> 42.80
Density (15 ºC)	kg/m^3	730	775–840
Viscosity (-20 ºC)	mm^2/s	5.45	< 8.0
Flash point	ºC	48.5	> 38.0
Distillation 10%	ºC	170.9	< 205.0
Distillation 100%	ºC	270.7	< 300.0

As can be seen, the obtained jet fuel stream simulated the targeted fuel relatively well with most of its properties meeting the specifications for Jet A-1. This can be considered as a form of validation for the model. Moreover, it has to be pointed out that the simulated jet stream consists only of normal paraffins. Although these paraffinic fuel fractions form a solid basis for the representation of the targeted drop-in fuels, the actual drop-in fuels usually contain also iso-paraffins, cycloparaffins and aromatics in order to meet the necessary standards for safe and efficient use in jet engines.

5.2.3 Energy and Mass balance

The Heat & Mass balances of the value chain were solved and the overall BtL performance is assessed via three (3) critical factors; the Energetic Fuel Efficiency (EFE), the Carbon Utilization (CU), and the liquid fuels mass yield ($yield_{liquid}$) (Chapter 4).

The energy balance of the integrated concept is presented in Figure 50 and the carbon balance in Figure 51.

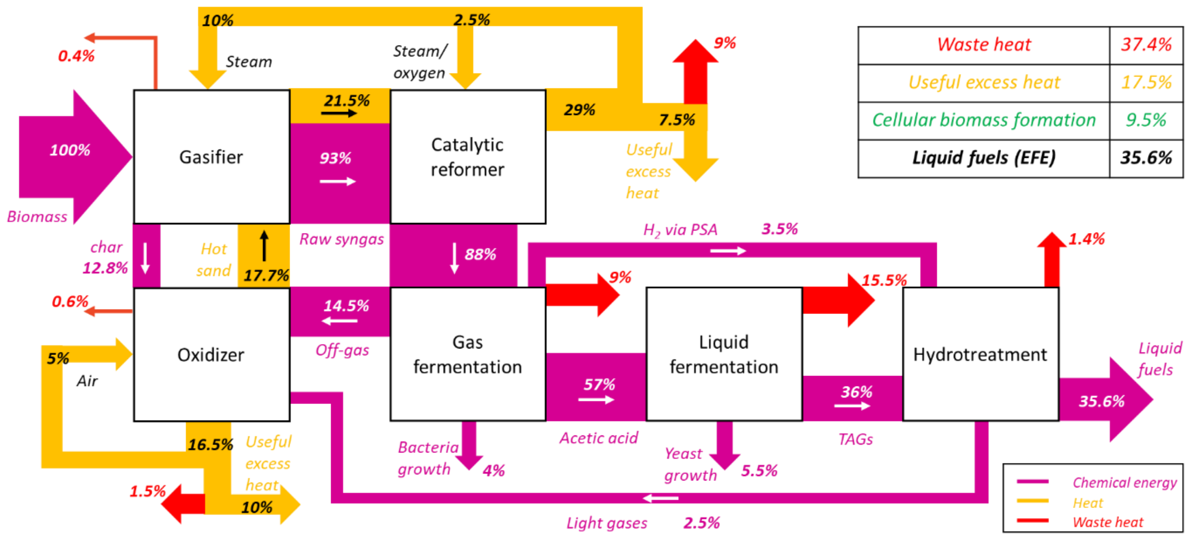

Figure 50. Energy balance of the integrated concept (200 MWth full-scale simulation).

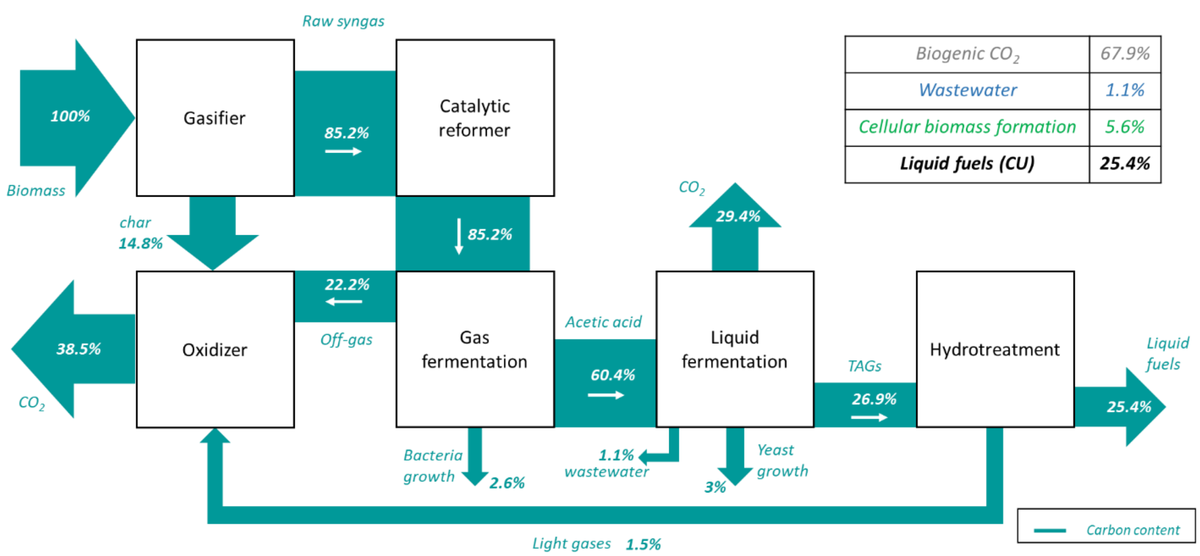

Figure 51. Carbon balance of the integrated concept (200 MWth full-scale simulations).

The estimated EFE from the full-scale simulations is measured at 35.6%. The main energy losses are observed in the double-stage fermentation, and especially during the aerobic conversion of acetic acid into TAGs. Moreover, a non-negligible amount of the inlet energy (9.5%) seems to be required by the microorganisms (bacteria and yeast) for their growth. The re-utilization of the off-gases from the gas fermentation for the thermal assistance of the oxidizer leads to enhanced gasification efficiency. The presence of the DFBG unit (two hot outlet gas streams) ensures a remarkable useful excess heat content (17.5%) that can serve any further thermal requirements of the plant (e.g. steam generation for TAGs purification) apart from the pre-heating of air and steam. The obtained Carbon Utilization (CU) of the integrated BtL plant has been calculated equal to 25.4%. A large portion of the inlet carbon (67.9%) ends up in the form of CO_2 either at the oxidizer outlet or at the outlet of the aerobic fermenter. The rest carbon 'expenses' of the process are minor and consist of the cellular biomass formation (5.6%) as well as the low organic content of wastewaters (1.1.%).

The electricity requirements of the entire process are estimated at 0.12 MWel/MWth of produced biofuel, mainly sourcing from the compression unit prior gas fermentation. The overall liquid fuel mass yield, expressed in $kg_{product}/kg_{feed}$, is estimated at 0.134. A summary of the main mass and energy balances as derived from the full-scale process simulations are shown in Table 24.

Table 24. Summary of the main simulation results for the integrated BtL concept.

Parameter	Unit	Value (simulation output)
Feed (crushed bark)	t/h	40.46
Liquid product (jet fuel)	t/h	4.36
Liquid product (diesel)	t/h	1.08
Cellular biomass (by-product)	t/h	1.21
Electric power demand	MWel	8.20
Energetic Fuel Efficiency (EFE)	%	35.60
Carbon Utilization (CU)	%	25.40
Liquid Fuel mass yield ($kg_{product}/kg_{feed}$)	%	13.44

Utilizing data from previous studies reported in the literature [30, 62, 71, 169], it is evident that the investigated BtL pathway demonstrates competitive values in terms of liquid fuel productivity when compared to already certified technologies that exploit similar feedstock (i.e. FT, AtJ). The following techno-economic assessment of the concept aims to enable a more comprehensive and equitable comparison with the mentioned well-established biofuel production technologies.

5.2.4 Techno-economic analysis and cost estimation methodology

The results of the mass and energy balances represent the basis for the cost estimation efforts. The discounted cash flow rate of return methodology is applied for the economic analysis. A cash flow analysis is performed in Microsoft Excel based on the estimated capital and operating costs. The Minimum Jet fuel Selling Price (MJSP) has been elected as the most suitable indicator for the assessment of the financial competitiveness of the concept as well as the direct comparison with other biofuel routes. The MJSP is obtained by iterating the jet fuel product cost to obtain a net present value (NPV) equal to zero at a specific discount rate.

For the estimation of the capital costs, all the critical equipment inside battery limits (ISBL) is considered. Simple equipment costs such as columns, compressors, pumps, heat-exchangers, and flash drums are predicted by Aspen Plus™ Economic Evaluator. On the contrary, the cost estimation for advanced equipment such as reactors and fermenters is based on data from relevant technical reports [62, 189-191] and adaptations via equipment scaling exponents. The assumed prices are normalized to the year 2023, using the average annual CEPCI (Chemical Engineering Plant Cost Index) value (803.2) [192]. The validity of the claimed overall costs for the novel biological part is reinforced with their revision from appropriate industry experts (i.e. Biobase Europe Pilot Plant BBEPP) who provide their industrial insight into the aimed cost breakdown of the present study.

The purchased equipment, erection, piping, site improvements, instruments, control systems, and integration are taken into account for the calculation of the direct costs (Total Installed Costs - TIC). The indirect costs (IC) including engineering, contractors, legal fees, etc. are set as 60% of total direct costs. An additional 10% contingencies-oriented cost is applied in the sum of total direct and indirect costs (TDIC) in order to obtain the fixed capital investment (FCI). The total capital investment (TCI) of the project is subsequently determined as the FCI plus the working capital (10% of the FCI) [62, 193]. The adopted methodology is presented in Table 25.

The annual operating costs are calculated by including the fixed costs (i.e. employee salaries, maintenance, property insurance) and the variable costs (i.e. feedstock costs, utilities, wastewater discharge, by-product credits). For the fixed costs, maintenance (repair, catalysts replacement, etc.) assumed to be 2% of the FCI and property insurance was set at 0.7% of the FCI [62, 189]. The variable annual costs are calculated using the results of the energy and mass balances combined with the market/literature values for the price of utilities, consumables, and disposal services. Revenue streams are generated from the selling of diesel and cellular biomass (yeast biomass) as valuable by-products. Yeast biomass, as derived from TAGs purification, can be utilized in various ways such as fertilizers, animal feed or for the enhancement of biogas production [194]. The complete list of consumables and prices as well as the boundary conditions for the economic analysis are presented in Table 26.

Table 25. Total Capital Investment (TCI) methodology.

Direct Capital Costs (Total Installed Costs – TIC)	Sum of the apparent installed costs for the thermochemical, biological, and thermocatalytic parts
Indirect Capital Costs (IC)	60% of TIC
Total Direct & Indirect Costs (TDIC)	TIC + IC
Contingencies	10% of TDIC
Fixed Capital Investment (FCI)	TDIC + Contingencies
Working Capital (WC)	10% of FCI
Total Capital Investment (TCI)	FCI + WC

Table 26. Economic assumptions.

Economic parameters	
Plant lifetime	25 years
On-stream factor	85% (7,446 h per year)
Discount rate	6%
Tax rate	0%
Construction period	2 years (40% 1st year, 60% 2nd year)
Fixed operating costs	
Maintenance	2% (FCI)
Property insurance	0.7% (FCI)
Personnel*	100 employees [193]
Average annual salary per employee**	35,000 €/year [195]
Variable operating costs	
Feedstock cost (crushed bark)	70 €/t [196]
Nutrients & chemicals (fermentation)	0.6% of biological part direct costs [189]
NaOH make-up for alkaline scrubber	230 €/t [197]
Wastewater discharge	4 €/t [198]
Electricity price (business)	0.09 €/kWh [199]
Diesel (by-product)	1800 €/t [200]
Cellular biomass (by-product)	700 €/t [201]

*according to annual plant capacity (liquid products).
**for European chemical industry.

5.3 Results and discussion

5.3.1 Cost estimation results

This section provides the results of the cost estimation process, starting with the TCI and continuing with the calculation of the annual operational financial streams that take part in the cash flow analysis.

5.3.1.1 Total Capital Investment

The breakdown of the capital costs of the BtL plant is presented in Table 27. Available technical reports [62, 190, 191] were considered for the cost estimation of the thermochemical part, while for the biological part, apart from available literature studies [202, 203], appropriate acetic acid and TAGs productivities-volumes correlations were utilized for the election of the required number of bioreactors [204]. The capital cost for the thermocatalytic part (hydrotreatment/hydrocracking) was estimated as a function of the annual capacity (liquid products) by utilizing relevant technical reports [205, 206]. The estimated direct costs of each section were rounded for convenience. A more detailed critical equipment list for each part, on which the estimation of the required capital expenses was based, is attached in the Appendix (Section A-4, Table A5).

Table 27. Capital Expenditures (CapEx) of the BtL plant.

Dual Fluidized Bed Gasification	80,000,000 €
Catalytic Reformer	8,500,000 €
Gas Conditioning (coolers, alkaline scrubber)	10,500,000 €
Gas Compression	5,000,000 €
Gas Fermentation	80,000,000 €
Liquid Fermentation	64,000,000 €
Downstream Processing (TAGs recovery)	16,000,000 €
Hydrotreatment/ Hydrocracking	22,000,000 €
Utilities & Storage	12,000,000 €
Total installed costs (direct costs)	**298,000,000 €**
Indirect costs	178,800,000 €
Total direct & indirect costs	476,800,000 €
Contingency	47,680,000 €
Fixed Capital Investment (FCI)	**524,480,000 €**
Working Capital	52,448,000 €
Total Capital Investment (TCI)	**576,928,000 €**

The required TCI for the establishment of a 200 MWth BtL plant is estimated at approximately €577 million. The largest proportion of the cost is incurred by the biological part, which represents 53% of the total installed costs. The assumed moderate productivities (3 g/L/h for acetic acid and 0.8 g/L/h for TAGs) for potential commercial applications, supported by relevant literature [207-209], led to relatively large required number of bioreactors (30 fermenters) and subsequently increased capital costs. Costs can be divided among the steps of the biological part as 50% gas fermentation, 40% liquid fermentation, and 10% TAGs recovery. The thermochemical part accounts for 36% of the total installed costs, with DFBG getting the lion's share (77%) of the relevant costs and the catalytic reformer (8%), gas conditioning (10%) as well as the gas compression unit (5%) combining for the remaining expenses of this part. Finally, the hydrotreatment unit represents 7% of the total installed costs, while the remaining 4% is attributed to storage/utilities. The presence of the hydrotreatment unit in an integrated BtL scheme comes up with design and cost benefits compared to standalone refineries, such as the avoidance of 'heavy' pre-treatment of the feed (TAGs) (since appropriate cleaning has been carried out in earlier stages of the value chain) or the avoidance of hydrogen production unit (since the required hydrogen is extracted internally from the off-gases of the biological part via PSA). (Figure 52)

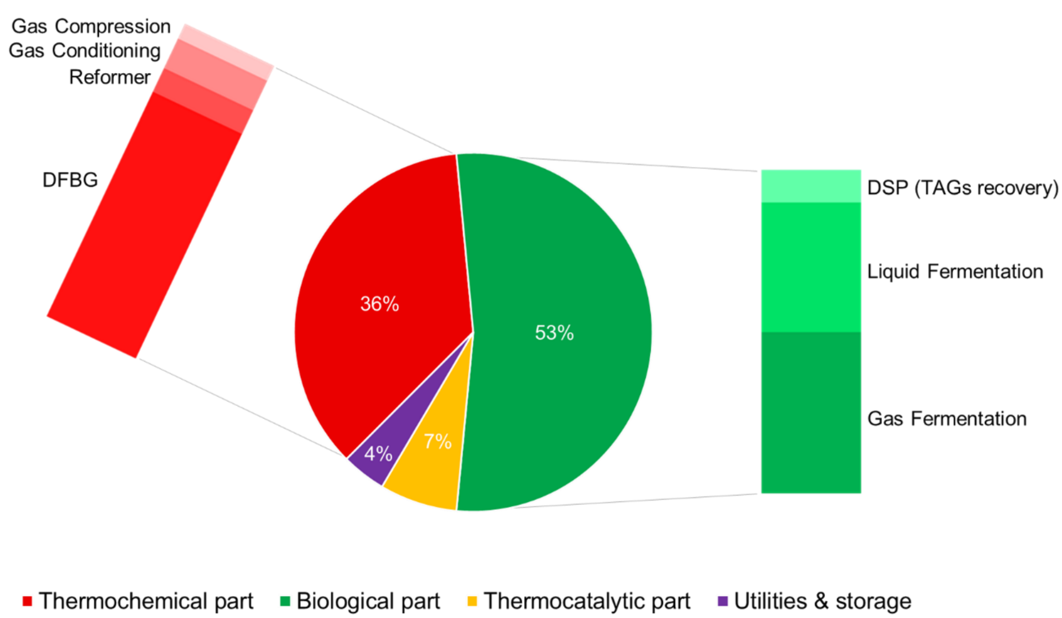

Figure 52. Installed cost breakdown of the main process parts.

The estimated TCI of €577 million lies in the typical range of €500-700 million that many recent techno-economic studies [63, 67, 69, 74] adopt for the required capital investment of gasification-driven BtL concepts (FT or AtJ) of similar capacity. The path to the decisive reduction of capital costs aimed by the proposed pathway seems to go through the reduction of capital costs related to double-stage fermentation. The latter can be achieved by ensuring higher commercial productivities of acetic acid (> 3.5 g/L/h) and TAGs (> 1 g/L/h) formation.

5.3.1.2 Annual operating costs

Utilizing the mass and energy balances of the concept detailed in section 5.2.3 (and Appendix) as well as the economic assumptions detailed in section 5.2.4, the annual operational financial streams are calculated and presented in Table 28.

Table 28. Annual Operational Expenditures (OpEx) of the BtL plant.

Feedstock costs	21,090,646 €/year
Electricity	5,361,120 €/year
Maintenance	10,489,600 €/year
Labor costs	3,500,000 €/year
Nutrients & chemicals	1,054,532 €/year
Property Insurance	3,671,360 €/year
Solvent make-up	2,959,338 €/year
Wastewater discharge	1,858,164 €/year
Annual operational expenses	**49,984,760 €/year**
Income from diesel	14,475,024 €/year
Income from cellular biomass	6,288,716 €/year
Annual revenue streams (by-product credits)	**20,763,740 €/year**

The estimated annual operational expenses are around €50 million. About 40% of these expenses appear to be covered by the revenue obtained from diesel and yeast biomass selling. The biomass supply (feedstock costs) represents the highest proportion (42%) of the annual operating costs. A remarkable percentage (21%) of the annual charges is due to fixed maintenance requirements because of the extensive infrastructure that accompanies almost every BtL concept that handles advanced feedstock. The low operating pressures of the biological part reflect on limited electricity demand (for gas compression) and consequently cost, accounting for just 10% of the annual sum. The remaining 27% of the annual operating costs is sourcing from the employee compensation (labor costs), the property insurance, the acquisition of necessary raw materials, and wastewater disposal fees. (Figure 53)

The estimated annual operating costs of €50 million correspond to a 15-40% OpEx reduction compared to recent techno-economic studies of typical gasification-driven BtL plants [69, 70, 74, 210]. This fact seems to justify the ambition of the present study to introduce a novel BtL scheme that enables reduced operational costs.

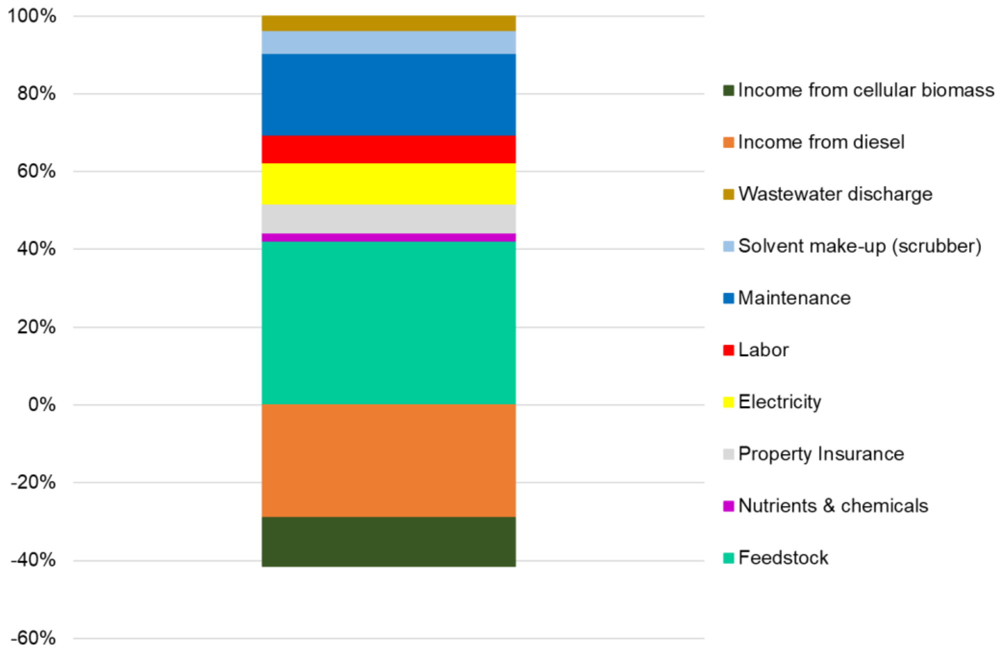

Figure 53. Cost breakdown of the annual operational streams.

5.3.2 Minimum Selling Price

The minimum selling price or break-even price of a techno-economic evaluation represents the price at which the targeted product of the BtL process should be sold, so that, at the end of the plant lifetime, its net present value is equal to zero.

For the main business case of the present study, in which jet fuel is the targeted product, a discounted cash flow analysis (Appendix, Section A-6, Table A8) was carried out by integrating all the above mentioned cost estimations and a MJSP equal to 1.83 €/L was calculated.

The thermocatalytic part of the proposed value chain is in essence a HEFA plant with microbial oil (TAGs) as feedstock instead of other typical oils. Therefore, taking into advantage the availability of such plants at commercial level and the similarity of the produced microbial oil with typical HEFA feeds [186], an additional business case is introduced, in which the hydrotreatment of the produced microbial oil is performed in such an external plant. In this case, the crude microbial oil is the end product of the process and the thermocatalytic part is excluded from the BtL concept and the capital investment. The rationale is not only the avoidance of the construction costs for a new refinery, but also the exploitation of the large existing refining infrastructure and experience. In the absence of the hydrotreatment/hydrocracking unit, the estimated TCI of the microbial oil scenario drops to around €527 million, while the annual operating costs are slightly influenced since the majority of them are sourcing from the process steps prior the hydrotreatment unit (Appendix, Section A-5, Table A7). A discounted cash flow analysis for the microbial oil scenario was performed with the updated boundary conditions and a Minimum Oil Selling Price (MOSP) equal to 1.32 €/L was obtained (Appendix, Section A-6, Table A9).

The TCI, the annual operating costs, and the mass balances that were utilized for the discounted cash flow analysis of each business case are presented in Table 29. The economic assumptions presented in Table 26 were kept common for both scenarios.

Table 29. Main boundary conditions for the selected business cases and calculated minimum selling prices.

Business case	Jet Fuel scenario	Microbial oil scenario
TCI (€)	576,928,000	526,592,000
Annual operating costs (€/year)	49,984,760	48,749,240
Income from diesel (€/year)	14,475,024	-
Income from cellular biomass (€/year)	6,288,716	6,288,716
Biomass feed (t/year)	301,295	301,295
Produced jet fuel (t/year)	32,435	-
Produced diesel (t/year)	8,042	-
Produced microbial oil (t/year)	-	50,395
MJSP (€/L)	1.83	-
MOSP (€/L)	-	1.32

5.3.3 Sensitivity analysis

Sensitivity analysis is probably the most critical aspect of the techno-economic analysis, since it not only allows the impact evaluation of various process parameters on the financial performance of the concept, but also limits in a way the effect of incorrect initial economic assumptions and sources of uncertainty. Section 5.3.3.1 is dedicated on the assessment of the influence that selected process parameters have on the MJSP formation. Section 5.3.3.2 presents the estimations regarding the discounted payback period and NPV of both business cases by increasing the potential selling price of jet fuel and microbial oil starting from MJSP and MOSP, respectively.

5.3.3.1 Minimum Jet Selling Price (MJSP)

The impact of ±40% variations in baseline TCI, feedstock price, discount rate, diesel selling price, and electricity price on the MJSP is investigated. TAGs recovery percentage (from their intracellular form) in the DSP and annual operating hours complete the set of selected parameters for the sensitivity analysis. (Figure 54)

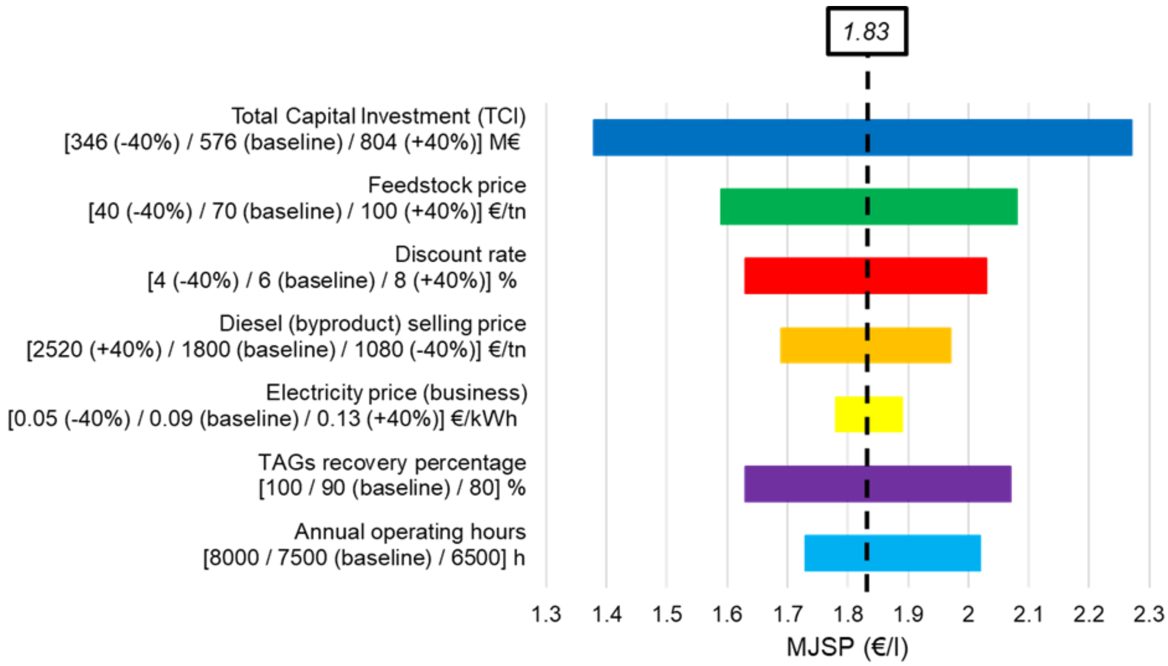

Figure 54. Sensitivity analysis on MJSP via the variation of key process parameters (dashed line refers to the baseline value).

TCI and feedstock costs are the parameters with the largest impact on the formation of MJSP and consequently the main cost-drivers of the process. Considering that a MJSP below 2 €/L would be the minimum prerequisite for competitiveness, TCI below €650 million and feedstock costs below 100 €/t would be desirable towards the financial sustainability of the concept. A TCI below €500 and the involvement of cheap feedstock (e.g. biogenic wastes) could move the MJSP in the very competitive for advanced biofuels range of 1-1.5 €/L. The relatively low electrical requirements of the examined BtL concept reflect on the small impact of the electricity price on the MJSP. Thus, utilization of RES electricity (even in cases that is more expensive than fossil) for further carbon footprint reduction of the plant seems affordable. Moreover, the TAGs recovery percentage (DSP efficiency) seems critical for the performance of the whole unit. Although 100% recovery is rather unattainable even in large-scale applications, percentages below 70-80% seem prohibitive for the process economics. The assumed maximization of jet fraction at diesel's expense leads to an unimpressive effect of diesel selling price on MJSP, but non-negligible as well, since diesel remains the main by-product of the process. A rather remarkable influence on the computed MJSP is also observed from the applied discount rate, while the plant on-stream factor should be over 80% (i.e. >7000 annual operating hours).

5.3.3.2 Discounted payback period and NPV

Discounted payback period provides the number of years it takes to break even from undertaking the initial capital investment, by discounting future cash flows and considering the time value of money. NPV is the difference between the present value of cash inflows and the present value of cash outflows over the plant lifetime. Positive NPV is a good initial indication for a potential investment, while a negative one is the opposite. Both discounted payback period and NPV are valuable metrics towards the feasibility and profitability of a given project. The shorter the discounted payback period and the higher the net present value, the better for the potential investment.

A sensitivity analysis based on these two parameters is performed for the jet fuel and the microbial oil business cases in order to assess the specifications of the concept and compare the potential of each investment. A fixed selling price increase rate is applied for the jet fuel and the microbial oil starting from the MJSP and MOSP, respectively. (Figure 55)

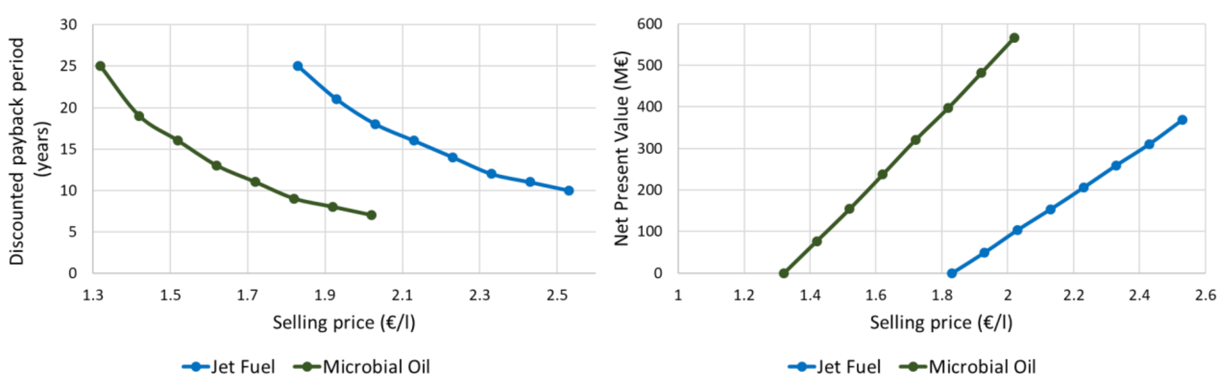

Figure 55. Sensitivity analysis on discounted payback period and NPV via the variation of final product selling prices.

The microbial oil scenario seems, as expected, the most attractive business case presenting the highest potential in terms of minimization of the payback period and maximization of the NPV. Of course, there is still some distance to cover between the conventional (fossil) fuels prices and the potential profitable selling prices of their low-carbon replacements. However, it becomes apparent that new BtL investments should target intermediate products (e.g. microbial oil) that can be exploited by current refineries (directly or via co-processing) rather than final products (e.g. jet fuel) that require brand new hydrotreatment facilities. The latter would entail higher risks for the financial sustainability of novel large-scale BtL plants. The connection of newly established sustainable BtL pathways with the current need of commercial refineries to decarbonize their activities via the exploitation of the large existing refining infrastructure could pave the way towards the validation of claims that the next two decades will be dominated by technologies handling advanced feedstock and by refineries that act as hubs of low-carbon oils [211].

5.3.4 Benchmarking with the dominant SAF technologies

This section aims to conduct an evaluation of the concept presented within this study in terms of financial capabilities and competitiveness compared to the current dominant SAF technologies (i.e. HEFA, FT, AtJ, e-fuels). MJSP has been elected as an appropriate indicator for this purpose since it is a metric that is often used for the primary economic assessment of a BtL technology and allows for comparison with relevant techno-economic studies. However, direct comparisons with other techno-economic studies are not proper due to possible differentiations in assumed methodology, boundary conditions, or scale. On the contrary, aggregated data, that take into account multiple studies, seem more suitable for the formation of a holistic perspective and an apt judgement regarding the estimated range of each technology. Hence, the findings of Chapter 1 (SAFs review study) are exploited for positioning the MJSP of the present work among a set of MJSP predictions for dominant SAF technologies. The global average price evolution of conventional jet fuel (Jet A-1) in recent years is attached as well, extracted from [91]. (Figure 56)

HEFA-produced SAF is the most cost-competitive option and the only route so far that can consistently compete with conventional jet fuel prices. With selling prices below 1.00 €/L seeming attainable, HEFA has already penetrated the market and can be considered the only state-of-the-art commercial SAF. The respective trend lines for the semi-commercialized FT and AtJ routes, which are also the technologies of greater interest in the context of this study, lie well within the range of 1.50-2.00 €/L. The feedstock flexibility of these two routes results in some deviations regarding the estimation of their production costs, but it is rather safe to claim that cost-effective feedstock can lead to cost-competitive FT and AtJ implementations. The recent establishment of the world's first ethanol to SAF (AtJ) commercial production facility by LanzaJet [39] acts as a proof for the latter claim and is a breakthrough towards the involvement and accelerated scale-up of additional pathways, apart from HEFA, for the commercial uptake of SAFs. Finally, the e-jet trend line moves around 3.00 €/L and illustrates the current uncertainty that characterizes this kind of fuels. Almost every recent techno-economic study struggles to determine affordable e-jet production costs at present, but they all highlight the significant cost reduction potential in the future, driven mainly by reductions in hydrogen and green electricity prices [22].

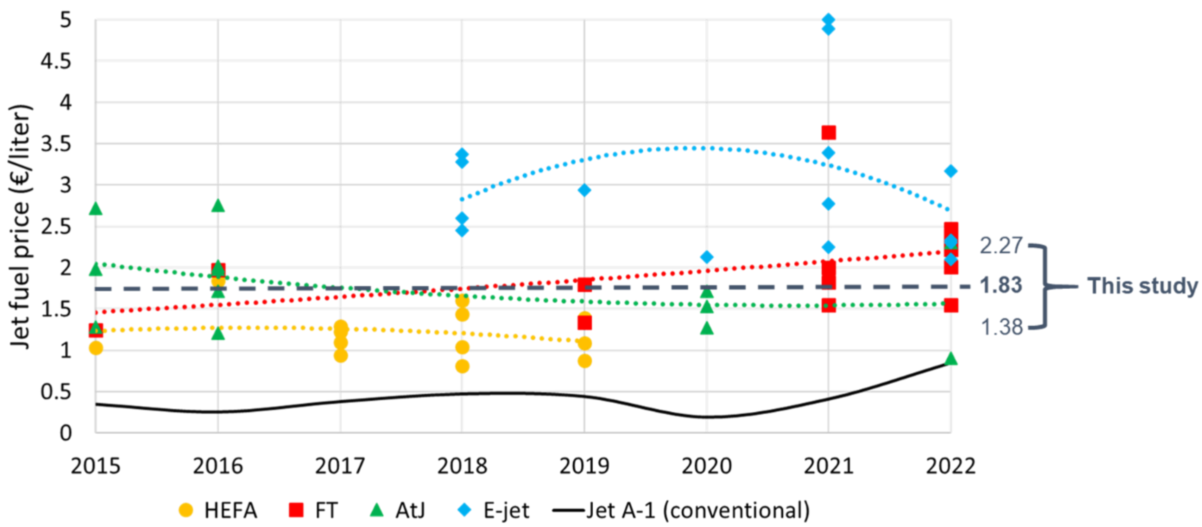

Figure 56. MJSP positioning of this study among recent MJSP predictions for the dominant SAF technologies (Chapter 1).

The obtained baseline MJSP of 1.83 €/L reveals the preliminary ability of the concept of this study to be financially competitive. The calculated MJSP of 1.83 €/L is within the range of the respective prices from the dominant BtL technologies (1.50-2.00 €/L). According to the performed sensitivity analysis of section 5.3.3.1, favorable economic conditions can drop the MJSP up to 1.38 €/L, while unfavorable economic conditions can raise this value to 2.27 €/L. Another factor that should be considered for the financial assessment of the proposed pathway is that the proof of concept has just been carried out at pilot scale (Technology Readiness Level – TRL 5) within BioSFerA project [9], while the technological maturity of FT and AtJ pathways are at pre-commercial level (TRL 8-9). Thus, there is rather more room for improvement in terms of technical performance and subsequently financial efficiency compared to more established technologies. Aiming to provide an overview of the production costs for the BtL scheme of this study and to identify the aspects to be improved, the calculated MJSP is presented in the form of levelized production costs and compared with the respective cost breakdowns of FT and AtJ gasification-driven pathways, as derived from relevant studies [62, 67]. (Figure 57)

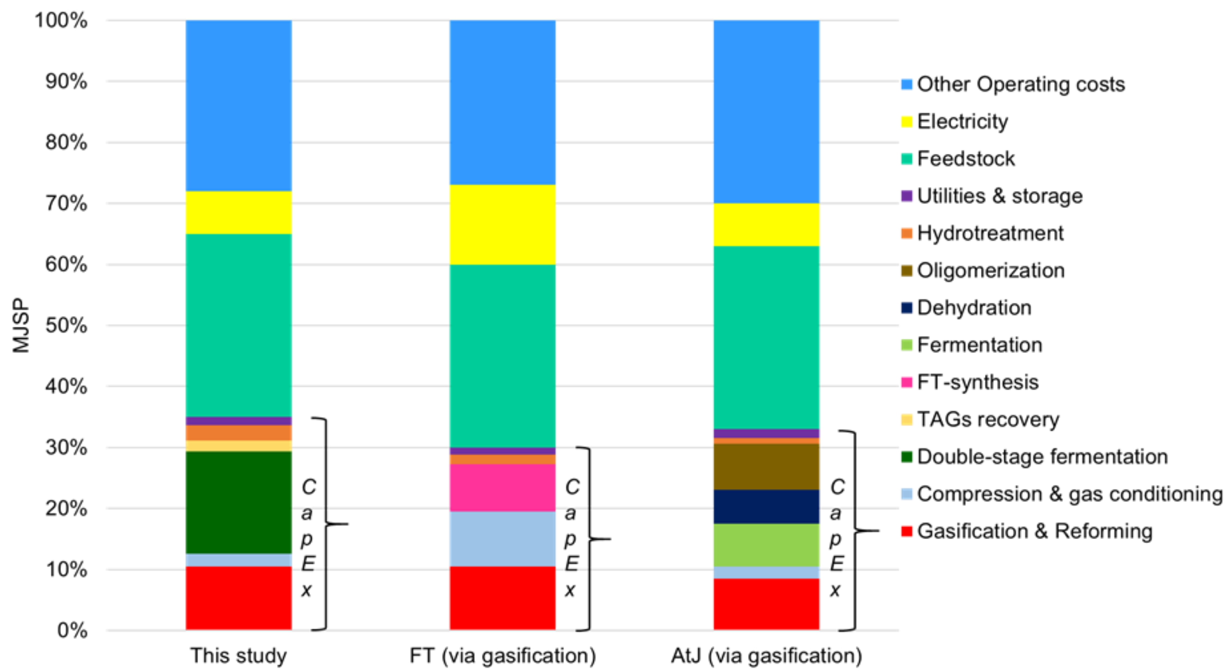

Figure 57. Comparative analysis of levelized production costs for the concept of this study, the FT via gasification, and the AtJ via gasification pathways (as a percentage of total).

Taking into account this study's estimated MJSP (1.83 €/L) as well as the respective positioning of FT's and AtJ's MJSPs mainly in the range of 1.50-2.00 €/L (Figure 56), a qualitative insight in the allocation of their production costs is provided in Figure 57. All three BtL routes present pretty similar distribution regarding the envisaged production costs of the final biofuels. As expected for BtL plants that target advanced feedstock, the CapEx (return on investment) and the feedstock costs combined account at least for the 60% of the production costs in each technology. While the feedstock capabilities and the relevant costs are the same for each pathway due to the common presence of gasification in the start of each process, the different terms of gas handling and fuel synthesis reveal the individual specifications of each route. Despite FT process being the value chain with the fewest conversion steps, the strict specifications of FT-synthesis (i.e. proper H_2/CO ratio, exhaustive acid gas removal, and high gas pressures/temperatures) burden the overall production costs with extensive equipment for gas conditioning and heavy electricity requirements. Gasification-driven AtJ is a process that, similarly with the concept of this study, is based on milder temperatures, pressures, and subsequently reduced electricity expenses. However, the multiple conversion steps lead to inevitable large capital expenses for this technology as well. Thus, the two dominant technologies usually result in similar production costs in total (Figure 56) and the regulator concerning their competitiveness seems to be the feedstock purchase cost.

The examined concept of this study aims to reach competitive performance levels by avoiding the strict specifications of FT or the several unit operations of the AtJ route that raise the total production costs. Although the simulated BtL scheme seems able to provide equal liquid biofuel yields (Chapter 4) with FT and AtJ based on reduced operational costs, the initially estimated capital investment of the concept seems as demanding as for the other technologies (30-35% of the levelized production costs). This is mainly due to the large working volumes of the double-stage fermentation and subsequently the large required number of bioreactors. Of course, as already mentioned in section 5.3.1.1, higher obtained productivities and concentrations for acetic acid/TAGs production can drastically reduce the capital costs of the double-stage fermentation, and upgrade the financial competitiveness of the concept.

To sum up, the investigated BtL scheme of the present study appears capable of providing an initially competitive pathway to add to the established and already at pre-commercial level FT and AtJ technologies. The reduction of the envisaged capital costs for the biological part via the optimization of the acetic acid/TAGs productivities and concentrations should be the priority on the way to the potential scale-up of the concept. In general, gasification-driven BtL technologies seem adequate to play a leading role towards the deployment of SAF production technologies since they usually offer the valuable aspect of feedstock flexibility (forestry/agricultural residues, biogenic wastes, etc.) which can be critical for the implementation of low-cost feedstock scenarios and subsequently the production of advanced biofuels at affordable costs. Finally, it should not be overlooked that BtL based on gasification has yet to be commercialized. Hence, a pioneer plant is expected to be more costly to build and operate than a Nth plant (beneficial scale effect).

5.3.5 Greek Biomass-to-Liquid (BtL) replication study

The revised National Energy and Climate Plan (NECP) of Greece, aligned with the RED III indications, mentions the potential of gasification-driven Biomass-to-Liquid (BtL) concepts towards the uptake of advanced biofuels in the country. In this context, a preliminary Greek replication study, based on the introduced BtL scheme of this study, is attached.

Taking into account the feedstock screening of Chapter 3, the Greek case study could be based on olive tree prunings. In particular, the area of Peloponnese seems able to cover the feedstock requirements of a full-scale plant locally [138]. Once the area to be used for the case study has been defined (Peloponnese), an average price range for the selected feedstock (olive tree prunings) was estimated. This estimation was generated with the assistance of the BIORAISE GIS platform [212]. In particular, after entering the willing study zone and a hypothetical delivery location within this zone, the platform returns an average collection/harvesting cost as well as an average transportation cost for the selected feedstock. The harvesting cost includes pruning, chipping, stocking, extraction, and loading costs. An average calculation is provided for the transportation cost that takes into account road distances, local fuel costs, consumptions, etc. For the case of Peloponnese, the average cost of 38 €/t and 14.86 €/t were obtained for the collection and transportation costs of olive tree prunings, respectively.

As analyzed in section 5.3.3.2, the microbial oil scenario seems the most promising market-wise choice for the establishment of a new BtL plant. The microbial oil scenario envisages the production of purified TAGs (microbial oil) that can be upgraded by existing refineries. Estimated TCI (526,592,000 M€) and most of the boundary conditions (defined in section 5.2.4) are kept common for the Greek case study. Feedstock cost, electricity price, and average annual salary are adjusted to the specifications of Greece. Hence, feedstock cost for the case of Greece was set at 53 €/t, the industry electricity price (average last 5 years) was set at 0.12 €/kWh [213], and the average annual salary for the chemical industry was assumed equal to 22,000 € [214]. (Figure 58)

Greece boundary conditions	
Thermal input	200 MWth
Plant lifetime	25 years
On-stream factor	85% (7446 h)
Feedstock cost (olive tree prunings)	53 €/tn
Electricity price (business)	0.12 €/kWh
Average annual salary	22000 €/year
Discount rate	6%
Tax rate	0%
Construction period	2 years (40% 1st year, 60% 2nd year)
Cellular biomass (as by-product)	700 €/t

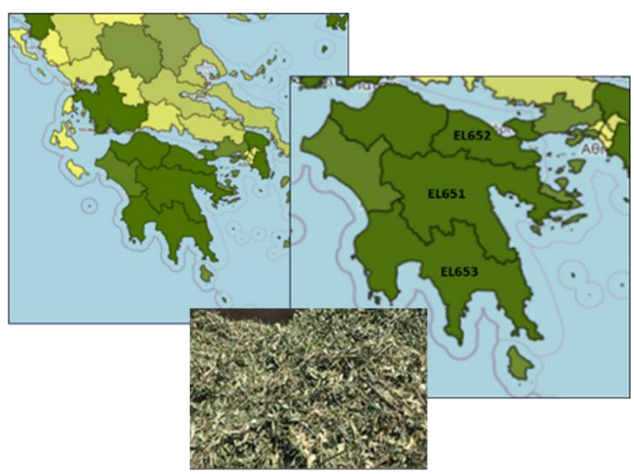

Figure 58. Selected area, feedstock, and boundary conditions for the Greek replication study.

The annual operating costs are transformed according to the Heat & Mass balances of the Greek replication study, the main elements of which are presented in Table 30. An annual revenue stream is considered from the selling of cellular biomass (yeast biomass) as a possibly valuable by-product. Table 31 provides an overview of the annual operational financial streams that take part in the cash flow analysis of the Greek replication study.

Table 30. Feedstock/production capacity for the Greek replication study.

Feedstock requirements (olive tree prunings)	302,205 t/year
Produced microbial oil (purified TAGs)	49,054 t/year
Produced cellular biomass (by-product)	8,711 t/year

Table 31. Annual operational expenses for the Greek replication study.

Feedstock costs	16,016,936 €/year
Electricity	7,148,160 €/year
Maintenance	9,574,400 €/year
Labor costs	2,200,000 €/year
Nutrients & chemicals	1,054,532 €/year
Property Insurance	3,351,040 €/year
Solvent make-up	2,959,338 €/year
Wastewater discharge	1,858,164 €/year
Annual operational expenses	**44,162,570 €/year**
Income from cellular biomass	6,097,700 €/year
Annual revenue streams (by-product credits)	**6,097,700 €/year**

A cash flow analysis is performed, based on the estimated capital and operating costs of the Greek replication study. The Minimum Oil Selling Price (MOSP) has been elected as the most suitable indicator for the initial financial evaluation of the concept. The MOSP is obtained by iterating the microbial oil product cost to obtain a Net Present Value (NPV) equal to zero at the selected discount rate. Thus, assuming a NPV equal to zero at the end of the plant lifetime, the computed baseline value for the MOSP of the Greek replication study is 1.29 €/L. The detailed cash flow analysis is attached in the Appendix (Section A-6, Table A10).

A sensitivity analysis was performed to evaluate the impact of different economic parameters and operational aspects on the formation of Greek MOSP (Figure 59). An additional sensitivity analysis was also perfomed to illustrate the effect of the microbial oil selling price on the discounted payback period and the NPV of the replication study (Figure 60).

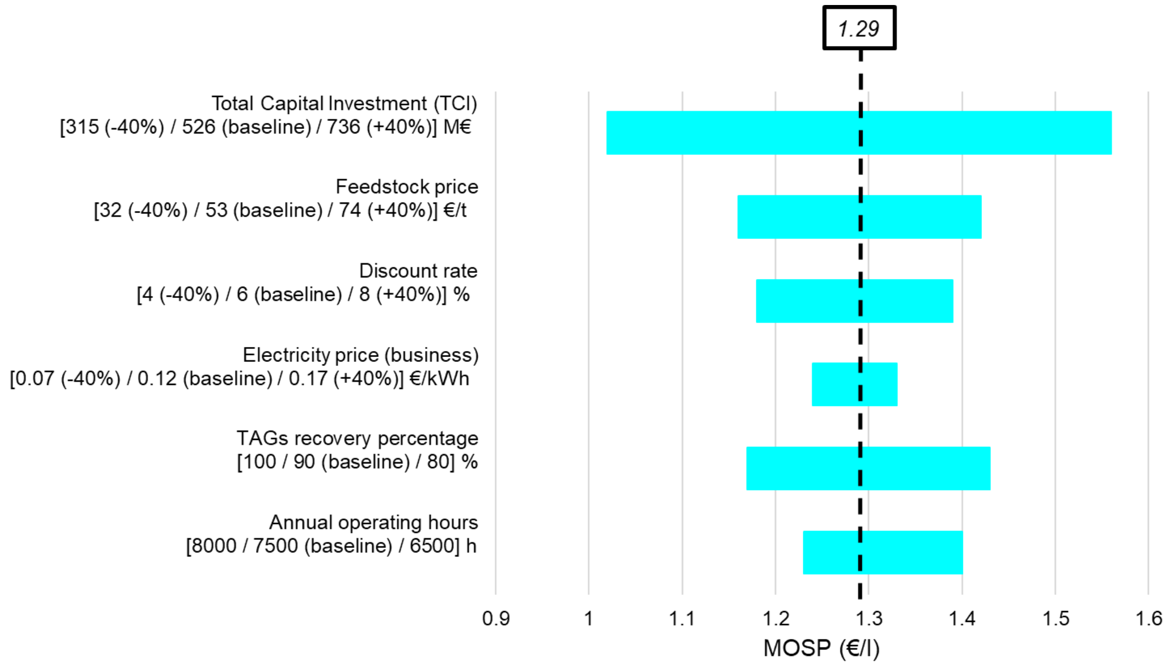

Figure 59. MOSP sensitivity analysis for the Greek replication study.

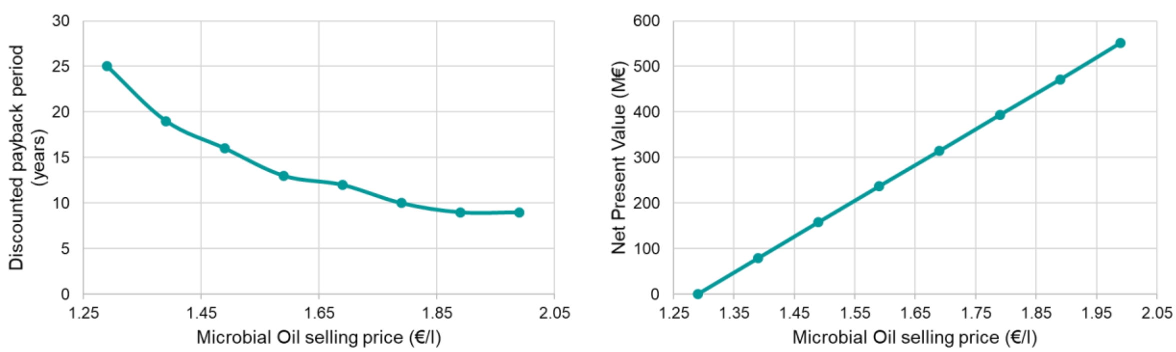

Figure 60. Discounted payback period and NPV in relation to the microbial oil selling price for the Greek replication study.

A combination of reduced capital and feedstock costs from the baseline seems necessary for the achievement of a MOSP value close to 1 €/L. The MOSP of 1.29 €/L corresponds to a NPV equal to zero and a discounted payback period equal to the plant lifetime (25 years). A microbial oil selling price over 1.75 €/L seems to be required for the accomplishment of a discounted payback period less than 10 years, while a selling price around 2 €/L is required to generate NPV comparable to the initial capital investment (over €500 million).

Considering that the current market prices for European UCOs or conventional vegetable oils (sunflower, soybean, rapeseed, palm) lie in the range of 0.6-0.9 €/L [215-217], the estimated competitive selling prices for the microbial oil of this study are well over (50-70% more expensive) than the majority of the primary renewable oils. However, the target of decisively decarbonizing several transport sectors with advanced biofuels and the lack of cheap appropriate feedstock (e.g. UCOs) are expected to bring to the fore the need for additional sustainable input refinery streams, such as the microbial oil. Furthermore, it is anticipated that continuous research efforts related to BtL plants will reduce the production costs and upgrade the financial viability of such concepts.

5.4 Conclusions

In this study, an alternative gasification-driven BtL concept for the production of SAFs is introduced and evaluated. In particular, a fuel synthesis scheme based on the double-stage fermentation of the produced syngas (syngas → acetic acid → TAGs) is investigated instead of the conventional FT or AtJ synthesis, aiming to the establishment of an additional competitive BtL technology characterized by mild operating temperatures, low pressures, and consequently affordable production costs. The environmental assessment of the concept has revealed 50-80% potential GHG emission savings compared to conventional (fossil) routes. The main objective of the present work is the techno-economic assessment of a large-scale (200 MWth) replication of the mentioned BtL concept, whose performance has been simulated in Aspen Plus™ with reasonable upscaling considerations and models validated at pilot scale.

The estimated baseline TCI of €577 million lies in the typical range of €500-700 million that many recent techno-economic studies adopt for the required capital investment of gasification-driven BtL plants (FT or AtJ) of similar capacity, while the estimated annual operating costs of €50 million correspond to a 15-40% OpEx reduction compared to such plants. A discounted cash flow analysis was carried out and a MJSP equal to 1.83 €/L was calculated. The obtained baseline MJSP reveals the preliminary ability of the concept to be financially competitive since it belongs in the range where the dominant BtL technologies (FT and AtJ) seem to fall (1.50-2.00 €/L). The performed sensitivity analysis indicates that the MJSP can decrease up to 1.38 €/L under good economic terms and increase up to 2.27 €/L under unfavorable economic conditions. TCI and feedstock costs are the main cost-drivers of the process, while the securement of a TAGs recovery percentage (DSP efficiency) over 70-80% seems also a critical aspect.

An additional business case was assessed, in which the hydrotreatment of the produced microbial oil is performed in an external existing plant (refinery). In this case, the microbial oil is the end product of the process and the thermocatalytic part is excluded from the BtL concept. The reasoning for the election of this scenario is not only the avoidance of the construction costs for a new hydrotreatment facility, but also the exploitation of the extensive refining infrastructure and experience already in place. New BtL investments should rather focus on intermediate products (low-carbon oils) that can be upgraded by existing refineries instead of final products (drop-in fuels) that require brand new hydrotreatment facilities. In this regard, a Greek microbial oil scenario was simulated in the area of Peloponnese based on olive tree prunings as feedstock. The respective discounted cash flow analysis resulted in a baseline MOSP equal to 1.29 €/L, which is more expensive than the current market prices (0.6-0.9 €/L) of typical renewable oils (e.g. UCOs, vegetable oils). However, the need for additional alternative input refinery streams (oils) towards the decarbonization of several transport sectors and the scarcity of inexpensive suitable feedstock (e.g. UCOs) are expected to form the conditions in the future for the exploitation of advanced sustainable oils, such as the microbial oil of this study.

In essence, the techno-economic assessment of this study sets the biological conversion of gasification-derived syngas into TAGs as a promising alternative route for the production of SAFs. The whole value chain was successfully demonstrated at pilot scale (TRL 5) within the BioSFerA project. The qualitative analysis of the production costs compared to established technologies revealed that the priority towards the potential scale-up of the concept should be the optimization of acetic acid/TAGs productivities and concentrations in order to reduce the capital costs related to the double-stage fermentation. The optimization of acetic acid/TAGs productivities and concentrations can be accomplished through advanced metabolic engineering of acetogenic bacteria/oleaginous yeasts, effective design of bioreactors, and proper fermentation conditions.

In general, gasification driven BtL technologies, led by FT and AtJ that are already at pre-commercial level, are capable of flourishing in the coming years based on their capability of advanced feedstock flexibility. Key prerequisites for this to happen are the continuous efforts for design optimization (reduction of capital costs), appropriate policy incentives, and the efficient connection with the existing refining infrastructure in a scheme that could deliver economic benefits to the industry and beyond.

Synopsis

Novel aspects of the present dissertation:

- ❖ A holistic review on the current alternative aviation fuels considering techno-economic efficiency, environmental impact, future projections, market status, and recent regulations. Reports and studies exclusively after 2015 were taken into consideration in order to get the most up-to-date information possible.
- ❖ The direct feedback from industrial stakeholders regarding the uptake of biofuels through a dedicated survey. The identification of market needs, expectations, and concerns set the implementation priorities of the present dissertation.
- ❖ Chemical Looping Gasification (CLG) model development and validation with data obtained from the largest CLG pilot test campaign up to now (1.5 MWth by TU Darmstadt).
- ❖ Design, model development, and techno-economic assessment of an innovative Biomass-to-Liquid (BtL) concept. Model validation with data obtained from the first pilot tests of the double-stage syngas fermentation scheme (syngas → acetic acid → microbial oil).
- ❖ A Greek BtL replication study. Election of feedstock, location, and preliminary techno-economic evaluation.

Major outcomes of the present dissertation:

- ➢ Hydroprocessed esters and fatty acids (HEFA) is expected to remain the most effective route for Sustainable Aviation Fuel (SAF) production, at least through to 2030. Nevertheless, the feedstock constraints of HEFA technology encourage the claims that the next two decades could be dominated by technologies handling advanced feedstock (biogenic residues/wastes) to cover the projected increasing SAF demand. In this regard, the deployment of effective BtL concepts seems essential. The 'ReFuelEU Aviation' initiative is an indication for decisive legislative support of SAFs.
- ➢ The interaction with industrial stakeholders (i.e. feedstock suppliers, refineries, fuel traders, final end-users, policy makers) highlighted technical (e.g. cold flow properties) as well as market (e.g. energy/price ratio) challenges associated with the use of biofuels. The aviation and maritime sectors have placed advanced biofuels and e-fuels high on the agenda, but it will need some time for fuel policies to be adopted into national fuel networks.

- The EU biofuels policy, as outlined in the RED III directive, mentions the promotion of residue-based biofuels (advanced biofuels). The primary biogenic sources that can be utilized for energy production via gasification are forestry and agricultural residues. Certain types of feedstock that could potentially fulfill the key requirements for the implementation of large-scale BtL applications are woody prunings (e.g. olive, vineyard), straw/stubbles (e.g. cereal straw), primary forestry residues (e.g. logging), and secondary wood residues (e.g. bark, sawdust).
- Dual Fluidized Bed (DFBG) and Chemical Looping Gasification (CLG) technologies are both capable of providing a high quality syngas (nitrogen-free, cold gas efficiency > 80%), and thus seem ideal for future BtL applications. DFBG is a semi-commercially proven technology, while CLG has just been demonstrated at pilot scale. CLG can be considered a slightly improved variant of the DFBG technology that enables higher carbon capture/utilization, but decisive mitigation of certain technical (e.g. intense agglomeration) and financial (e.g. oxygen carrier make-up costs) risks is required prior utilization in large-scale BtL applications.
- The double-stage fermentation of gasification-derived syngas (syngas → acetic acid → microbial oil) into triglycerides (TAGs) is a viable alternative approach for the production of SAFs, according to the performed techno-economic assessment. Although it is still far from the current conventional jet fuel prices (0.6-0.7 €/L), the obtained baseline Minimum Jet Selling Price (MJSP) of 1.83 €/L reveals the concept's preliminary ability to be financially competitive with the dominant BtL technologies, such as Fischer-Tropsch (FT) and Alcohol-to-Jet (AtJ). According to the sensitivity analysis that was performed, the MJSP can rise to 2.27 €/L in adverse economic conditions and fall to 1.38 €/L in positive economic terms. The qualitative analysis of the production costs revealed that the priority towards the potential scale-up of the concept should be the optimization of acetic acid/TAGs productivities and concentrations in order to reduce the capital costs related to the double-stage fermentation.
- New BtL investments should rather focus on intermediate products (low-carbon oils) that can be upgraded by existing refineries instead of final products that require brand new hydrotreatment facilities. Using olive tree prunings as feedstock, a Greek microbial oil scenario was replicated in the Peloponnese region. The respective discounted cash flow

analysis resulted in a baseline Minimum Oil Selling Price (MOSP) equal to 1.29 €/L. This price is higher than the market pricing of typical renewable oils (e.g. UCOs, vegetable oils) which are now between 0.6 and 0.9 €/L. However, it is anticipated that the need for additional alternative input refinery streams (oils) towards the decarbonization of several transport sectors and the scarcity of affordable suitable feedstock (e.g. UCOs) will form the conditions for the exploitation of advanced sustainable oils, such as the microbial oil of this study.

- Gasification-driven BtL pathways, led by the relatively mature FT and AtJ technologies, are capable of thriving in the upcoming years due to their advanced feedstock flexibility. The successful integration with the current refining infrastructure, the appropriate legislative incentives, and the continuous efforts towards design optimization (reduction of production costs) are essential conditions for this to happen.

<u>Future prospects:</u>

SAFs are a recognized and widely acknowledged necessity for the instant decarbonization of the aviation industry. The current challenge for SAFs is to scale up production and progressively enter the market with a positive and lasting impact. While HEFA is the only route so far that can consistently compete with conventional jet fuel prices, its feedstock constraints turn the valorization of additional waste streams through efficient BtL concepts necessary.

The present work assessed, apart from the established FT and AtJ, the double-stage fermentation of syngas into TAGs (syngas → acetic acid → microbial oil). The ongoing European projects FUELPHORIA (https://fuelphoria.eu/) and CAPTUS (https://captusproject.eu/) have undertaken to advance the double-stage syngas fermentation. Moreover, multiple other projects are active towards the development of sustainable fuel production pathways.

In general, it is expected a great deal of research and development on both new and existing SAF technologies in the near future prioritizing the reduction of production costs. This includes BtL concepts, e-fuel pathways, as well as the exploitation of novel feedstock. The ambitious target of net-zero carbon emissions by 2050 for the aviation sector envisages the involvement and accelerated scale-up of several SAF production routes.

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Appendix

Section A-1: Filled questionnaire forms

A – Feedstock suppliers

Considering the type of your organization, please provide the requested information concerning your product/s distribution and characteristics:

1. **In which type of activity would you classify your business?**
   - Farmer *X*
   - Transporter
   - Wood supply industry
   - Distributor, wholesaler
   - Other: …………………………

2. **What type of product do you distribute or you could be able to distribute?**
   - Cereal bales *X*
   - Forestry products
   - Pruning bales
   - Pruning chips
   - Pellets
   - Other: …………………………

3. **What type of service do you provide for this product?**
   - Transport to end user
   - Transport and storage
   - Commercialization
   - Other: *X straw collection and transport to the local project partner*

4. **Which is the estimated quantity of this product that you are capable of distributing annually (t/year)?**

100 hectares grown for forage, corn, wheat, and triticale

5. **Up to which point the seasonality affects your productivity and how you handle this issue?**

The seasonal rhythm of crops is followed and dried crops are stored

6. **Could you give an estimation of the average energy content of your distributed products (MJ/t)?**

Not available data

7. **Which is according to your opinion the most important barrier that prevents biomass feedstock price decrease?**

- cultivation costs
- harvesting costs
- logistics costs
- labor costs *X*
- biomass pre-treatment (i.e. drying, pelletizing, torrefaction) investment cost
- Other: ………………………….

Any other issue/comments:

None

A – Feedstock suppliers

Considering the type of your organization, please provide the requested information concerning your product/s distribution and characteristics:

1. **In which type of activity would you classify your business?**

- Farmer *X*
- Transporter
- Wood supply industry
- Distributor, wholesaler
- Other: ………………………….

2. **What type of product do you distribute or you could be able to distribute?**

- Cereal bales
- Forestry products
- Pruning bales
- Pruning chips *X*
- Pellets
- Other: ………………………….

3. **What type of service do you provide for this product?**

- Transport to end user
- Transport and storage *X*
- Commercialization
- Other: ………………………….

4. **Which is the estimated quantity of this product that you are capable of distributing annually (t/year)?**

An initial goal is to manage mobilize around 1000 t/year of olive tree prunings from the wide area

5. **Up to which point the seasonality affects your productivity and how you handle this issue?**

Unfortunately, the seasonality affects the productivity in the wide area since pruning is carried out from December till March, but prunings cannot remain at the soil after a certain time since there is a danger of soil infection. Moreover, olive tree pruning is not performed every year in the same volume which affects the final quantities of the olive tree prunings.

6. **Could you give an estimation of the average energy content of your distributed products (MJ/t)?**

For the olive tree prunings the average low heating value is 17.7 MJ/kg (d.b.) or 14.2 MJ/kg (a.r.)

7. **Which is according to your opinion the most important barrier that prevents biomass feedstock price decrease?**

- cultivation costs
- harvesting costs *X*
- logistics costs
- labor costs
- biomass pre-treatment (i.e. drying, pelletizing, torrefaction) investment cost
- Other: ………………………….

Any other issue/comments:

None

A – Feedstock suppliers

Considering the type of your organization, please provide the requested information concerning your product/s distribution and characteristics:

1. **In which type of activity would you classify your business?**

- Farmer
- Transporter
- Wood supply industry
- Distributor, wholesaler
- Other: *X Wood chip and pellet production from vineyard prunings*

2. **What type of product do you distribute or you could be able to distribute?**

- Cereal bales
- Forestry products
- Pruning bales
- Pruning chips *X*

- Pellets *X*
- Other: ………………………….

3. What type of service do you provide for this product?

- Transport to end user
- Transport and storage
- Commercialization *X*
- Other: ………………………….

4. Which is the estimated quantity of this product that you are capable of distributing annually (t/year)?

This vineyard pruning wood pelleting plant is the largest of its kind in the world, with a production capacity of 20,000 t per year

5. Up to which point the seasonality affects your productivity and how you handle this issue?

Usually pruning is carried out from December to March but prunings have to remain between 2 and 3 months on the soil to lose enough moisture content. In this way, it is expected that this feedstock will be available at the right conditions between March and June. Based on our estimations there are around 320,000 t_{fm}/year (moisture content: 30%, after 60-90 days left on the field) of vineyards pruning that could be potentially valorized in an area of 30,000 ha, enough to cover our productivity needs.

6. Could you give an estimation of the average energy content of your distributed products (MJ/t)?

The quality requirements for the final produced pellets are:

- *Pellets: Low Heating Value of 16.7 – 18.0 MJ/kg*

7. Which is according to your opinion the most important barrier that prevents biomass feedstock price decrease?

- cultivation costs
- harvesting costs *X*
- logistics costs *X*
- labor costs
- biomass pre-treatment (i.e. drying, pelletizing, torrefaction) investment cost *X*
- Other: ………………………….

Any other issue/comments:

None

B – Refineries

Considering your commercial fuel production experience, please provide the requested information concerning biofuels and their challenges:

1. **What type of fuels are the final products of your refineries?**
    - *Propylene/LPG*
    - *Gasolines (ETBE, Mogas/LCN/Naphtha)*
    - *JP1 (Jet fuel)*
    - *Diesel/Gasoil*
    - *Heavy Fuel Oil (own use, power)*

2. **Which is your estimated annual production (t/year), and which are the average energy contents of your final products (MJ/t)?**
    - *Average yearly production: 421000 barrels/day ~ 10 million tons/year*
    - *Crude source = 42000 [MJ/ton]*
    - *LPG(Butane/Propane/LPG MIX) = 45000- 48000 [MJ/ton]*
    - *Gasoline/Jet fuel/Gasoil = 43000-47000 [MJ/ton]*
    - *Heavy Fuel Oil : ~40000 [MJ/ton]*

3. **Is it imposed any obligatory biobased percentage in your final products and, if yes, how much is this percentage?**
    - *The products at the refinery itself do not have to contain bio-components by law. In other words, a refinery has no obligations.*
    - *There's one leading directive → the 'Renewable Energy Directive' that states that 30% of energy in transport must be renewable by 2030 (revised). You can do it with BEV, FCEV, biodiesel, ethanol, biomethane… The obligation is for the supplier of the product to the market, and is different for each member state. The obligation is changing every year.*

4. **Do you perform co-processing (conventional/renewable fuels parallel processing)? If yes, what kind of renewable fuels are these? If no, would you be interested to this initiative?**

Confidential

5. **Which are, according to you, the main challenges from the technical point of view for biofuels establishment?**

Everything depends on the type of biofuel.

- *FAME:*
    - *Cold properties, oxygen content and oxidation stability give the main quality issues.*
    - *The quality of FAME largely depends on the used feedstock. It is either stable (but freezes to soon) or unstable (but then is has good cold properties)*
    - *The 'Fuel Quality Directive' puts a limit on the addition of FAME to EN590 diesel to 7%. This is the so-called "blend wall". Since the RED requires much higher blend percentages, we need other type of products like HVO (which is much more expensive).*
    - *Energy density of FAME is lower → higher consumption*

- *Density of FAME is higher than diesel, so watch out when blending!*
- *Oxygen content is high, so the product is polar and keeps water in the product. This makes FAME unsuitable for aviation! On top water pick-up leads to increased microbial contamination of diesel*

- *HVO:*
  - *There are not many challenges for HVO, because it is a perfect fuel in use.*
  - *The density is rather low, what limits the use to about max; 30% in EN590 diesel.This is the main challenge for HVO.*
  - *Due to low density, the fuel-consumption/L is also higher than conventional diesel. HVO has no other technical disadvantages. It is paraffinic. That is perfect! HVO can be used for aviation.*

- *Ethanol:*
  - *The main challenge with ethanol is that addition of ethanol has impact on the quality of EN228 gasoline. Especially the effect on the vapour pressure, but the issue is solved by the introduction BOB-gasoline*
  - *Ethanol is polar, so tends to attract water. Therefore, it is added to the product as late as possible in the supply chain*
  - *Not all cars are compatible with E10 (= blend of 10% ethanol in gasoline), so a protection grade is needed*

Any other issue/comments:
Road vs. Air → Biofuel for road transport is easier, because "just" the final blend of biofuel + conventional fuel must comply with EN590 or EN228. It is "just" a blend component. But when you make biofuel for aviation then the 100% biofuel must comply to almost 99% of the final jetfuel specification, so the quality of the biofuel must already be excellent. This is driven by risk-analysis!

B – Refineries

Considering your commercial fuel production experience, please provide the requested information concerning biofuels and their challenges:

1. **What type of fuels are the final products of your refineries?**

Gasoline, diesel, jet fuel, IMO fuel oil, high sulfur fuel oil, gasoil, LPG, naphtha

2. **Which is your estimated annual production (t/year), and which are the average energy contents of your final products (MJ/t)?**

16,5 Mt/y

3. **Is it imposed any obligatory biobased percentage in your final products and, if yes, how much is this percentage?**

7% v/v biodiesel in diesel
1% v/v bioethanol in gasoline

4. **Do you perform co-processing (conventional/renewable fuels parallel processing)? If yes, what kind of renewable fuels are these? If no, would you be interested to this initiative?**

Confidential

5. **Which are, according to you, the main challenges from the technical point of view for biofuels establishment?**

Cloud point and CFPP

Any other issue/comments:

None

B – Refineries

Considering your commercial fuel production experience, please provide the requested information concerning biofuels and their challenges:

1. **What type of fuels are the final products of your refineries?**

   Gasoline
   Jet
   Diesel
   LSFO
   HSFO

2. **Which is your estimated annual production (t/year), and which are the average energy contents of your final products (MJ/t)?**

Gasoline 1 600 000 ton
Jet 200 000 ton
Diesel 3 500 000 ton
LSFO 80 000 ton
HSFO 60 000 ton

3. **Is it imposed any obligatory biobased percentage in your final products and, if yes, how much is this percentage?**

Yes, there is volumetric mandate
4,1 % vol. of BioEtOH in Gasoline
6,0 % vol. of biodiesel in Diesael
Plus there is mandate to reduce 6% of GHG emission along FQD directive

4. **Do you perform co-processing (conventional/renewable fuels parallel processing)? If yes, what kind of renewable fuels are these? If no, would you be interested to this initiative?**

No

5. **Which are, according to you, the main challenges from the technical point of view for biofuels establishment?**

Oxygenation stability, affinity to water

Any other issue/comments:

Biofuels are rather ineffective source of energy

B – Refineries

Considering your commercial fuel production experience, please provide the requested information concerning biofuels and their challenges:

1. **What type of fuels are the final products of your refineries?**

We produce the whole range of liquid fuels: gasoline, diesel, marine and jet fuel. Regarding biofuels, we produce ETBE and HVO.

2. **Which is your estimated annual production (t/year), and which are the average energy contents of your final products (MJ/t)?**

Confidential

3. **Is it imposed any obligatory biobased percentage in your final products and, if yes, how much is this percentage?**

We meet the percentages of the Renewable Energy Directive as transposed to our National Legislation.

4. **Do you perform co-processing (conventional/renewable fuels parallel processing)? If yes, what kind of renewable fuels are these? If no, would you be interested to this initiative?**

Yes, we co-process conventional vegetable oils and used cooking oils (UCOs) in our assets, for the production of hydrogenated vegetable oil (HVO).

5. **Which are, according to you, the main challenges from the technical point of view for biofuels establishment?**

Currently, the major challenge for us is the production of biofuels by co-processing renewable feedstocks. The presence of contaminants in these feedstocks pose operational problems in the industrial units and ultimately limit the maximum amount that can be fed to the units for co-processing. Another challenge is the cost of the feedstock.
Regarding properties: in general, biofuels produced from vegetal oils have poor cold properties, which represent a difficulty, especially for the case of biojet fuel, which specification is stricter.

Any other issue/comments:

None

C – Fuel traders

Considering the type of fuels that you usually trade, please provide the requested information concerning technical and supply requirements:

1. **What type of fuels do you mainly trade for aviation or maritime use?**
   - *HVO*
   - *FAME*
   - *Waste residual oils from various industries*

2. **Which are the main specifications that must be followed in order an aviation/maritime fuel to reach the market?**
   - *Fuel standards*
   - *Price*
   - *Logistics*
   - *Scalability potential*
   - *Combustion characteristics/fit for use*
   - *Compatible with current fuel infrastructure*

3. **In the fuels that you trade, are there any cleaning requirements or they can be directed straight to the bunker?**

- *The fuels we currently deliver are drop-in fuels, which means no adjustments or cleanings are required to bunker them*

4. **How much important is for you the blending ability of the fuels that you trade?**
- utmost important *X*
- very important
- medium important
- low important
- no important at all

Any other issue/comments:

- *Feedstock used for the fuel should meet RED sustainability criteria*
- *Supply chain should be certified by a sustainability system (e.g. ISCC or RSB)*

D – Final end-users

Considering the type of fuel that you usually use for your activities, please provide the requested information concerning your infrastructure fuel compatibility, fuel standards and performance:

1. **Which is the type of fuel that you usually involve in your infrastructure?**

Bunker fuels (Heavy Fuel Oil 0.5 Sulphur Content and Marine Gasoil).

2. **Which are the main criteria that lead your fuel selection and define its performance?**

Our engine maker's requirements and IMO, local port, or other pertinent regulation.

3. **Which is the annual fuel consumption for your activities?**

Non-disclosed.

4. **Are you satisfied from the prices and the supply chain of the fuels that you currently use?**

Yes.

5. **Do you use fuel blendings and, if yes, which is their typical composition?**

No.

6. **Which fuel parameter improvement could lead you to investigate alternative options for your fuel?**

Emissions, cost and energy content.

7. **How much negotiable would you be in partial retrofitting of your existing infrastructure due to new fuel requirements?**

We would consider it depending on cost, classification, flag, and operational requirements.

Any other issue/comments:

None

D – Final end-users

Considering the type of fuel that you usually use for your activities, please provide the requested information concerning your infrastructure fuel compatibility, fuel standards and performance:

1. **Which is the type of fuel that you usually involve in your infrastructure?**

Several types of Marine Gas Oil (IFO, LSFO, VLSFO, ULSFO, MGO, MDO)

2. **Which are the main criteria that lead your fuel selection and define its performance?**

- *Price*
- *Rules compliance*

3. **Which is the annual fuel consumption for your activities?**

Given that a vessel consumes approximately 40 ton/day, for 300 and for the whole fleet (60 vessels), our annual consumption is around 720k tons

4. **Are you satisfied from the prices and the supply chain of the fuels that you currently use?**

As far as it concerned the price, you can never be fully satisfied, although the same principal does not apply on the supply chain.

5. **Do you use fuel blendings and, if yes, which is their typical composition?**

This is forbidden.

6. **Which fuel parameter improvement could lead you to investigate alternative options for your fuel?**

In order to be compliant with new rules and in case that there is improvement in energy/ price ratio.

7. **How much negotiable would you be in partial retrofitting of your existing infrastructure due to new fuel requirements?**

These decisions will be made based on multicriteria life cycle analysis of different alternatives. Operational, tactical, environmental and strategic attributes should be identified and assessed.

Any other issue/comments:

None

D – Final end-users

Considering the type of fuel that you usually use for your activities, please provide the requested information concerning your infrastructure fuel compatibility, fuel standards and performance:

1. **Which is the type of fuel that you usually involve in your infrastructure?**

- *Marine Gas Oil*

2. **Which are the main criteria that lead your fuel selection and define its performance?**

- *Specifications set by engine manufacturer as well as restrictions set by class*
- *Environmental regulations*

3. **Which is the annual fuel consumption for your activities?**

- *Groups total annual consumption is around 30.000 tons.*

4. **Are you satisfied from the prices and the supply chain of the fuels that you currently use?**

- *Fuel costs remain the main cost element of any vessel operation. Therefore, it is critical to find ways to reduce them.*
- *Supply chain is adequate.*

5. **Do you use fuel blendings and, if yes, which is their typical composition?**

- *No, we are not.*

6. **Which fuel parameter improvement could lead you to investigate alternative options for your fuel?**

- *Cost Reduction*
- *Environmentally friendly operation*
- *Maintenance cost reduction*

7. **How much negotiable would you be in partial retrofitting of your existing infrastructure due to new fuel requirements?**

- *It could be an option providing cost/benefit positive results.*

Any other issue/comments:

None

D – Final end-users

Considering the type of fuel that you usually use for your activities, please provide the requested information concerning your infrastructure fuel compatibility, fuel standards and performance:

1. **Which is the type of fuel that you usually involve in your infrastructure?**

JET A-1

2. **Which are the main criteria that lead your fuel selection and define its performance?**

Combustion
High Temperature

3. **Which is the annual fuel consumption for your activities?**

Non-disclosed.

4. **Are you satisfied from the prices and the supply chain of the fuels that you currently use?**

From a scale 1 -10, [7]

5. **Do you use fuel blendings and, if yes, which is their typical composition?**

No.

6. **Which fuel parameter improvement could lead you to investigate alternative options for your fuel?**

-Freezing point
-Combustion
-Temperature

7. **How much negotiable would you be in partial retrofitting of your existing infrastructure due to new fuel requirements?**

For Aviation industry, if requirements are mandatory it would be fully adopted.

Any other issue/comments:

None

D – Final end-users

Considering the type of fuel that you usually use for your activities, please provide the requested information concerning your infrastructure fuel compatibility, fuel standards and performance:

1. **Which is the type of fuel that you usually involve in your infrastructure?**

   JET A-1 Aviation fuel

2. **Which are the main criteria that lead your fuel selection and define its performance?**

   Nowadays, regulation framework, availability, fuel cost (quality is the same), the source of origin, and the location of the plant.

3. **Which is the annual fuel consumption for your activities?**

   8.362.417.045 liters of JET-A1 (2018 all airlines JET-A1 consumption operated in 46 airports from Aena's net in Spain)

4. **Are you satisfied from the prices and the supply chain of the fuels that you currently use?**

   Yes

5. **Do you use fuel blendings and, if yes, which is their typical composition?**

   Not by the moment

6. **Which fuel parameter improvement could lead you to investigate alternative options for your fuel?**

   WtW emissions

7. **How much negotiable would you be in partial retrofitting of your existing infrastructure due to new fuel requirements?**

   Very much negotiable

Any other issue/comments:

The main problem is that nowadays there is not large SAF production in the EU and the price of the little SAF that is produced in the EU is too high compared to conventional JETA-1

E – Policy makers

Considering the present and the forthcoming legislative framework, please provide the required information concerning biofuels placement in the energy map:

1. **Which is currently the highest permissible blending ratio (conventional/biofuel), and which are the main obstacles for higher biofuels involvement?**

-7%v/v biodiesel (flat rate)
-3.5%v/v bioethanol (flat rate)

2. **Which is your prediction concerning the forthcoming transportation fuel policies, and how these will affect aviation and maritime sectors?**

The new ReFuelEU Aviation and FuelEU Maritime Regulations set the targets for the introduction of renewable fuels in these sectors. The forthcoming transportation fuel policies will need time to be incorporated in the Greek system.

3. **How important is the role of liquid biofuels towards the energy transition in aviation and maritime sector?**

   - outmost important
   - very important *X*
   - medium important
   - low important
   - no important at all

4. Which is your current strategy for promoting advanced liquid biofuels? o subsidy/national funds o tax relaxation policies o compulsory blending of renewable and conventional fuels o Other: …. *X Measures and incentives to support biofuel production activity in Greece, involving both the agricultural and industrial sectors, including economic instruments for research and development of the sector. Targeted support and funding at national level, as well as public-private partnerships, can improve the availability and financial sustainability of relevant fuels to further accelerate their supply and deployment.*
Any other issue/comments: *There is currently no production of advanced biofuels in Greece. However, the contribution of advanced biofuels is expected to reach 2.4% of transport fuels by 2030 and 17% by 2040.* *There is currently no production or use of renewable fuels of non-biological origin in Greece. However, it is projected to reach 1% of transport fuels by 2030 and 23% by 2040.*

Section A-2: Feedstock properties

Table A1. Ultimate analysis and calorific value of collected feedstock samples (d.b.: dry basis, a.r.: as received).

Sample		**Olive tree prunings (Peloponnese)**	**Vineyard prunings (Spain)**	**Cereal straw (Italy)**	**Logging chips (Finland)**	**Crushed bark (Finland)**
Parameter	Units	Measured values				
Ash	% (d.b.)	4.20	3.70	4.50	2.60	3.70
C	% (d.b.)	49.05	48.47	47.51	52.20	51.50
H	% (d.b.)	7.78	5.99	7.39	5.70	5.80
N	% (d.b.)	0.36	0.84	0.10	0.50	0.30
O	% (d.b.)	38.55	40.85	40.44	38.96	38.64
S	% (d.b.)	0.06	0.08	0.06	0.04	0.06
CL	% (d.b.)	Not detected	0.07	0.08	Not detected	Not detected
High Heating Value	MJ/Kg (a.r.)	19.42	18.99	18.08	20.80	20.69
Low Heating Value	MJ/Kg (a.r.)	17.74	17.69	16.48	19.64	19.42

Section A-3: Integrated Process Flow Diagram (PFD) & stream results

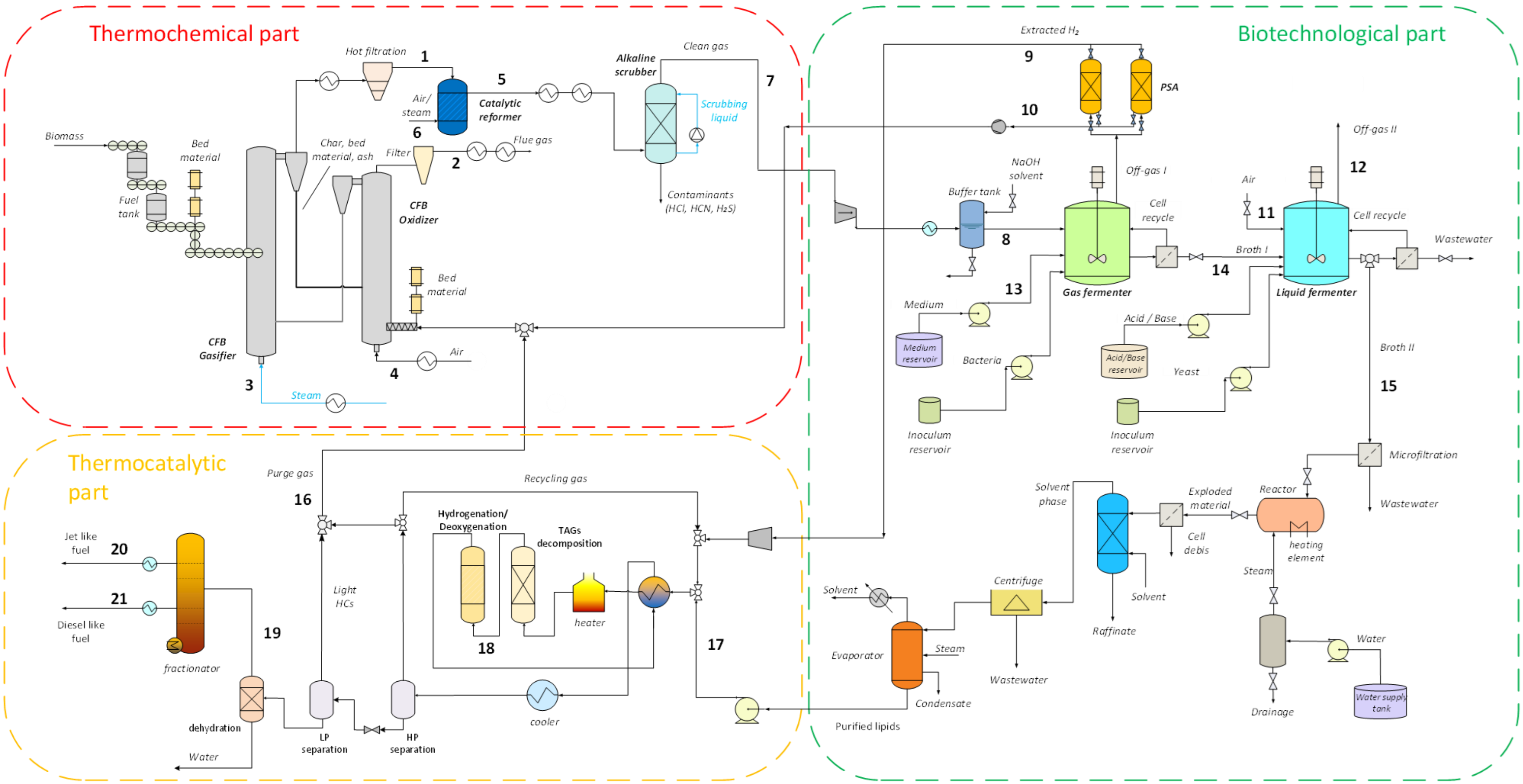

Figure A1. Integrated PFD of the BtL concept.

Table A2. Stream results for the thermochemical part.

Stream No	1 Syngas after filtration	2 Flue gas after filtration	3 Pre-heated steam	4 Pre-heated air	5 Reformed syngas (ATR)	6 Air (ATR)	7 Cooled syngas
Mass flow (kg/s)	16.99	35.86	7.92	25.40	24.19	7.21	19.19
Temp (°C)	780	880	350	400	900	400	35
Press (bar)	1.3	1.1	1.5	1.5	1.1	1.5	1.1
				Composition (vol. %)			
H_2	30.89	-	-	-	32.61	-	41.53
CO	12.79	-	-	-	15.33	-	20.34
CO_2	14.58	14.20	-	-	13.15	-	15.86
H_2O	31.95	8.04	100	-	22.73		1.71
N_2	2.04	73.71	-	79.00	15.38	79.00	19.58
H_2S	178 ppm	-	-	-	127 ppm	-	21 ppm
CH_4	5.26	-	-	-	0.75	-	0.96
NH_3	0.19	-	-	-	273 ppm	-	84 ppm
HCN	12 ppm	-	-	-	-	-	-
COS	10 ppm	-	-	-	7 ppm	-	7 ppm
C_2H_4	1.74	-	-	-	-	-	-
C_6H_6	0.37	-	-	-	27 ppm	-	27 ppm
$C_{10}H_8$	0.17	-	-	-	-	-	-
O_2	-	4.05	-	21.00	-	21.00	-

Table A3. Stream results for the biological part.

Stream No	8 Gas prior fermenter	9 Purge H_2	10 Gas fermenter off-gas	11 Air	12 Liquid fermenter off-gas	13 Medium	14 Broth-I	15 Broth-II
Mass flow (kg/s)	19.18	0.10	9.50	109.9	115.2	236.5	245.7	14.07
Temp (°C)	55	15	55	28	28	55	55	28
Press (bar)	5	100	5	1	1	5	5	1
	Composition (vol. %)					**Composition (wt. %)**		
H_2	41.53	100	15.02	-	-	-	-	-
CO	23.34	-	6.56	-	-	-	-	-
CO_2	12.86	-	18.31	-	3.28	-	0.15	0.10
H_2O	1.71	-	2.65	-	3.74	100	96.74	87.05
N_2	19.58	-	54.85	79.00	75.16	-	-	0.10
H_2S	10 ppm	-	44 ppm	-	-	-	-	-
CH_4	0.96	-	2.69	-	-	-	-	-
NH_3	88 ppm	-	330 ppm	-	-	-	-	-
C_6H_6	27 ppm	-	51 ppm	-	-	-	-	-
O_2	-	-	-	21.00	17.81	-	-	-
Acetic acid	-	-	-	-	-	-	3.11	-
Tripalmitin	-	-	-	-	-	-	-	3.15
Triolein	-	-	-	-	-	-	-	5.93
Trilinolein	-	-	-	-	-	-	-	1.65
Tristearin	-	-	-	-	-	-	-	1.99

Table A4. Stream results for the thermocatalytic part.

Stream No	16 Light gases	17 Purified TAGs	18 Fatty acids/ propane	19 Jet/Diesel paraffins	20 Jet-like fuel	21 Diesel-like fuel
Mass flow (kg/s)	0.29	1.82	1.92	1.51	1.21	0.30
Temp (°C)	30	50	370	30	30	30
Press (bar)	1	100	100	1	1	1
	Composition (vol. %)	**Composition (wt. %)**				
Tripalmitin	-	24.76	-	-	-	-
Triolein	-	46.63	-	-	-	-
Trilinolein	-	12.99	-	-	-	-
Tristearin	-	15.62	-	-	-	-
Palmitic acid	-	-	22.36	-	-	-
Oleic acid	-	-	42.29	-	-	-
Linoleic acid	-	-	11.78	-	-	-
Stearic acid	-	-	14.17	-	-	-
H_2	78.08	-	4.58	-	-	-
CO	4.59	-	-	-	-	-
CO_2	8.41	-	-	-	-	-
Propane	4.97	-	4.83	-	-	-
Methane	3.95	-	-	-	-	-
C_9H_{20}	-	-	-	4.03	8.52	-
$C_{10}H_{22}$	-	-	-	7.03	14.87	-
$C_{11}H_{24}$	-	-	-	4.36	9.23	-
$C_{12}H_{26}$	-	-	-	3.68	7.78	-
$C_{13}H_{28}$	-	-	-	3.52	7.44	-
$C_{14}H_{30}$	-	-	-	22.92	47.15	1.21
$C_{15}H_{32}$	-	-	-	6.90	3.11	10.29
$C_{16}H_{34}$	-	-	-	6.59	1.90	10.80
$C_{17}H_{36}$	-	-	-	28.34	-	53.74
$C_{18}H_{38}$	-	-	-	12.64	-	23.96

Section A-4: Critical equipment list

Table A5. Main equipment considered for the industrial layout of the BtL concept.

Equipment type	Additional information
Thermochemical part	
Biomass feeding system	-
Gasifier	CFB reactor + hot gas ducts including refractories
Oxidizer (combustor)	CFB reactor + hot gas ducts including refractories
Air, steam, and nitrogen systems	Pre-heating and auxiliaries
Ash systems	Ash handling and storage
Hot gas filters	-
Gas coolers	-
Catalytic tar reformer	Air/steam driven autothermal reformer (ATR)
Alkaline scrubber	NaOH solvent feeding mode
Gas compression system	-
Biological part	
Media preparation	Substrate/powder handling, chemical dosing for pH-correction, dissolving, sterlisation
15 x gas fermenters (acetic acid)	CSTR (500 m3) including agitators and circulation pumps
3 x seed fermenters (acetic acid)	CSTR (250 m3) including agitators and circulation pumps, 10% inoculation ratio
15 x liquid fermenters (TAGs)	CSTR (500 m3) including agitators and circulation pumps
3 x seed fermenters (TAGs)	CSTR (25 m3) including agitators and circulation pumps, 1% inoculation ratio
Microfiltration	DSP train for TAGs purification
Steam explosion	
Solvent extraction	
Centrifugation	
Evaporation	
Thermocatalytic part	
Hydrotreating reactor	Hydrogenation/hydrocracking, deoxygenation
Fractionating column	Jet/diesel fraction separation
Flash tanks	High pressure and low pressure liquid (paraffins)/ gas (unreacted hydrogen, light hydrocarbons) separation
Reactor feed-effluent heat exchanger	-
Reactor feed heater	-
Reactor effluent air-blown cooler	-
PSA hydrogen unit	-

Section A-5: Microbial Oil business case

Table A6. Capital Expenditures (CapEx) of the BtL plant (microbial oil scenario).

Dual Fluidized Bed Gasification	80,000,000 €
Catalytic Reformer	8,500,000 €
Gas Conditioning (coolers, alkaline scrubber)	10,500,000 €
Gas Compression	5,000,000 €
Gas Fermentation	80,000,000 €
Liquid Fermentation	64,000,000 €
Downstream Processing (TAGs recovery)	16,000,000 €
Hydrotreatment/ Hydrocracking	-
Utilities & Storage	8,000,000 €
Total installed costs (direct costs)	**272,000,000 €**
Indirect costs	163,200,000 €
Total direct & indirect costs	435,200,000 €
Contingency	43,520,000 €
Fixed Capital Investment (FCI)	**478,720,000 €**
Working Capital	47,872,000 €
Total Capital Investment (TCI)	**526,592,000 €**

Table A7. Annual Operational Expenditures (OpEx) of the BtL plant (microbial oil scenario).

Feedstock costs	21,090,646 €year
Electricity	5,361,120 €/year
Maintenance	9,574,400 €/year
Labor costs	3,500,000 €/year
Nutrients & chemicals	1,054,532 €/year
Property Insurance	3,351,040 €/year
Solvent make-up	2,959,338 €/year
Wastewater discharge	1,858,164 €/year
Annual operational expenses	**48,749,240 €/year**
Income from diesel	-
Income from cellular biomass	6,288,716 €/year
Annual revenue streams (by-product credits)	**6,288,716 €/year**

Section A-6: Discounted cash flow analysis

Table A8. Discounted cash flow analysis for the calculation of MJSP (jet fuel scenario).

Year	Total Capital Investment (TCI)	Income*	Operational Expenses	Cash flow	Discount factor 1/(1+i)^year	Net Present Values	Discounted payback
-1	€ 230,771,200.00			-€ 230,771,200.00	1.00	-€ 230,771,200.00	
0	€ 346,156,800.00			-€ 346,156,800.00	1.00	-€ 346,156,800.00	
1		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.94	€ 42,576,588.76	-€ 534,351,411.24
2		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.89	€ 40,166,593.17	-€ 494,184,818.07
3		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.84	€ 37,893,012.42	-€ 456,291,805.65
4		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.79	€ 35,748,124.93	-€ 420,543,680.72
5		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.75	€ 33,724,646.16	-€ 386,819,034.56
6		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.70	€ 31,815,703.92	-€ 355,003,330.64
7		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.67	€ 30,014,815.02	-€ 324,988,515.62
8		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.63	€ 28,315,863.23	-€ 296,672,652.39
9		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.59	€ 26,713,078.52	-€ 269,959,573.87
10		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.56	€ 25,201,017.47	-€ 244,758,556.40
11		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.53	€ 23,774,544.78	-€ 220,984,011.62
12		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.50	€ 22,428,815.83	-€ 198,555,195.79
13		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.47	€ 21,159,260.22	-€ 177,395,935.57
14		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.44	€ 19,961,566.24	-€ 157,434,369.33
15		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.42	€ 18,831,666.27	-€ 138,602,703.06
16		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.39	€ 17,765,722.89	-€ 120,836,980.16
17		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.37	€ 16,760,115.94	-€ 104,076,864.22
18		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.35	€ 15,811,430.13	-€ 88,265,434.09
19		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.33	€ 14,916,443.52	-€ 73,348,990.57
20		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.31	€ 14,072,116.53	-€ 59,276,874.05
21		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.29	€ 13,275,581.63	-€ 46,001,292.42
22		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.28	€ 12,524,133.61	-€ 33,477,158.80
23		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.26	€ 11,815,220.39	-€ 21,661,938.41
24		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.25	€ 11,146,434.33	-€ 10,515,504.08
25		€ 95,115,944.90	€ 49,984,760.82	€ 45,131,184.08	0.23	€ 10,515,504.08	**€ 0.00**
***(jet fuel + diesel + yeast biomass)**					**NPV**	**€ 0.00**	**MJSP = 1.83 €/l**

Table A9. Discounted cash flow analysis for the calculation of MOSP (microbial oil scenario).

Year	Total Capital Investment (TCI)	Income*	Operational Expenses	Cash flow	Discount factor 1/(1+i)^year	Net Present Values	Discounted payback
-1	€ 210,636,800.00			-€ 210,636,800.00	1.00	-€ 210,636,800.00	
0	€ 315,955,200.00			-€ 315,955,200.00	1.00	-€ 315,955,200.00	
1		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.94	€ 38,861,852.83	-€ 487,730,147.17
2		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.89	€ 36,662,125.31	-€ 451,068,021.86
3		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.84	€ 34,586,910.67	-€ 416,481,111.20
4		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.79	€ 32,629,161.01	-€ 383,851,950.19
5		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.75	€ 30,782,227.37	-€ 353,069,722.82
6		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.70	€ 29,039,837.14	-€ 324,029,885.68
7		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.67	€ 27,396,072.77	-€ 296,633,812.91
8		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.63	€ 25,845,351.67	-€ 270,788,461.24
9		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.59	€ 24,382,407.24	-€ 246,406,054.00
10		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.56	€ 23,002,270.98	-€ 223,403,783.03
11		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.53	€ 21,700,255.64	-€ 201,703,527.39
12		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.50	€ 20,471,939.28	-€ 181,231,588.10
13		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.47	€ 19,313,150.27	-€ 161,918,437.84
14		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.44	€ 18,219,953.08	-€ 143,698,484.75
15		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.42	€ 17,188,634.98	-€ 126,509,849.77
16		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.39	€ 16,215,693.38	-€ 110,294,156.39
17		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.37	€ 15,297,823.94	-€ 94,996,332.45
18		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.35	€ 14,431,909.38	-€ 80,564,423.07
19		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.33	€ 13,615,008.85	-€ 66,949,414.22
20		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.31	€ 12,844,347.97	-€ 54,105,066.24
21		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.29	€ 12,117,309.41	-€ 41,987,756.84
22		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.28	€ 11,431,423.97	-€ 30,556,332.87
23		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.26	€ 10,784,362.23	-€ 19,771,970.63
24		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.25	€ 10,173,926.64	-€ 9,598,044.00
25		€ 89,942,804.81	€ 48,749,240.82	€ 41,193,564.00	0.23	€ 9,598,044.00	**€ 0.00**
***(microbial oil + yeast biomass)**					**NPV**	**€ 0.00**	**MOSP = 1.32 €/l**

Table A10. Discounted cash flow analysis for the calculation of MOSP (Greek replication study).

Year	Total Capital Investment (TCI)	Income*	Operational Expenses	Cash flow	Discount factor 1/(1+i)^year	Net Present Values	Discounted payback
-1	€ 210,636,800.00			-€ 210,636,800.00	1.00	-€ 210,636,800.00	
0	€ 315,955,200.00			-€ 315,955,200.00	1.00	-€ 315,955,200.00	
1		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.94	€ 38,861,852.83	-€ 487,730,147.17
2		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.89	€ 36,662,125.31	-€ 451,068,021.86
3		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.84	€ 34,586,910.67	-€ 416,481,111.20
4		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.79	€ 32,629,161.01	-€ 383,851,950.19
5		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.75	€ 30,782,227.37	-€ 353,069,722.82
6		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.70	€ 29,039,837.14	-€ 324,029,885.68
7		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.67	€ 27,396,072.77	-€ 296,633,812.91
8		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.63	€ 25,845,351.67	-€ 270,788,461.24
9		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.59	€ 24,382,407.24	-€ 246,406,054.00
10		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.56	€ 23,002,270.98	-€ 223,403,783.03
11		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.53	€ 21,700,255.64	-€ 201,703,527.39
12		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.50	€ 20,471,939.28	-€ 181,231,588.10
13		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.47	€ 19,313,150.27	-€ 161,918,437.84
14		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.44	€ 18,219,953.08	-€ 143,698,484.75
15		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.42	€ 17,188,634.98	-€ 126,509,849.77
16		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.39	€ 16,215,693.38	-€ 110,294,156.39
17		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.37	€ 15,297,823.94	-€ 94,996,332.45
18		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.35	€ 14,431,909.38	-€ 80,564,423.07
19		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.33	€ 13,615,008.85	-€ 66,949,414.22
20		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.31	€ 12,844,347.97	-€ 54,105,066.24
21		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.29	€ 12,117,309.41	-€ 41,987,756.84
22		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.28	€ 11,431,423.97	-€ 30,556,332.87
23		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.26	€ 10,784,362.23	-€ 19,771,970.63
24		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.25	€ 10,173,926.64	-€ 9,598,044.00
25		€ 85,356,134.45	€ 44,162,570.46	€ 41,193,564.00	0.23	€ 9,598,044.00	**€ 0.00**
***(microbial oil + yeast biomass)**					**NPV**	**€ 0.00**	**MOSP = 1.29 €/l**