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&
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MSc Thesis

On the Logic of Technology Scaling: The Case of Wind Energy Technology

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Abstract

In this thesis we attempt to investigate wind energy technology scaling process and the way it is embedded in its social and physical context.

We recount the modern wind turbines scale up technology in terms of their historical development. In particular, we try to examine the way social interests and conditions are embedded in modern large-scale wind technology artefacts.

Furthermore, we discuss the impacts of industrial scale wind turbines installations and their contradiction to the renewability character of wind energy.

Finally, we propose some directions for further research.

Keywords: Scaling technology, Wind energy technology scaling, Wind Turbines, Science, Technology, Society or Science and Technology Studies (STS).

Table of Contents

List of Figures

1 Introduction[1]

The installation of renewable energy across the world has expanded rapidly during the last decades. By the beginning of the 21st century, wind power has become a source for alternative energy, facilitated mainly by technological improvements and motivated by the increasing awareness associated with the combustion of fossil fuels. It has been proven the fastest energy resource among all renewable energy resources. Wind energy promises to deliver energy free of carbon dioxide emissions and other air pollutants while producing no toxic wastes, bearing no risk of nuclear meltdown, using no fuel and few heavy metals and requiring no water. Nowadays, wind power has become a global multi-billion-euro industry and nearly all countries in the world have developed its utilization politically, legally, and technically.

According to the International Renewable Agency (IRENA)[2] "*the global installed onshore and offshore wind-generation capacity has increased by a factor of almost 75 in the past two decades, jumping from 7.5 gigawatts (GW) in 1997 to some 564 GW by 2018. Production of wind electricity doubled between 2009 and 2013, and in 2016 wind energy accounted for 16% of the electricity generated by renewables*".

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[1] Information for this chapter has been obtained from the following resources:

- IRENA; Renewable Capacity Statistics, 2019.
- Veers P. et al.; Grand challenges in the science of wind energy; Science 10.1126/science.aau 2027 (2019).
- Rohriq K. et.al.; Powering the 21st century by wind energy—Options, facts, figures; Appl. Phys. Rev. 6, 031303 (2019).
- http://www.cleanfuture.co..
- Hellenic Ministry of the Environment and Energy; National Climate and Energy Plan; November, 2019, Athens.
- Saïd Business School, University of Oxford; From Scale to Scalography: an international workshop, Wednesday 8th July,
- Pyyhtinen Olli; Matters of Scale: Sociology in and for a Complex World; New Social Research Programme; Faculty of Social Sciences, University of Tampere, FI-33014 Tampere, Finland, 2017.
- Bijker E. Wiebe, Pinch J. Pinch, The Social Construction of Facts and Artefacts: or How the Sociology of Science and the Sociology of Technology might Benefit Each Other; Social Studies of Science 1984; 14; 399, SAGE Publications, 1984.
- Heymann Matthias; Signs of Hubris: The Shaping of Wind Technology Styles in Germany, Denmark, and the United States, 1940-1990; Technology and Culture, Vol. 39, No. 4 (Oct., 1998), pp. 641-670.
- Sovacool K. Benjamin; The importance of open and closed styles of energy research; Social Studies of Science, Vol. 40, No. 6 (December 2010), pp. 903-930, Sage Publications, Ltd.
- Jamieson Peter; Innovation in Wind Turbine Technology (2nd edition), 2018 John Wiley & Sons Ltd.

[2] IRENA; Renewable Capacity Statistics, 2019

The global investment in wind energy is now approximately $100 billion (US dollars) per annum and the wind energy demand and scale of deployment is expected to grow by a factor of 10 by 2050, bringing the industry to a trillion-dollar scale—and positioning wind as one of the primary sources of global electricity generation.

Utility-scale use of wind energy started in the late 70s, in USA and Denmark. According to the Public Policies Act signed by US President Carter in 1978, utilities had been requested so as to buy a certain amount of electricity from renewable energy sources. At the time, wind turbines of roughly 30–70 kW nameplate capacity were available, mostly of American or Danish design.

Wind power technology is continuously evolving by scaling up in two directions. The first one is “vertical” and oriented towards perpetually increasing height and output. The second entails a “horizontal” scale-up in the form of wind farms—either onshore (in hilly or mountainous regions) or offshore (in wind turbine agglomerations/multiplicities, which are installed and operate as virtual power plants).

In 1985, typical turbines had a rated capacity of 0.05 megawatts (MW) and a rotor diameter of 15 meters, while most current wind turbine models range from 3 MW to 7 MW and are equipped with rotors and towers of over 100 m in diameter and height, respectively. The following figure highlights the evolution of wind turbine height and output.

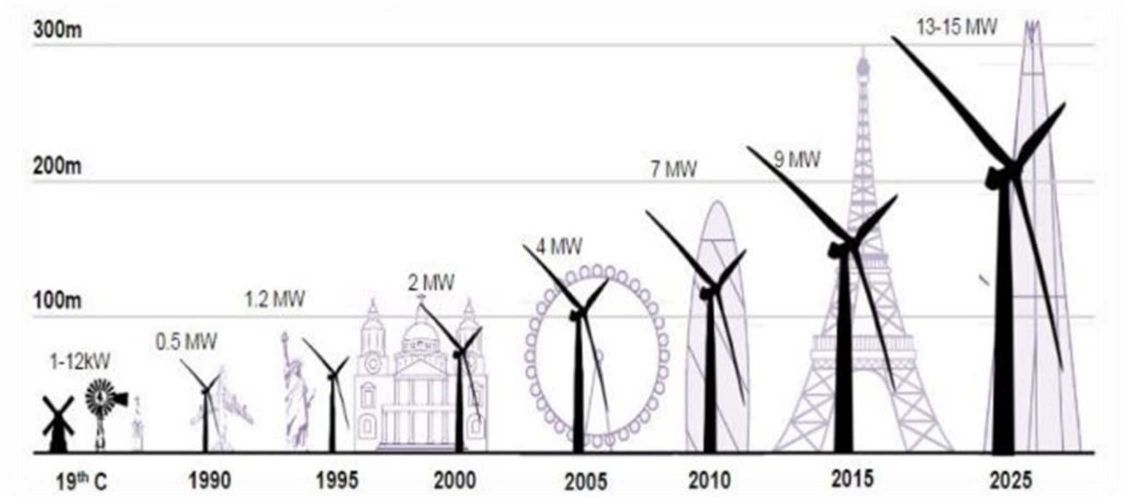

Figure 1: Wind turbines evolution in height and output[3]

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[3] http://www.cleanfuture.co..

In order to achieve the targets set for higher power production (of an order of 500–1000 MW), larger and larger turbines are required. While for onshore applications, transport and installation obstacles are posing barriers for further scale up, for offshore applications the difficulties are fewer and the benefits from the reduction of operational and other costs could justify the size increase.

In the other direction, the horizontal one, the scale-up timeline led from the world's first wind farm at 0.6 MW (consisting of 20 wind turbines rated at 30 kilowatts each, as installed in New Hampshire in December 1980) to the current huge installations whose capacity is in the GW scale (see Table 1).

In the last 40 years, research and development have focused on every wind turbine aspect: not only on size, but also on site assessment, manufacturing, and construction to improve operation and maintenance. According to European policy documents, large-scale RES production development is directly related to the full functioning of the electricity market model. RES energy is represented (i.e., bought and sold) like any other commodity: in energy exchanges.

Furthermore, lighter licensing procedures, the digitization of the energy system and the expansion of energy infrastructures do allow for maximum RES penetration in power generation and maximum RES share in final energy consumption. **That means that the scaling up of wind power, like any other “RES”, is synchronizing with the “conventionally” produced electricity market model, being fully integrated in the national grid both technically and financially. Thus, large-scale modern wind turbines development embeds the social and economic interests of the environment in which they have been developed and operate.**

Considering the rough outline of wind turbine development for the last few decades, this thesis aims to answer some of the questions that may arise:

- Why is there a tendency for a wind turbine scale-up?
- Which are the social groups or interests involved in scaling?
- Which was the socioeconomic environment that facilitated the wind turbine scale-up?
- Which were the problems encountered and what failures occurred?
- Are there any limits to scale-up?

This worldwide expansion of wind turbine installations is “accompanied” by increasing social opposition at the local and national level, due to the environmental, aesthetic and operational impacts of wind power installations, especially because of their increasing size.

Therefore, the following questions may also arise:

- Is there a conflict between scale-up and locality and what are its implications?
- Is wind turbine scaling up compliant with the RES technology characteristics?
- Are there any renewability characteristics in modern wind turbines?
- Do they transform electricity to a market commodity?
- Are utility-scale wind turbines appropriate for the landscape in which they operate?

Given the fact that large wind turbines operate as actual power plants that are tightly integrated into the national power grid (both technically and market-wise), we argue that the wind turbine—the device (artifact) relying on wind as an energy source—does not define per se renewability.

In this thesis, we shall not deal with the concepts of "scale" and the "scaling process" per se, but the analysis shall be limited to the "wind power technology" scaling. The former was examined by Steve Woolgar and his colleagues in the "From Scale to Scalography" event they organized at the Saïd Business School in 2009, where he coined the term "scalography" (which transforms scale from a matter of fact into a matter of concern).

Scale is a critical concept in contemporary scientific literature, especially for complexity theory. According to Olli Pyyhtinen "*everything is constructed and compared in terms of scale. One should choose to study the 'micro', 'meso' or 'macro' levels. Phenomena and observations that are valid for one level are not necessarily valid on other levels. Respectively, 'grand theories', 'meso-theories', 'micro-theories' or 'no-theories' are proposed. There are also those who like to scrutinize 'issues of scale' and, also, those who ignore them altogether. Furthermore, it is unclear what mechanisms lead from one level to another.*

Disputes are organized around dualisms like the following: micro/macro, large/small, global/local, societal/interactional, particular/general and near/far. Dealing with this problem is crucial for a wide range of social science interventions, policy, management and business.[4]

Some scholars prefer to replace the concepts of 'sizes' and 'levels' with the flat surfaces of 'scale-free networks' and they do this by replacing size and level as a problem of 'connections'—scale-free descriptions—in order to bypass the above mentioned dualisms.

In this thesis, in order to investigate 'wind power technology scaling', we focus on the "Wind Power Technology" part of the statement—namely the "artifact"

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[4] Pyyhtinen Olli; Matters of Scale: Sociology in and for a Complex World; New Social Research Programme; Faculty of Social Sciences, University of Tampere, FI-33014 Tampere, Finland, 2017

scaling and not the "scaling" process, in line with the history of technology and STS points of view.

Thus, we shall try to identify the social interests that contribute to the construction of this technology (i.e., wind turbine scaling). "*The most basic relevant groups are the users and the producers of the technological artifact. Yet, more often than not, numerous subgroups can be delineated: users with different socioeconomic status, competing producers or groups that are neither users nor producers (like journalists, politicians, political parties, civil organizations, etc.)".*[5]

Wind turbines designs are considered to reflect the interpretations of these relevant groups. Thus, each design is a single actuality within a big set of technical possibilities.

Concerning the different engineering approaches in wind turbine manufacturing (as followed in countries like Denmark, Germany, the United States or the Soviet Union), these pertained not only to the form and characteristics of the technical artifact but, also, to local processes and conditions—e.g. to the professional backgrounds of the actors involved, their technical experience, construction goals and development approaches.

Non-academic engineers (technicians) have mostly developed reliable and successful wind turbine designs (as in the case of Denmark), while the designs proposed by academic engineers in the 1970s and 1980s mostly failed.

It seems that the norms and values of the social groups involved in the design and manufacturing process influenced the meaning, usability and importance given to an artefact (for instance, see the different national R&D styles followed in Denmark and the US).

This thesis is organized in four chapters. Following this first, introductory one, the second chapter provides a very short presentation of wind power technology and technology scale-up. In the third chapter, we try to outline the historical scale-up of wind turbines from windmills to modern utility-scale energy production facilities. In the fourth chapter, wind turbine issues related to their scaling up will be discussed (e.g. siting, wildlife, landscape integration etc.). In the final, fifth chapter of this thesis, we summarize our work and state possible directions for further research.

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[5] Bijker E. Wiebe, Pinch J. Pinch, The Social Construction of Facts and Artefacts: or How the Sociology of Science and the Sociology of Technology might Benefit Each Other; Social Studies of Science 1984; 14; 399, SAGE Publications, 1984

2 Wind Energy Technology[6]

In this chapter, we present a short introduction to wind turbines technology and their technical scaling and scaling laws.

2.1 About Wind Turbines

2.1.1 Wind Turbine Physics

The main characteristic of wind turbines—regardless of their design type or size—is the conversion of the kinetic energy of aerial floating masses into mechanical energy by virtue of their rotation.

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[6] Information for this chapter has been obtained from the following resources:

- Sarkar Asis, Kumar Dhiren Behera; Wind Turbine Blade Efficiency and Power Calculation with Electrical Analogy; International Journal of Scientific and Research Publications, Volume 2, Issue 2, February 2012.
- Veers P. et al.; Grand challenges in the science of wind energy; Science 10.1126/science.aau 2027 (2019).
- Wagner Hermann-Josef; Introduction to wind energy systems; EPJ Web of Conferences 189, 00005 (2018).
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- Sieros G. et, al.; Upscaling wind turbines: theoretical and practical aspects and their impact on the cost of energy; Wind Energy. 15:3–17, John Wiley & Sons, Ltd., 2012.
- Maeder Thierry, Schepers Gerard; Perspectives and guidelines for up-scaling to 20 MW wind turbines, October 31, 2017, FP7-ENERGY-2013-1/ n° 608396.
- Wiser Ryan et al.; Expert elicitation survey on future wind energy costs; NATURE ENERGY VOL 1 | OCTOBER 2016; Macmillan Publishers Limited, part of Springer Nature.
- Wiser Ryan et al. The Future of Wind Energy; Berkeley Lab, Report, Electricity Markets and Policy Group, 2016.

The amount of electricity produced from a wind turbine depends on the following factors:[7]

1) **Wind speed**: the higher the speed of the blowing wind, the greater the amount of energy produced.

2) **Wind turbine availability**, which is the capability to operate when the wind is blowing, i.e. when the wind turbine is not undergoing maintenance. This is typically 98% or above for modern European machines.

3) **The way wind turbines are arranged**: In order to continue reducing energy production costs, complex models of wind turbine interactions within a wind farm have been developed, so that a given turbine does not deprive another of any air currents.

There is ongoing research on the technical issues, due to the systemic complexity of wind farms. The fundamental equation for wind turbine energy capture (the physics of the wind turbine) is shown below[8]:

$$P = \frac{1}{2} \rho C_p A V^3$$

Where,

- P is the instantaneous power produced,
- ρ is the air density,
- C_p, the power coefficient, is the ratio of actual electric power produced by a wind turbine divided by the total wind power flowing into the turbine blades at specific wind speed,
- A is the swept area of the rotor, and
- V is the free-stream air velocity.

According to this equation, wind power increases to the cube of wind speed. The design of the machine affects the access to higher velocities (V), as well as performance (C_p) and the attainable area (A).

In order to reduce the cost of wind-turbine-produced energy, designers **increase their height, power rating and rotor diameter**. Increased height reduces

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[7] Sarkar Asis, Kumar Dhiren Behera; Wind Turbine Blade Efficiency and Power Calculation with Electrical Analogy; International Journal of Scientific and Research Publications, Volume 2, Issue 2, February 2012

[8] Veers P. et al.; Grand challenges in the science of wind energy; Science 10.1126/science.aau 2027 (2019).

the influence of surface friction, allowing wind turbines to operate in higher-quality resource regimes where wind velocities, V, are higher—with a compounding effect on power production.

Furthermore, embedded **power electronics**—which enable variable-speed operation—provide more power per machine installed at a given location (assuming a constant C_p). More power per turbine allows fewer turbine installations, lower balance-of-system costs and fewer moving parts (for a given level of power capacity), thereby enhancing reliability.

Larger and more efficiently designed wind turbine rotors (that sweep a greater area) capture more of the energy passing through each turbine. Since blade lengths can be increased while many other costs remain fixed, these designs provide a significant cost reduction.

Thus, apart from the performance improvements due to scaling up, the relative cost of wind power plant development and operation has also decreased because of the increase in turbine size, allowing for economies of scale in manufacturing.

Unfortunately, Betz's law indicates the upper bound on the annual energy that can be extracted from a site, which is independent of the wind turbine's design. The German physicist Albert Betz published this law in 1919. According to it, no turbine can capture more than 59.3% of the wind's kinetic energy (known as the Betz coefficient), thus setting up an upper limit for wind turbine efficiency. Current utility-scale wind turbines peak at 75–80% of the Betz limit.

2.1.2 Wind Turbine Types

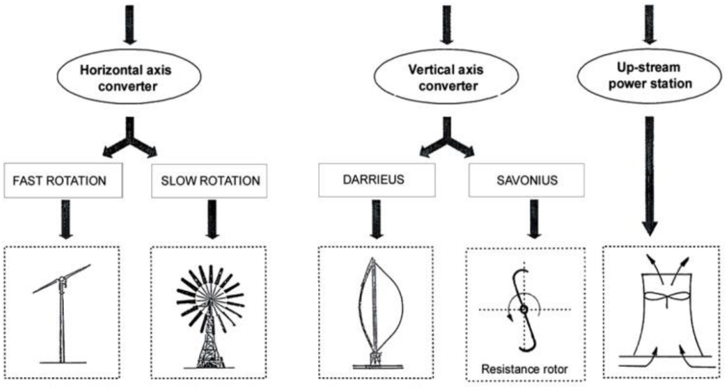

Figure 2: Main types of wind turbines[9]

Modern wind turbines can be divided into two types: (1) horizontal axis wind turbines (HAWTs) and (2) vertical axis wind turbines (VAWTs).

HAWTs dominate the wind industry due to their greater efficiency and energy output in comparison to VAWTs. VAWTs present disadvantages like less power output (due to lesser wind exposure) or greater manufacturing costs (so that they can compete with the HAWTs power output). The VAWTs advantages include productive functioning at lower winds and low noise levels.

Furthermore, wind turbines are divided into **onshore** and **offshore**: onshore wind turbines are installed on land, have 50–100 m tower heights with a rotor diameter of 50–100 m. Modern turbines are capable of effectively generating power at much lower wind speeds.

Wind turbines installed beyond the coast are known as **offshore power systems**. The development of offshore wind energy has accelerated in the past few years, so as to harness the significant wind resources available over the oceans and, also, due to the increasing social opposition against onshore wind turbine installation projects (which stems from the associated environmental issues). Moreover, the world's largest cities are generally situated in coastal areas. Therefore, power transmission over longer distance can be avoided.

Offshore turbine technology is similar to that of the onshore ones. The major difference can be found in the design of the foundations, which calls for floating and/or other special foundations (either steady or floating for deeper waters).

According to the Renewables 2020 Global Status Report, *"While the current wind turbine market is dominated by 33 manufactures, the top ten of them deliver 85.5% of the overall installed capacity (up from 85% in 2018, 80% in 2017 and 75% in 2016). The leading four companies—Vestas (Denmark), Siemens Gamesa (Germany/Spain), Goldwind (China) and GE Renewable Energy (United States)—were responsible for about 55% of the capacity installed in 2019."*[10]

2.1.3 Wind Turbines Architecture

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[9] Wagner Hermann-Josef; Introduction to wind energy systems; EPJ Web of Conferences 189, 00005 (2018).

[10] REN21; Renewables 2020 Global Status Report, 2020.

The major visible components of a utility-scale wind turbine are the blades, the rotor, the tower, the gearbox, the generator and the nacelle.

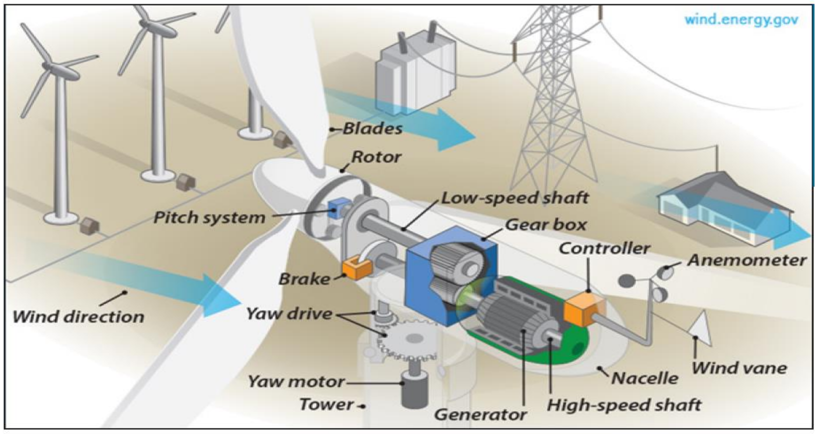

Figure 3: Major wind turbine components[11]

The turbine blades capture the kinetic energy from the wind and convert it into torque that is transmitted to the gearbox through a rotational shaft.

A yawing mechanism allows the turbine to rotate on its vertical axis to orient the rotor in the direction of the wind, maximizing energy capture. The nacelle houses the major components: namely, a gearbox and a generator. A low-speed shaft connecting the rotor to the gearbox and a high-speed shaft connecting the gearbox to the generator make up the turbine's **drive train**. Using a series of gears, the gearbox converts the low-speed, high-torque input from the rotation of the blades to a high-speed, low-torque rotational force that is transmitted to the generator. Next, a transformer increases the voltage from the generator's voltage level to the on-site collection system's voltage. The rotor and nacelle sit atop a steel or concrete tower that is typically around 80 to 110 meters tall.

To eliminate gearbox failure and transmission losses, manufacturers have developed wind turbines without gearboxes. This type of wind turbine was introduced in 1991 and is known as the **variable speed direct-drive wind turbine**. A direct-drive wind turbine's generator speed is equivalent to the rotor speed, because the rotor is connected directly to the generator. As the rotational generator speed is low, designers placed several magnetic poles in the generator to achieve the appropriate high output frequency.

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[11] New York Wind Energy Guide for Local Decision Makers; https://energy.gov/eere/wind/how-do-wind-turbines-work

The **control system** (controller) for a wind turbine (which consists of sensors, power amplifiers, intelligence etc.) is important with respect to both machine operation and power production.

Distinct from the tower height, the vertical distance from the ground to the centerline of the rotor is often referred to as the turbine's hub height.

2.2 Scaling, Scaling Laws, and Scaling Limits

In order to increase the penetration of wind power to the European energy market, there is a continuous scaling up of wind turbine technology.

As stated forty years ago in the Sun & Wind Energy magazine[12], "*500 kW had been considered as the upper wind turbine size limit. Twenty years later, a turbine in the 70 to 80-meter rotor diameter size range was assumed to be an economic optimum that is difficult to exceed"*. Today's configurations (e.g.: GE's Haliade X) have long surpassed these limits.

A large number of onshore and (mostly) offshore wind farms are planned for the next years all over the world. Typical sizes of current wind farms are in the range of several hundreds of MW.

According to Leithead[13] E. W the key drivers for up-scaling wind turbines that generate into an electrical network are as follows:

- Utilities prefer power in multi-megawatt scale units (large industrial size production installations).
- In a wind farm, a larger unit capacity implies fewer numbers of the turbine units to realize a given total capacity.
- Larger turbines can often use wind and land (if their installation costs are constant) more effectively.
- When it comes to the public funding of wind energy, size tends to be regarded as a metric of technological progress.

Concerning the historical evolution of 20th century wind turbine designs, it seems that the growth of turbine size has been quite irregular—especially at the early phase of their development, when wind technology primarily relied upon experimental expertise.

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[12] Sun & Wind Energy Magazine 1; is there a limit to wind turbine size? 2008.

[13] Leithead E. W.; Wind Turbine Scaling and Control; Supergen Project, 2ndTraining Seminar, 2011.

In 2000, Henrik Stiesdal, the then technical director of the Danish supplier Bonus AS (now owned by Siemens), observed a consistent exponential growth in turbine size, which stopped around 2004 (see Figure 4: the 'y' axis is scaled logarithmically).

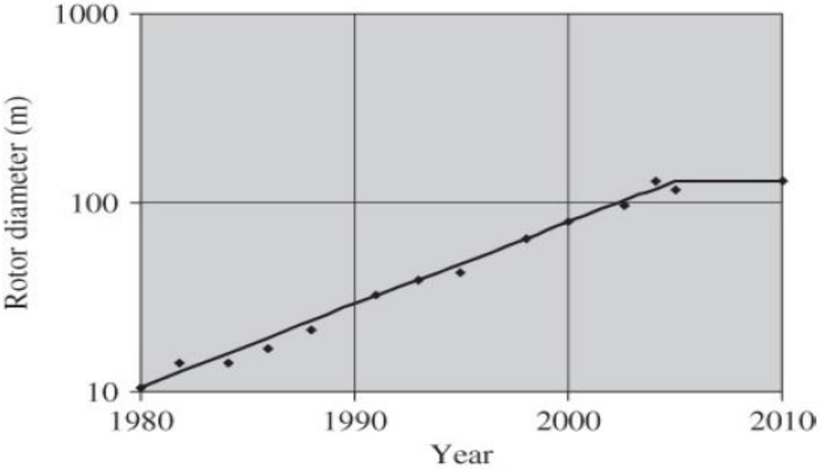
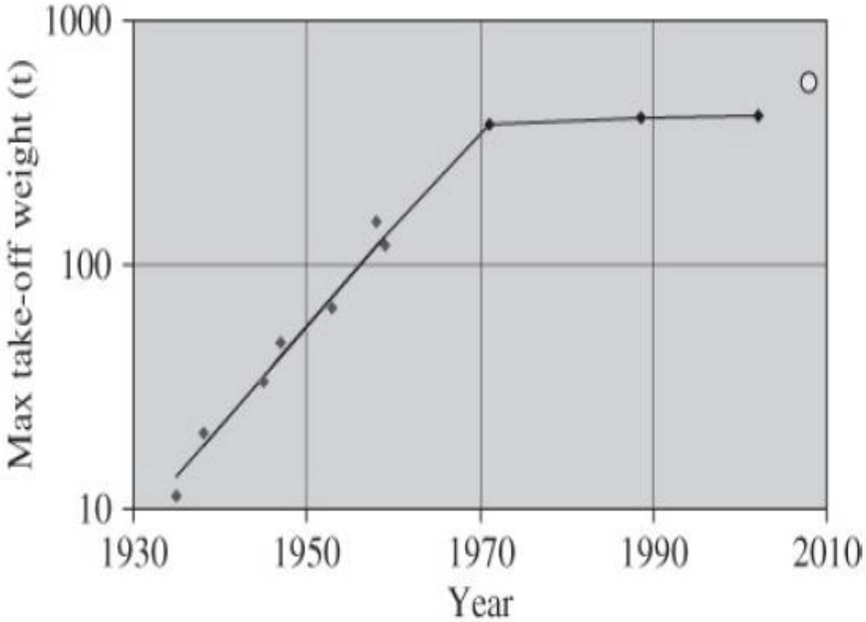


Figure 4: Growth in the size of wind turbines[14]

Stiesdal also noticed a similarity between the growth patterns of wind turbine technology and aircraft technology (see Figure 5).



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[14] Jamieson Peter; Innovation in Wind Turbine Technology (2nd edition), 2018 John Wiley & Sons Ltd.

Figure 5: Growth pattern in the aircraft industry.[15]

Both technologies have in common an underlying square-cube law (explained later in this section) reflected in the ratios of rotor swept area (wind turbines) and lifting wing area (aircraft) to system volume and mass.

Both technologies exhibited an extended initial period of exponential growth until a limiting size was approached.

It is envisaged that these limits are probably fundamentally economic than technological.

The flat top time period (Figure 5) lasted for more than 30 years and indicated with reasonable certainty that few much larger aircrafts would appear. Respectively, wind turbines size ceased to grow exponentially.

Thus, a key question is the following: how big will wind turbines get? Modern wind turbines seem to be the largest examples of rotating machinery in the history of humankind.

In order to predict the economics of up-scaled wind turbine systems, cost models have been developed. In addition, during the last decade, several projects set out to develop and evaluate multi-megawatt designs, even for as much as a 20 MW rating, (e.g. the UPWIND Project). [16]

Current wind turbines are used in numerous applications of widely varying performance requirements—ranging from the power supply of a small cottage (approximately 1.5 to 2 kW with a turbine rotor diameter of 7 to 8 m) to that of a large farm (approximately 50 to 100 kW with a turbine rotor diameter of 15–20 m).

Thus, it is useful to develop a family of wind turbines suitable to serve such diverse requirements. Development costs can be reduced if the experience gained from a smaller wind turbine can been used in the design of a bigger one, with no need to redesign a larger turbine from scratch. Often, engineers test models of prospective wind turbines in wind tunnels, in order to analyze their operational behavior. For both development directions (scale-up and scale-down), the manufacturing industry saves calculation time and development costs by resorting to the theory of similarity.

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[15] Jamieson Peter; Innovation in Wind Turbine Technology (2nd edition), 2018 John Wiley & Sons Ltd.

[16] The UPWIND sixth Framework project of the EU addressed questions regarding the viability of 10 and 20 MW wind turbine systems based on the standard three-bladed concept. This project also created cost models where intrinsic scaling effects are logically separated from the mass and cost reductions that arise from technological progress.

According to P. Jameson[17], "*the scaling of wind technology means an extrapolation to larger sizes. It is in that context especially that empirical models—which may effectively describe data within the historical compass due to design variations and technology advances—are anchored to physical models of components and fundamental rules of scaling with similarity".*

Laws of similarity or scaling laws are of importance to the designer not only during the scale-up of wind turbines but, also, during the initial design phase of a new wind turbine concept (e.g. during wind tunnel testing as stated above). The standard geometric similarity laws assume that:

- rated power scales as the square of length scale,
- strength scales as square of length scale,
- mass scales as cube of length scale,
- Inertia scales as fifth power of length scale.

Scaling affects the individual components in the wind turbine too. Several methods have been proposed by scholars to assess the effects of size increase on these wind turbine components.

The term 'scaling' implies a similarity between a set of objects, so that their main difference is size alone. The **Square Cube Law (SQL)** suggests that a homogeneous solid object with a characteristic dimension D will have a surface area scaling as D^2, while volume and mass will scale as D^3.

If we think of a cube with all sides having a length of 1 and if we double all the lengths, the volume (and, therefore, the mass) of the object increases eight-fold (cf. $1^3 = 1$ and $2^3 = 8$). Without proper SQL counter-measures, wind turbine upscaling processes can add excessive mass to the system, resulting in excessive manufacturing costs. In addition, extra nacelle mass increases dynamic loads within the entire system. In order to overcome these problems, designers are introducing new, advanced materials that save weight and new computer tools for optimizing architectural design decisions. Thus, the preferred weight is only one parameter to be taken into account among several wind turbine design variables.

The square-cube rule, although essentially true, is subject to many modifications during the detailed modeling phase of a system. E.g. today's 5 to 6 MW class turbines feature 30 to 40-tonne rotor hubs and mainframes with masses of up to 70 tones. Only a few specialized foundries are capable of handling such enormous components. Other key challenges can be found in the

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[17] Jamieson Peter; Innovation in Wind Turbine Technology (2nd edition), 2018 John Wiley & Sons Ltd.

manufacturing, transportation and installation of heavy components (like huge rotor blades of 60m lengths).

"*Concerning wind turbine behavior, in the upscaling of any real design, strict similarity is always violated. This is because of the existence of absolute scales with characteristic dimensions that affect wind turbine behavior but will not ever change with the scale of the turbine"*.[18] Such absolute scales are as follows:

1. Atomic scale: the atomic scale is relevant to the viscosity of the wind, which affects wind turbine performance.

2. Scale of the earth's seas and terrain: e.g. in the earth's boundary layer, there is usually a gradient of wind speed with height. Thus, a large wind turbine at a given site will not see the same wind as a smaller one.

3. The related scale of atmospheric structures (including wind turbulence): the spatial and temporal variation of wind conditions across a rotor disc varies with turbine size.

4. Human scale: the 'human scale' is another absolute scale that applies as different manufacturing and handling methods are required during systems growth in scale, whilst the size of personnel access dimensions does not change. Therefore, there is some violation of similarity due to the (approximately) fixed scale of human beings.

Moving beyond technical issues to costs, in order to estimate how scaling will influence the cost of large wind turbines, it is critical to consider a number of non-technical factors, such as exchange rates, labor cost variations, etc.

In the course of the EU funded UpWind project[19], it has been examined if the continuous upscaling would result in a reduction of the cost of energy, regarding the development of wind turbines of size up to 20 MW, resulting to a rotor diameter up to 250 m and a hub height of more than 150 m.

By applying the above-mentioned similarity laws and based on a simplified problem, it was known that, for a given technology level, upscaling always results in an unfavorable weight increase.

Although these conclusions are 'exact' concerning the tower structure, there was no obvious reason why they should not apply to other wind turbine components that can be modelled similarly. Using a linearized weight-based cost

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[18] Jamieson Peter; Innovation in Wind Turbine Technology (2nd edition), 2018 John Wiley & Sons Ltd.

[19] The UPWIND sixth Framework project of the EU addressed questions of the viability of 10 and 20 MW wind turbine systems based on the standard three-bladed concept.

model, it was shown that, without additional technology improvements, the levelized component cost increases with turbine size. It is nevertheless necessary to reduce the rate at which the levelized component cost increases, so that the overall cost of energy may benefit from the transition to larger scales.

Another EU funded project, the AVATAR project[20], concluded that "*even if a 20 MW wind turbine is "similar" to modern horizontal-axis, three-bladed multi-MW machines, it will not be a "simple" scale-up of the latter. New technologies have to be embedded (e.g. new materials and control mechanisms) and much more accurate and sophisticated tools should be used in the design process so that the 20 MW turbine can operate safely, efficiently and reliably*".

The basic question, however, has not been answered yet. Is the scale-up of turbines (practically) limitless or is it running into physical and/or logistical constraints? The question of a limit in wind turbine size growth went hand in hand with every major turbine design evolution.

According to the *Nature Energy* journal[21], "*land-based wind turbines and, especially, offshore turbines do have room to grow, which promises that this already-mature energy technology will see still lower costs in the future"*.

The story of wind power is a story of growing machine size. "*At the same time, Levelized Cost of Energy (LCOE)[22] has been reduced due to economies of scale and an increased wind turbine performance".*[23] Recent research results show that wind turbines with higher towers can be more smoothly integrated into the grid, since they have steady output and, thus, leverage the value of wind energy in electricity markets. Of course, turbine size varies by market, by wind resource, by site topography and wind turbine type. There is no universal 'optimal' wind turbine.

The wind industry has a history of under-predicting the growth rates of turbines. It is expected that at some specific size (not the same for all cases), the costs of further scale-up will grow faster than the resulting energy output and revenue, making further size increases uneconomic. The question is if the socioeconomic environment will facilitate approaches (both technologies and processes) that will allow bypassing these limits.

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[20] Maeder Thierry, Schepers Gerard; Perspectives and guidelines for up-scaling to 20 MW wind turbines, October 31, 2017, FP7-ENERGY-2013-1/ n° 608396.

[21] Wiser Ryan et al.; Expert elicitation survey on future wind energy costs; NATURE ENERGY | VOL 1 | OCTOBER 2016; Macmillan Publishers Limited, part of Springer Nature.

[22] LCOE measures lifetime costs divided by energy production, driven by both research and technological learning curves.

[23] Wiser Ryan et al. The Future of Wind Energy; Berkeley Lab, Report, Electricity Markets and Policy Group, 2016.

3 Wind Turbines Scaling History[24]

3.1 A Short Introduction to Wind Energy Technology

Wind energy use can be traced back to many ancient civilizations, thousands of years ago. The first known such application was sailing, as practiced by the ancient Chinese at about 4,000 BC and the ancient Egyptians at about 3,400 BC. Later on, wind-powered ships dominated water transport for a long time—until the invention of steam engines in the 19th century.

The second known use of wind energy was by the ancient Sinhalese at about 300 BC, who used the powerful monsoon winds to provide furnaces with an air flow sufficient for raising the temperatures inside them to above 1100°C

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[24] Information for this chapter has been obtained from the following resources:

- Tong Wei; Wind Power Generation and Wind Turbine Design; WIT Press Ashurst Lodge, Ashurst, Southampton, SO40 7AA, UK, 2010.
- Dykes Katherine et al.; Results of IEA Wind TCP Workshop on a Grand Vision for Wind Energy Technology; IEA Wind TCP Task 11 Technical Report, April 2019.
- Manwell F. J., McGowan G. J., Rogers L. A., Wind Energy Explained - Theory, Design and Application, Second Edition; 2009 John Wiley & Sons Ltd.
- Maegaard Preben, Krenz Anna, Palz Wolfgang; The Rise of Modern Wind Energy, Wind Power for the World; CRC Press, 2013.
- Owens N. Brandon, The Wind Power Story; A Century of Innovation that Reshaped the Global Energy Landscape; 2019 IEEE, John Wiley & Sons, Inc.
- Carlin W. P., Laxson S. A. and Muljadi B. E.; The History and State of the Art of Variable-Speed Wind Turbine Technology; Wind Energy. 2003; 6:129–159, 2003 John Wiley & Sons, Ltd.
- Fleming D. P. and Proben D. S.; The Evolution of Wind-Turbines: An Historical Review; Applied Energy 18 (1984) 163 177; Elsevier Applied Science Publishers Ltd. England, 1984.
- Divone V. Louis; Evolution of Modern Wind Turbines Part A: 1940 to 1994, in David A. Spera ed., WIND TURBINE TECHNOLOGY, Fundamental Concepts of Wind turbine engineering, 2nd edition, 2009 by ASME, Three Park Avenue, New York, NY 10016, USA.
- Lines W. C.; Percy Thomas Wind Generator Designs; Federal Power Commission, Washington, D. C., 1973, NASA Technical Reports.
- https://en.wikipedia.org/wiki/NASA_wind_turbines
- Kumar Jogesh et al.; Wind energy: Trends and enabling technologies, Renewable and Sustainable Energy Reviews 53(2016)209–224.
- Sovacool K. Benjamin; The importance of open and closed styles of energy research; Social Studies of Science, Vol. 40, No. 6 (December 2010), pp. 903-930, Sage Publications, Ltd.
- Busby L. Rebecca; Wind Power: The Industry Grows Up; 2012, PennWell Corp.
- https://en.wikipedia.org/wiki/Wind_farm
- https://en.wikipedia.org/wiki/Whitelee_Wind_Farm
- https://en.wikipedia.org/wiki/Middelgrunden
- Heymann Matthias; Signs of Hubris: The Shaping of Wind Technology Styles in Germany, Denmark, and the United States, 1940-1990; Technology and Culture, Vol. 39, No. 4 (Oct., 1998), pp. 641-670.

(during iron smelting processes). This technique led to the development of metallurgy in ancient China.

The third application of wind energy was the windmills. China has a history of approximately 1,800 years of windmill use. Later on, windmills disappeared due to the development of the steam engine and, also, due to the emergence of technologies that combust fossil fuel to release energy.

Vertical axis windmills were first built in Persia and were meant to address farming needs. The horizontal axis windmills were invented in northwestern Europe in the 1180s. These early windmills had typically four blades and were known as *post mills*. Later, several types of windmills were developed in the Netherlands and Denmark, based on improvements upon the post mill.

The horizontal axis windmills have become the dominant windmill type in Europe and North America for many centuries due to their higher operation efficiency and their technical advantages over the vertical axis windmill (see previous chapter).

The re-emergence of the wind as a significant source of the world's energy is a development of the late 20th century, thanks to the pioneering work of Albert Betz, Ludwig Prandtl, Nikolay Zhukovsky and others in the field of aerodynamics, all of which set the foundations of modern wind energy technology.

Windmills are used to directly deliver work (such as water pumping, etc.), while wind turbines are used to convert wind energy to electricity.

We should note that during this technology's development, factors such as environmental considerations, economics, national and international policies, as well as technical requirements like grid connection, had taken precedence over any optimal, "technical" wind turbines designs.

It was the oil crisis of the 1970s that leveraged the turn towards RES technologies and led to the commercial adoption of grid-integrated wind energy systems. This growth in wind energy deployment was associated with a dramatic decline in the levelized cost of energy (LCOE). After more than fifty years of continuous innovation in wind energy technology, levelized costs became a fraction of the early-1970s costs.

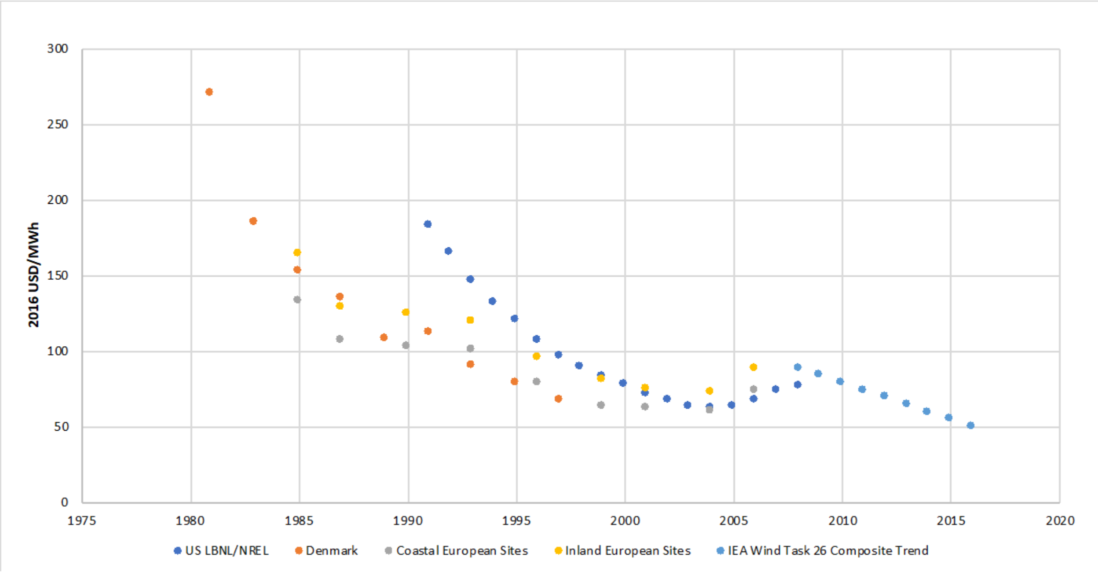

Figure 6: Wind energy LCOE from 1980 through 2016[25]

The 90s of the 20th century wind turbines development has been marked by an enormous increase of installed capacity, and by a shift to large, megawatt-sized wind turbines, consolidation in wind-turbine manufacturing industry and the development of the offshore wind power industrial sector.

This tendency continued at the beginning of the 21st century with European countries (and manufacturers) leading the increase via government policies focused on developing their domestic RES markets and reducing pollutant emissions.

The modern electricity-generating horizontal-axis wind turbine (HAWT) is a direct descendant of the historic European windmill and the small, DC-generating wind turbines of the 1930s.

3.2 The Period before World War II

The beginning of the 20th century in the western world has been the start of the electric era, marked by the inventions of Edison, Steinmetz, Tesla and others. Thousands of wind turbines have been put into operation in order to address the electrification needs of isolated American homes and farms.

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[25] Dykes Katherine et al.; Results of IEA Wind TCP Workshop on a Grand Vision for Wind Energy Technology; IEA Wind TCP Task 11 Technical Report, April 2019.

3.2.1 Europe

The reason for the development of wind energy technology can be traced to the old tradition of using windmills (Dutch windmills) in rural districts for agricultural activities. By 1890, windmills in Denmark produced the equivalent of half as much energy as all the animal power that supported Danish agriculture.

Poul la Cour (called by many "the Danish Edison") and his protégé, Johannes Juul, were the dominant figures of the wind energy technology sector in Denmark during the pre-WWII period.

From 1891 till his death in 1908, Poul la Cour was in charge of a windmill experimental station established by the Danish State in Askov.

Figure 7: Poul la Cour's first experimental windmill from 1891. (Photo: The Poul la Cour Museum) [26]

The research program he has managed with the support of the Danish government aimed at an improved rotor performance and an economical production of electricity by means of wind-powered machines. Poul la Cour built more than 100 electricity-generating turbines in the 20-35 kW size range.

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[26] Maegaard Preben, Krenz Anna, Palz Wolfgang; The Rise of Modern Wind Energy, Wind Power for the World; CRC Press, 2013.

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Figure 8: Participants of the first class of "rural electricians" in 1904. Poul la Cour is sitting at the left end of the middle row. Number three from the right in the back row is the young Johannes (Photo: The Danish Energy Museum).[27]

By 1910, there were hundreds of such machines (wind turbines) equipped with 100 to 300 Ampere-hour capacity storage batteries, supplying electrical power to villages around Denmark.

By the end of World War I, more than one fourth of all rural power stations in Denmark used wind turbines and, by 1920, it is estimated that wind turbines produced about 120 to 150 MW.

In Germany, due to the extended electrification during the first three decades of the 20th century, wind power technology lost its economic importance, resulting in the decommissioning of thousands of windmills.

During the 1920s, Kumme in Germany designed a six-bladed wind rotor. His idea to place the rotor at the base of the tower has not been successful.

Germany capitalized on la Cour's work in Denmark to further develop wind energy technology under the leadership of a young, charismatic and visionary engineer, Hermann Honnef. He proposed the construction of giant wind power plants of up to 430 meters in tower height and 160 meters in rotor diameter, delivering 60 MW of power. His ambition was to free Germany from its dependence upon fuel imports. Furthermore, Honnef was the first to propose an offshore wind power installation.

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[27] Maegaard Preben, Krenz Anna, Palz Wolfgang; The Rise of Modern Wind Energy, Wind Power for the World; CRC Press, 2013.

Figure 9: Wind power plant by Hermann Honnef[28]

Hermann Honnef was drawn to National Socialism. Several Nazi leaders supported his ideas and he has been hired together with other engineers like Ferdinand Porsche and the young and promising thirty-year-old Austrian Ulrich Huetter to develop wind turbines. The latter, who has studied aircraft engineering at the technical universities of Vienna and Stuttgart, has been described by his colleagues as an ingenious engineering artist. He developed and tested new wind turbines during the World War II period.

In 1942, he submitted his doctoral dissertation to the technical university of Vienna. In it, he tried "to determine the size and concepts of wind turbines that give the best cost efficiency". **Huetter was the first to develop and promote a science-based design of wind turbines.**

During the pre-WWII period in France (and by 1929), the French engineer Darrieus (who had already patented the vertical-axis rotor that bears his name) designed a two-bladed horizontal-axis wind turbine (20 m in diameter, 20 m high tower), producing 150 kW DC.

At the same time, British engineers showed a similar interest. In Oxford University's Institute of Agricultural Engineering, seven wind turbines from five manufactureres were tested and it was reported that the electricity produced would be reasonable for use in rural areas.

A thousand miles to the east, the Soviets launched their wind power research program that sought to develop a 100 kW wind turbine. As the Soviet economy was not integrated to those of Europe and the United States, Soviet research programs had not been affected by the Great Depression and were still

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[28] Maegaard Preben, Krenz Anna, Palz Wolfgang; The Rise of Modern Wind Energy, Wind Power for the World; CRC Press, 2013.

progressing during the 1930s. According to the Russian scientist V.R. Sektorov (of the Central Wind-Power Institute), "*the history of capitalist technology does not reflect any significant attempts for using wind energy for permanent power stations. In the USSR, socialist economy makes it possible to build wind power*".[29] In 1931, under the direction of Kranovsky, the Russians developed Balaclava, a large-power utility-scale wind generator of 100 kW.

It was the first wind-powered system to be connected to an existing power supply network: it was coupled via a 6.3 kV power line to the 20 MW steam power station at Sevastapol, 20 miles away. Although the design was relatively simple, the Balaclava wind turbine achieved an output of 279 MWh. It operated for 10 years, until it was destroyed during the Second World War. Also in the 1930s, the Soviet Union considered the construction of a 5 MW wind turbine that was never implemented.

The focus of the Soviet Union's wind energy research program was not the development of big wind turbines but their integration into the transmission networks in agricultural regions, in order to provide supplemental power for agricultural use.

3.2.2 United States of America

The American large-scale turbine (dynamo) was built in 1886 by Charles Brush, a scientist from Cleveland Ohio, at the backyard of his mansion. His experiments were limited by the lack of electricity. His wind turbine was of immense dimensions: it was a 40 tons (46.300 kg) tower of an 18.3 m height. The diameter of the rotor was 17.1 m. Within the tower he located his dynamo and the necessary gearing to drive it. The produced electric energy was being stored in 12 batteries. The whole configuration provided electricity for his electrical equipment.

The Brush dynamo worked incredibly well for approximately 15 years, producing 12 kW of direct current (DC) power for battery charging at variable speeds. After 1900, Brush used his dynamo only occasionally and finally abandoned it in 1908 as, at that time, Cleveland began to deliver centrally generated electricity.

Experimentation continued sporadically between 1890 and 1920, without applied results. It was only after World War I that advances in aeronautics led to the design of practical and inexpensive wind turbines.

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[29] Owens N. Brandon, The Wind Power Story; A Century of Innovation that Reshaped the Global Energy Landscape; 2019 IEEE, John Wiley & Sons, Inc.

In 1920, only few North American farms were equipped with gasoline-powered generators. There was room for wind turbines to provide electricity to the American farm family. The most successful of the companies that produced wind turbines were Jacob's Windelectric and Windcharger.

In 1925, Marcelleus and Joseph Jacobs—although not engineers—invented their first small-size battery-charging wind turbine, so as to provide electricity to their parents' eastern Montana ranch. They have converted a farm windmill from pumping water to generate electricity. Gradually, they perfected the design of their wind turbine and begun to successfully sell it to neighboring ranches. In order to increase their production capacity, they chose Minneapolis, Minnesota in 1927. In the next 20 years, the Jacobs brothers produced approximately 30.000 small wind turbines of 32 and 110 V DC. The Jacobs machines became legendary for their reliability and have been characterized as the "Cadillac" of wind chargers.

Apart from the Jacobses, there also were other successful brands in America at that period. One of them was Windcharger, which produced models from 6 to 110 V and from 200 to 3000 W. These could be set up and maintained easily. In 1945, some 400.00 of the company's wind plants were operating worldwide.

Other brands included the Miller Airlite, Universal Aeroelectric, Paris-Dunn, Airline, Wind Kind and Windpower. Although most of these turbines were small and could only power a radio and, perhaps, a couple of 40 W lights, they have continued to meet the needs for electricity in North America's rural regions, even after AC utility power begun to spread through cities and towns.

By the 1930s, wind turbines were especially used in rural places, where there was no general supply of electricity. Engineers and entrepreneurs were committed to the creation of a centrally controlled grid to carry electricity. It was at that time that the Rural Electrification Act (REA) came into existence.

"*This enormously successful Act (that was passed in 1936) called for local farmers to establish cooperatives with the authority to get loans to bring electrical power to their farms. Thus, centralization and the government subsidies for the cooperatives killed the wind turbine industry. The future of electricity would no longer depend upon the autonomous operation of small-scale, locally controlled devices but, rather, upon large central power plants that deliver electricity over long transmission lines and require higher voltage for efficient distribution. By 1957, every American wind electric company had ceased its operations*". [30]

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[30] Fleming D. P. and Proben D. S.; The Evolution of Wind-Turbines: An Historical Review; Applied Energy 18 (1984) 163 177; Elsevier Applied Science Publishers Ltd. England, 1984.

While at the time the market needed small, farm-oriented wind turbines, young engineer Palmer Cosslett Putnam was thinking of a larger-scale wind turbine capable of connecting to the grid. Because of the high rates of electricity, he thought of using the centrally provided electric power, selling the surplus back to the utility company.[31] Thus, Putnam designed a huge experimental wind turbine that would generate AC, operating like a conventional power plant. The project has been implemented with the support of the S. Morgan Smith Company of York, Pennsylvania (which manufactured controllable-pitch hydraulic turbines) and the participation of several engineers and universities. The wind turbine would connect to the Central Vermont Public Corporation Supply Services. The turbine was erected in 1939 on a 610 m high hill in the Green mountains, which has been selected among 50 possible sites (Figure 7).

The wind turbine was composed of a two-bladed, 53.3 m diameter rotor mounted atop a 33.5 m high tower capable of producing 1250 kW. It was the world's largest wind power plant in the USA (prior to the 1970s), constructed in a time of standalone wind turbines decline. Except for a period of two years (because of maintenance problems during WWII), it operated intermittently until 1945, for a total running period of 1000h.

Figure 10: Smith-Putman's 1.25 MW wind turbine. Smith–Putnam wind turbine, the world's first MW-size wind turbine in 1941, installed in Grandpa's Knob in Castleton, Vermont, USA (Photos: NREL/DOE).[32]

Putnam's turbine development was practically a sole successful project that did not led to further developmental efforts in the United States.

3.3 The Period from 1945 to 1970

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[31] This is a form of the present-day *Net Metering* concept.

[32] Maegaard Preben, Krenz Anna, Palz Wolfgang; The Rise of Modern Wind Energy, Wind Power for the World; CRC Press, 2013.

After World War II, there has been an increased interest in the use of wind energy for producing electricity. According to Flemming D.P. the main reasons for this were[33]:

- Fuel shortages and the increasing demand for electricity.
- The supposedly high and rising costs of electricity generated from steam-driven plants.
- The economic and political problems of the post-war years encouraged countries to become more dependent upon indigenous power resources.
- The realization that fossil fuel reserves were finite.
- An increasing knowledge of aerodynamics.

The majority of this period's developments were rather experimental and did not lead to any commercial exploitation. There were two main reasons for this:

1. The prices of fossil fuels during the post-war period were low with a decreasing trend. Although wind is a no-cost energy source, the final costs of power production from wind energy is derived when the total construction operation and maintenance costs of the wind turbines are taken into account. In the period before the oil crisis of 1973, total production cost was higher than the cost of producing electricity from coal, gas or oil.
2. During the 1950s and 1960s there was an increasing confidence in the production of electricity by nuclear fission.

3.3.1 Denmark

As stated in the previous section, in Denmark there has been extensive use of wind energy in the agricultural sector. Windmills helped introduce electricity to rural districts and helped the country's agricultural economy to survive during both world wars—when there were extensive oil supply shortages. About 4 million KWh annually have been produced in Denmark during the war.

The Dutch *F. L. Smith Company* (FLS) developed a series of small-scale wind turbines in the 45 kW range. FLS was one of the first companies that introduced aerodynamics to the design of wind turbine blades. At the beginning, they used a two-blades configuration, but, due to vibration problems, the

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[33] Fleming D. P. and Proben D. S.; The Evolution of Wind-Turbines: An Historical Review; Applied Energy 18 (1984) 163 177, Elsevier Applied Science Publishers Ltd. England, 1984.

company switched to three blades. The FLS wind turbines produced DC current, since, at that time, some areas of Denmark have been equipped with small DC grids.

The success of the F.L.S. wind turbines led to further experiments for the construction of larger configurations in the years immediately after the end of World War II.

After the war, DC-producing wind turbines have been gradually replaced by AC producing ones. The dominant figure of this time—and, perhaps, one of the most prominent wind energy technology engineers ever—was Johannes Juul. He focused his research efforts on the development of AC-producing wind turbines that would complement fossil power plants and reduce Denmark's dependence on fuel imports. Juul was born in 1887 and followed the Danish craft school tradition. Thus, he was a traditionally trained engineer who worked outside academia—the exact opposite from Huetter in Germany. He was trained as an electrician by Poul la Cour until 1904. After his education, he worked for several workshops and companies in Denmark and Germany. In 1928 he joined the Danish Sydostsjaellands Elektricitets Aktieselskab (SEAS) utility in Zeeland to build and maintain electrical installations and develop new electrical devices.

By 1952 Juul, based on the FLS machines experience, built a bigger, 40-kilowatt wind turbine, which operated satisfactorily and cleared the way for his most important development. With the help of Marshall Plan funding, he designed a 200-kW, 24-meter diameter wind turbine that incorporated the design principles Juul had developed through experimentation. This wind turbine was installed in 1956-57 on the island of Gedser, in the far southeast of Denmark (Figure 11). Like its smaller predecessors, the Gedser wind turbine had a three-bladed rotor located upwind of a concrete tower but it supplied AC power to the local utility, Sydøstsjaellands Elektricitets Aktieselskab (SEAS), and produced approximately 400 MWh per year from 1958 until 1967. The 'Gedser" wind-turbine ran successfully until 1968, when the expansion of the rural electrification network made it financially uneconomical for it to remain operational.

Figure 11: Johannes Juul's Gedser turbine with 200-kilowatt capacity, 24-meter diameter rotor and 25-meter tower height.[34]

Research on medium and large-scale wind energy development was discontinued in Denmark in the mid-'60s. Yet, the wind energy technology restart of the mid-1970s relied heavily upon the reliability and simplicity of the designs of the Gedser wind turbine. In 1977 the machine was refurbished and equipped with modern instrumentation. It operated intermittently for research purposes. Tests of aerodynamic performance and structural loads were successfully conducted.

3.3.2 France

During the period from 1958 to 1964, three large-scale HAWTs were built and tested in France by Electricité de France (EDF), in collaboration with two companies: BEST and Neyrpic. The first turbine was called the Type Best-Romani and was erected at Nogent-le-Roi near Paris. Its three-bladed rotor had a

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[34] Divone V. Louis; Evolution of Modern Wind Turbines Part A: 1940 to 1994, in David A. Spera ed., WIND TURBINE TECHNOLOGY, Fundamental Concepts of Wind turbine engineering, 2nd edition, 2009 by ASME, Three Park Avenue, New York, NY 10016, USA.

diameter of 30 m and the system rating was 800 kW at a wind speed of 16 m/s. It operated for five years, from 1958 to 1963, connected to the EDF network. There were some technical difficulties in its operation but its connection to the AC grid was successful.

The second French wind turbine, called Type Neyrpic, had a smaller diameter of 21 m. Its rated power was 132 kW at a wind speed of 13.5 m/s. Erected near the English Channel at Saint-Remy-des-Landes, it operated successfully for three years and accumulated only 60 days of outage for various technical reasons. A larger Type Neyrpic turbine, with a three-bladed rotor of 35m diameter of 35 m and 1,085 kW max power, was built at the same site and operated for seven months in 1963 and 1964. During November 1963 it produced 200,000 kWh of electricity. Its total energy output during a period of seven months was about 28 percent of the wind energy available, which is a performance level seldom achieved even by modern turbines. The tests ended in June 1964, when the turbine shaft broke.

Although these three prototype turbines clearly demonstrated the feasibility of grid-coupled operation, in 1964 the French decided to discontinue further wind energy research.

3.3.3 United Kingdom

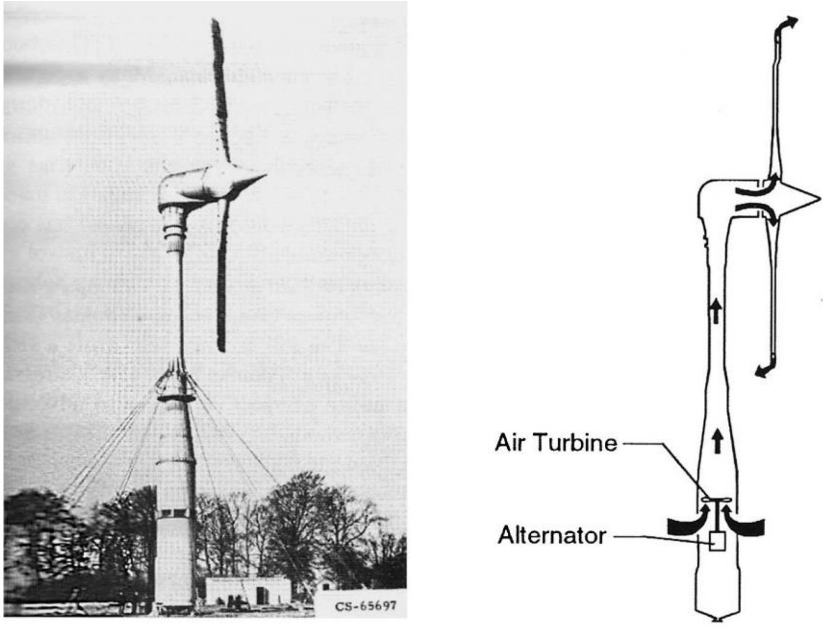
The post-WWII wind power trend resulted in the development of an extensive wind energy research programme by the British *Electrical Research Association* (ERA) from 1945 to 1960. Although several medium-scale wind turbines have been built during this programme, most of the studies done concerned site selection and the wind mapping of the UK.

The three largest of the turbines built were 100 kW HAWTs of entirely different designs, each developed as a prototype for a wind power plant connected to a utility grid.

The first of the prototypes was built and installed in the Orkney Islands in the early 1950s by John Brown & Co. It initially had a rotor of 18 m in diameter, later reduced to 15 m after an accident in which one of the blades struck the tower during a high wind. A series of configuration modifications followed, in order to overcome vibration problems. Its operation stopped in 1956.

The second one, an l00 kW HAWT (25 m in diameter) was built in the early 1950s by Enfield Cables and initially installed at St. Albans, in the U.K. It has been called the Enfield-Andreau turbine, because it was based on the design of the

French engineer Andreau—a unique concept in which mechanical coupling between the turbine and the generator is eliminated by driving the generator pneumatically.



(a) (b)

Figure 12: The 100 kW, 25 m Enfield-Andreau turbine in the early '50s.[35]

The turbine rotor has hollow blades with open tips and acts as a centrifugal air pump. As illustrated in Figure 12, air is drawn in through side vents in the tower shell, passing upward to drive an enclosed high-speed air turbine coupled directly to the generator. After flowing through the rotor hub into the hollow turbine blades, it is finally expelled from the blade tips. Despite its engineering perfection, the overall efficiency of the Enfield-Andreau turbine is low, because of drag losses in the internal flow paths. The turbine was later moved to Algeria, where it is said to have operated intermittently for about 180 hours (till 1961) but was permanently decommissioned after suffering bearing failures at the blade roots.

A third 100 kW wind turbine, built by Smith (Horley) Ltd., was installed on the Isle of Man in the late 1950s and operated until 1963. The Isle of Man wind turbine was relatively low in cost ($20,000 installation) and had pioneering characteristics, like a two rotor design and inexpensive blades made from extruded aluminum (which have been used successfully in more recent times). The Isle of Man win turbine operated successfully for several years and was

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[35] Divone V. Louis; Evolution of Modern Wind Turbines Part A: 1940 to 1994, in David A. Spera ed., WIND TURBINE TECHNOLOGY, Fundamental Concepts of Wind turbine engineering, 2nd edition, 2009 by ASME, Three Park Avenue, New York, NY 10016, USA.

purported to produce electricity at an economic price. However, the project was discontinued in 1963 after a severe storm damaged the blades. However, the main reason of its termination was that Britain embarked on a major nuclear-energy program that promised cheap and abundant energy production.

3.3.4 Germany

Wind turbine activities in Germany resumed after World War II, based on earlier tests of the Nazi-party (prominent members) owned Ventimotor GMBH wind turbines (8 m and 18 m in diameter) in Weimar and continued through the '50s and '60s under the guidance of Professor Dr. Ulrich Huetter (a former member of the NSDAP). As stated in the previous section, Huetter was a formally educated engineer. He was the first to develop and promote a science-based design of wind turbines.

He continued the work he started before the war, producing several small, elegant, lightweight designs. One of his designs was an ingenious single-blade turbine, which was never built because of technical and financial problems. In the late 1940s, he designed a small 7-kilowatt turbine for DC production; in 1952, he built and tested a similar small turbine that produced AC power, the 10 kW, 10 m Huetter-Allgayer HAWT that could be connected to a utility grid.

But Huetter's masterpiece in the 1950s was a sophisticated 100-kilowatt, 34 m wind turbine (see Figure 13). This was the most technologically advanced system of its time (and for decades to follow) and was called the W 34 – Huetter-Allgaier. Tests began in October 1957. After only three weeks, a heavy storm broke a shaft and its rotor blades were destroyed. Repairs took years, mainly due to a lack of funds. It was eventually dismantled in August 1968.

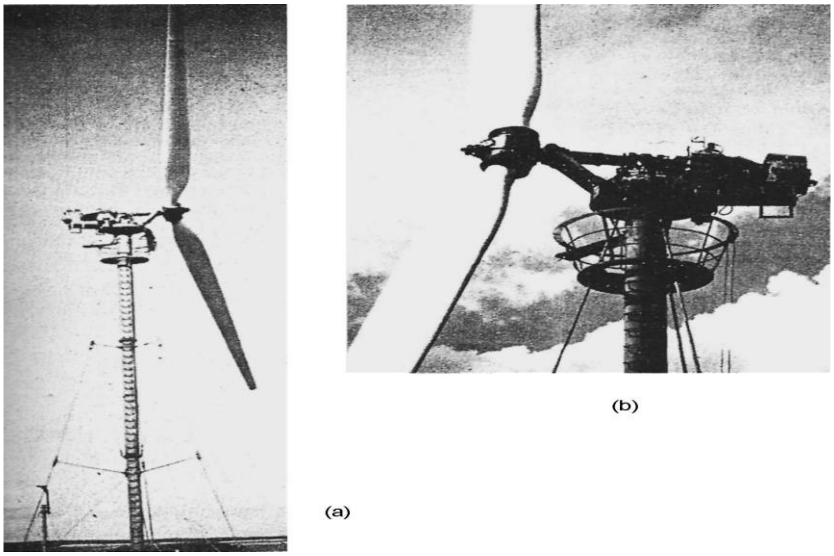

Figure 13: The technologically-advanced 100 kW, 34 m Huetter-Allgaier wind turbine. (a) General view of the turbine mounted on its 22.3-m guyed shell tower. (b) View of the fiberglass blade roots, teetered hub, and in-line power train. [36]

This period in the United States is marked by the presence of Percy Thomas, who worked for the US Federal Power Commission. He was impressed by the work of Putnam and firmly believed that a wind-powered future would benefit his country. From 1945 through 1954, he wrote a series of relevant monographs, stressing the economics and the size requirements from a utility perspective. Percy Thomas proposed multiple rotors on a single tower (see Figure 16) as a method of obtaining multi-megawatt capability within the constraints of the rotor blade technology of his time.

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[36] Divone V. Louis; Evolution of Modern Wind Turbines Part A: 1940 to 1994, in David A. Spera ed., WIND TURBINE TECHNOLOGY, Fundamental Concepts of Wind turbine engineering, 2nd edition, 2009 by ASME, Three Park Avenue, New York, NY 10016, USA.

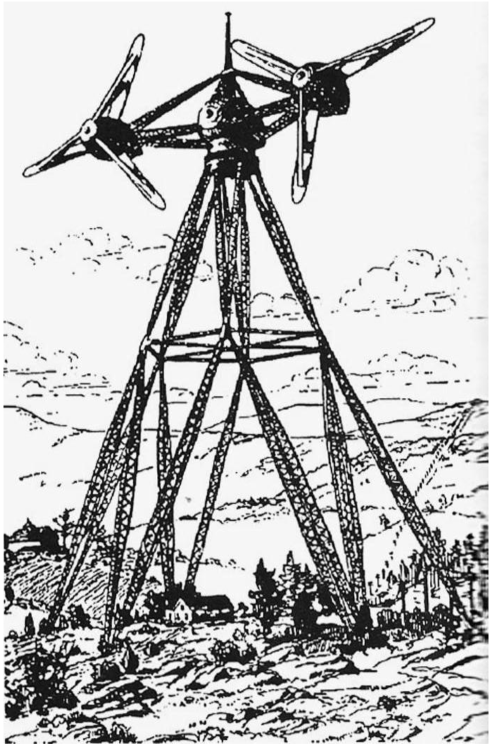

Figure 14: Percy Thomas' dual-rotor concept for a multi-megawatt wind turbine.[37]

Unfortunately, he received no funds, even though there was a Congressional hearing on the subject in 1951. No actual design work—much less experimental work—was undertaken. He was rather considered to be working on the fringes of technology (and bordering science fiction).

3.4 The Period after 1970

The period after 1970 has been marked by the oil crisis of 1973, as well as the economic and safety issues arising from the use of nuclear energy. This situation resulted in economic difficulties for the majority of industrialized countries. These two factors led decision makers and scientists to realize the limits of a fossil-fuel-based economy. Thus, they convinced governments to invest in research programs for renewable energy technologies.

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[37] Divone V. Louis; Evolution of Modern Wind Turbines Part A: 1940 to 1994, in David A. Spera ed., WIND TURBINE TECHNOLOGY, Fundamental Concepts of Wind turbine engineering, 2nd edition, 2009 by ASME, Three Park Avenue, New York, NY 10016, USA.

Especially with regard to wind energy, more money has been invested than ever before. From 1975 to 1988, total R&D expenditures on wind technologies in Denmark, Germany and the United States reached $19.1 million and $103.3 million respectively. Although the overall budget sizes mentioned above seem high, they were extremely small compared to those allocated for nuclear energy research.

These research programs included basic technology development, the direct and indirect support of the private development of smaller wind turbines and government-funded development of medium scale or larger systems.

Testing centers have been established in several countries (e.g., in the USA at Cleveland, Ohio, in Denmark at Risø, in Germany at Pellworm Island, in the Netherlands at Petten). These centers test both experimental and commercial machines, as well as setting in place certification programs as a requirement for tax or subsidy benefits, preventing machines from entering the market too early.

By 1970, there was little or no worldwide activity that produced wind power electricity. Some water-pumping windmills were still being constructed, principally for use in the developing world.

At the same time, initiatives concerning date and information exchange begun. At the end of the 1960s, there was, unfortunately, little useful documentation and almost no experimental data from all the previous decades of wind technology activities worldwide. The engineers of the 1970s had no or little knowledge of the relevant developments after the end of the nineteenth century.

Since the mid-1970s, international information exchange has been accomplished through the International Energy Agency (IEA), headquartered in Paris. IEA was modeled after the International Atomic Energy Agency and has been established in order to coordinate western cooperation in energy policy, research and development after the shock of the 1973 oil embargo.

3.4.1 Europe

3.4.1.1 Denmark

Denmark, like all other western countries, was affected by the oil crisis. In 1973, oil imports made up about 94 percent of the country's energy supply. Additionally, nuclear energy faced a very strong public opposition and has been eventually rejected by the social-democratic government in January 1980. Therefore, in order to meet the challenges above, Danes responded with a national research program to support technicians and small enterprises that engaged in wind technology development, starting from the low-tech windmill designs and, then, scaling-up to larger machine configurations.

In 1977 the 200 kW Gedser turbine was restored and put into test operation until March 1979, with positive results.

Between 1978 and 1980, the first two large-scale turbines were erected at Nibe, near Alborg in northern Jutland—the "Nibe twins". Their capacity was 630 kW and each was 40m in diameter. Project leaders reported a lot of technical problems during testing. Nibe B outperformed Nibe A, having completed more than eighteen thousand hours of operation by the fall of 1988. The Nibe twins were the first of a new generation of European wind turbines to reach the testing stage. Therefore, they provided valuable information about operation and maintenance costs and supported the expansion of the Danish wind energy industry. As part of an agreement with the Danish government, in 1989 the Nibe twins were taken over by ELSAM (a Danish multinational power company) and resumed operation after thorough repairs. However, their performance remained inferior to that of smaller, commercially manufactured Danish turbines.

In the following years, Danish engineers continued their efforts to design large industrial scale wind turbines within the framework of a national initiative of installing 1000 MW of wind power by the year 2000.

In March of 1985, with the support of a joint European Community-Danish wind power program, five 750 kW turbines have been constructed in Masnedo, in south Zeeland. These turbines were based on Nibe B and suffered many problems after they begun operating. One of them completely burnt down in October 1987, forcing the engineers to limit its maximum power to 450 kW.

In another project supported by the EC, in 1988 Denmark completed a final large-scale 2-MW machine with a 61-meter diameter, near Tjaereborg in Jutland. This wind turbine behaved better that its predecessors, but its economic performance, like theirs, was disappointing.

Eventually, the Danish government's wind power support program for the development of large scale wind turbines had no more commercial impact than the German and American programs had.

Although Denmark would become self-sufficient in oil a decade later (following such discoveries in the North Sea), the country continued its wind development program as a means of reducing greenhouse gas emissions. They managed to increase the wind's expected contribution to 10% of the nation's electricity supply by the year 2000—a target they would actually exceeded. In 2001, wind energy contributed 16% of the county's total energy supply.

In the Netherlands, a 300 kW experimental wind turbine has been constructed in 1980, with the support of the Dutch government. It was designed for maximum test flexibility, having the ability to be easily reconfigured and operate in various modes.

3.4.1.2 Sweden

In the European North, Sweden proceeded rapidly into a large-scale turbine research program, after first experimenting with a SAAB-Scania 100 kW HAWT, tested near Uppsala. Further Swedish efforts included a 2.5-MW, 75-m diameter turbine with two blades, built by a consortium named KaMeWa. They installed it at Nasudden, on the island of Gotland. A 3-MW, 78-m rotor diameter wind turbine called WTS-3 was built by a joint venture between Karlskronavarvet (KKRV) in Sweden and Hamilton Standard in the US. It was placed near Malmö, in southern Sweden.

Although more conventional than the KaMeWA design, the 3-MW WTS-3 was nonetheless technologically advanced. While both turbines encountered various early problems (the KaMeWa turbine was once nearly destroyed), they both operated successfully for an extended period of time.

An up-scaled version of the WTS-3, the Hamilton Standard/KKRV WTS-4, was purchased by the US Bureau of Reclamation (USBR) and was set in Wyoming, according to the framework of a project managed by the NASA Lewis Research Center. The purpose of the project has been to investigate the connection of large-scale wind turbines with hydroelectric systems. WTS-4 was the most powerful wind turbine ever built.

3.4.1.3 United Kingdom

The United Kingdom continued to investigate large scale wind turbine designs in its test site on Scotland's Orkney Islands.

The approach taken was to construct two machines—one of a 250 kW production output with a rather rigid design (called MS-1) and a second one, the privately developed 300 kW Howden, with a more flexible ('soft') design. Both machines operated in parallel for testing purposes.

Based on the experience gained, a consortium composed by Taylor-Woodrow Construction, British Aerospace and GEC constructed the 3-MW LS-1 prototype wind turbine. LS-1 has been installed in the Orkney Islands and its testing started by 1987.

3.4.1.4 Germany

In Germany, though the political establishment was skeptical about the feasibility of renewable resources use, in 1974 the powerful Ministry for Research and Technology (Bundesministerium für Forschung und Technologie—BMFT) decided to support wind power research. Like in all western countries, the German wind power research program focused on the development of large-scale wind turbines.

Ulrich Huetter, by this time a professor and director of the Institute of Aircraft Construction at Stuttgart University, was the program’s dominant figure. His and his coworkers’ vision was to turn Germany into the world leader in wind energy technology. They suggested the immediate construction of an upgraded version of the W 34 (with an 80-meter rotor diameter) that would put out 1-megawatt of power. They also considered technically feasible turbines with a 160 to 200-meter rotor diameter and up to 10 megawatts of power output.

Based on Huetter's vision, the BMFT funded the construction of the world's largest wind turbine. Called the Growian (after Grosse Windenergie Anlage-Grosswindalange, "big wind power plant"), it featured a 100-meter-diameter rotor, a 100-meter-high tower and 3 megawatts of maximum power output. It is worth mentioning that the turbine's enormous dimensions were chosen for political rather than technological reasons. Its construction took four years, from 1979 to 1983, and was implemented by a consortium of leading utilities and the machine company MAN.

Its construction represented the greatest technological achievement of all times in wind energy technology, but included high technological risks as well. It encompassed about every advanced feature yet considered. The majority of the turbine was assembled at a site near Bremerhaven, with less factory assembly than most other machines. Despite its “scientific” project management, the design had to be significantly altered during construction and costs and construction time doubled.

Although all technical advancements were embedded in the Growian design, the wind turbine encountered a lot of problems during operation, including fatigue cracking of major components in the hub. In 1988, after only 420 hours in operation over a four-year period, the machine was dismantled.

Figure 15: The 3-MW Growian HAWT near Bremerhaven, Germany. It was one of the largest wind turbines ever built, with a 100-m diameter rotor and a 100-m tall tower [38]

Although the Growian project offered significant contributions to the understanding of large wind turbines, it turned out to be a disaster.

The Growian turbine has been followed by a second, more ambitious project to construct a huge large scale, one-blade wind turbine with 10-megawatt power output, called Growian II. The project was suggested by the aviation and aircraft company Messerschmidt-Boelkow-Blohm (MBB).

Funded by the BMFT and the European Community (EC), MBB developed one-blade turbines, in much smaller versions than the originally proposed max 640 KW, named Monopteros. After more than ten years of research and numerous design changes, the Monopteros turbines remained far from profitable and MBB stopped producing them in the early 1990s.

A 270-kilowatt and 26-meter blades turbine constructed by the machine company Voith was based on a design provided by Huetter. Although the turbine utilized the most advanced technologies and had high specific construction costs, Huetter's plans failed due to severe stability problems.

Finally, like all similar national programs of the time, the German large-scale wind turbine R&D program had no impact on the development of

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[38] Maegaard Preben, Krenz Anna, Palz Wolfgang; The Rise of Modern Wind Energy, Wind Power for the World; CRC Press, 2013.

commercial wind turbines. By the early 1990s, the major German companies involved in this program had left the field of wind turbine development.

3.4.2 United States

In the US, the National Science Foundation (NSF)—under their new “Research Applied to National Needs” (RANN) program—after examining the overall long term issues of energy supply, concluded that renewable energy sources could play a major role in the future.

By the end of 1973, the first US federal wind power program was launched. It was oriented towards the development and commercialization of wind energy technology. The programs were heavily centered on a 'big science' approach, aiming at the construction of mammoth-scale turbines, since the dominant model of energy production in the US relied upon big companies delivering power to heavy industries with mass production. Engineers, managers, and the whole social and economic environment was adapted to power plants in the 100 to 1000 MW range. Their approach was top-down, from large-scale turbines downwards smaller ones. Thus, the US research style sought to develop big turbines from the beginning. Megawatt-class (providing 1 megawatt or more power output) wind turbines were believed to have the greatest potential for application in utility networks due to economies of scale. The development of these megawatt-class wind turbines was managed by the National Aeronautics and Space Administration (NASA) and coordinated by the NASA Lewis Research Center (LRC) in Cleveland. The LRC conducted indoor research and hired subcontractors, mainly large companies such as Boeing, McDonnell Douglas, Lockheed, Grumman Aerospace, General Electric/Space Division, Kaman, and Westinghouse. Except for Westinghouse, all were leading aircraft companies with traditionally good relations with NASA. Though no subcontractor had experience in wind technology, aircraft engineering was considered most applicable to large-scale wind turbine development. This was the start of the NASA/DOE wind turbine research program that continued for over 20 years.

In parallel to these NSF-NASA research activities, the signing of the Public Utility Regulatory Policy Act (PURPA) by president Ford in 1978 further boosted the wind energy industry. PURPA required electric utilities to interconnect with small power generators utilizing renewable energy sources and to purchase their power generation and, also, exempted small power generators utilizing renewable energy sources from certain federal and state utility regulations. As a result, within few years, thousands of wind turbines were installed in California.

The LRC federal program resulted in the design, construction, and testing of 12 medium and large-scale horizontal-axis wind turbines. A plentiful of relevant papers and research reports has been published.

The entire project started with the organization of a Wind Energy Workshop sponsored by NSF and NASA-Lewis in 1973. In this workshop has been invited the crème de la crème of the international wind energy technology, like the pioneers of the '30s (such as Marcellus Jacobs, Palmer Putnam, Ulrich Hütter), together with the new generation of wind energy technology experts, so as to discuss and recommend research needs. NASA engineers consulted with Huetter and Putnam and studied the operation of Juul's Gedser turbine. NSA engineers and their subcontractors clearly preferred Huetter's design principles.

Based on the recommendations of this workshop, NSF and NAS launched their wind energy research plan in 1974. The oil crisis intensified the program's significance and guaranteed a rapid growth of research funding.

The initial plan of the program prescribed R&D projects closely coupled with the design and testing of experimental wind turbines. The overall plan assumed three cycles or "generations" for experimental turbines. The first generation should act as basis to investigate design issues and obtain basic data. The second generation was envisioned to investigate the first generation wind turbines use. Finally, a third generation of wind turbines would be required to reach a level of performance and reliability that could be cost effective on a broad scale in order for private capital to be attracted, so that unremitting development and commercial production are ensured.

Since the importance of turbine size and its effects on the economics of the wind turbine market were not known at the time, the second direction of the federal program was to to develop in parallel three sizes of prototype wind turbines: small-scale turbines (1 kW to 99 kW) for rural and remote use; medium-scale turbines (100 kW to 999 kW) for a remote community or industrial market; and large-scale systems (1 MW to 5 MW), primarily for the electric utility market.

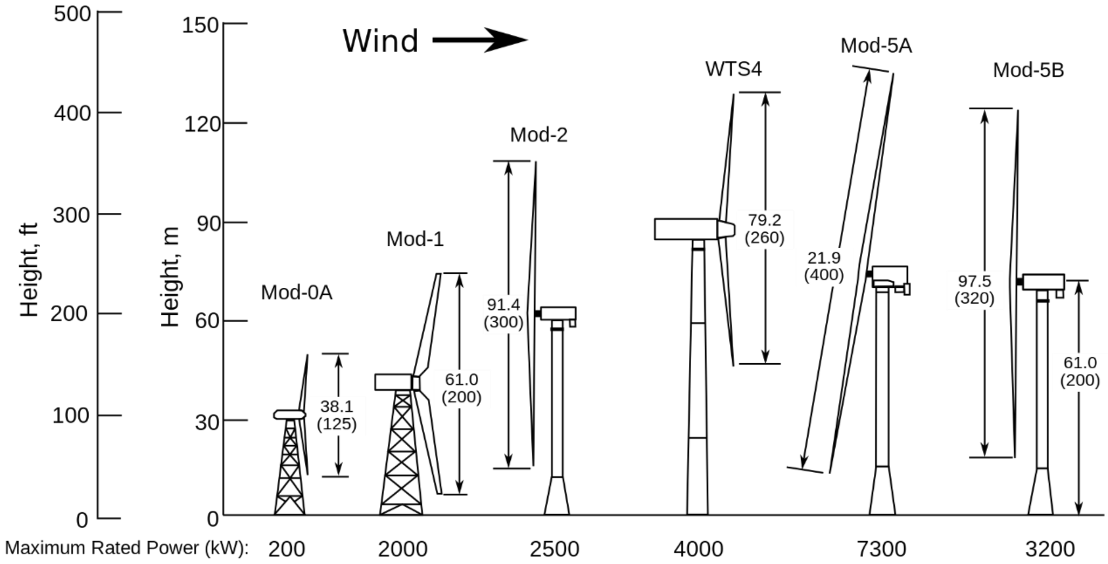

Figure 16: NASA experimental wind turbines drawn to the same scale. (Mod-5A wingspan is 121,9 m) [39]

The first wind turbine developed, the Mod-0, was a medium-scale HAW with a 38.1 m rotor and a 100 kW output, based on Huetter's W 34. This turbine served as a test bed for the next dozen years. The purpose of the Mod-0A program was to identify and resolve technical and operational utility interconnection issues.

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[39] https://en.wikipedia.org/wiki/NASA_wind_turbines

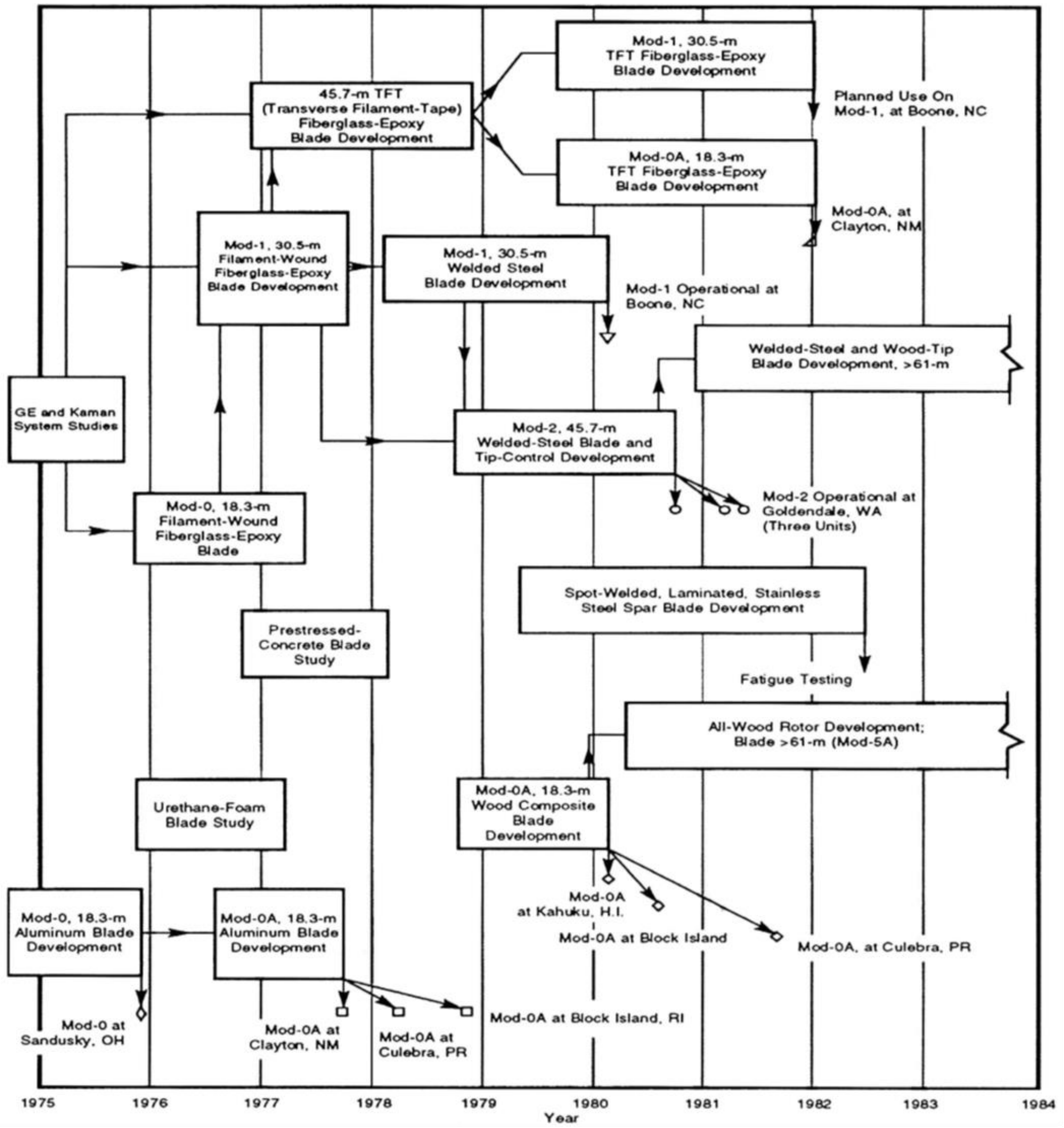

Figure 17: Chronology of the development and application of rotor blade materials for medium- and large-scale HAWTs, at the NASA-Lewis Research Center.[40]

A two-bladed rotor located downwind of the tower (see Figure 18) was selected, following the examples of the Smith-Putnam and Huetter turbines, since three-blade systems were found to be cost-ineffective large-scale systems.

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[40] Divone V. Louis; Evolution of Modern Wind Turbines Part A: 1940 to 1994, in David A. Spera ed., WIND TURBINE TECHNOLOGY, Fundamental Concepts of Wind turbine engineering, 2nd edition, 2009 by ASME, Three Park Avenue, New York, NY 10016, USA.

Figure 18: Final assembly of the 100 kW Mod-0 HAWT test bed in 1975. It was located at the NASA Lewis Plum Brook Test Station near Sandusky, Ohio.[41]

The Mod-0 wind turbine failed due to loads on the blades, while vibration problems turned out to be more than estimated.

The Mod-0 development followed four upgraded versions from 125 kW to 200 kW production capacity. All were scrapped when none of the host utilities wanted to assume their maintenance.

The most important contribution of the four Mod-0A HAWTs was that they could be successfully integrated into a utility's normal operations and that they could produce high-quality AC power of value to that utility. They also provided a technology base for the growth in size of privately-developed wind turbines, from the 10 to 15 m diameter and 10 to 25 kW sizes of the early 1970s to the 100 to 300 kW and 20 to 30 m diameter turbines that were developed and installed in the late 1980s.

By 1976, NASA had also hired General Electric to build the two-blade downwind turbine MOD-1, a 2 MW, 61 m rotor diameter experimental HAWT, with a design that was similar to the Mod-0 one. It was the first megawatt-scale wind turbine on a utility grid since the 1939 Smith-Putnam turbine. Mod-1 was installed in 1979, on a small mountain in North Carolina. The local utility, the Blue Ridge Electric Membership Cooperative, operated the Mod-1 for two years. Although the project proved that megawatt-scale wind turbines could be successfully interfaced with a large, conventional utility power system, the company

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[41] Divone V. Louis; Evolution of Modern Wind Turbines Part A: 1940 to 1994, in David A. Spera ed., WIND TURBINE TECHNOLOGY, Fundamental Concepts of Wind turbine engineering, 2nd edition, 2009 by ASME, Three Park Avenue, New York, NY 10016, USA.

underestimated the difficulties involved. The six-million-dollar MOD-1 failed after only eighteen months of test operation, when a shaft broke.

Despite the problems encountered in the Mod-0 and Mod-2 projects, NASA resolutely continued with the MOD-2 project assigned to Boeing.

Three porotypes of this wind turbine have been installed at Goodnoe Hills, Washington, a fourth turbine in Wyoming for the Bureau of Reclamation and a fifth, ordered by the California utility Pacific Gas & Electric (PG&E), in Solano County, California.

Power control at one of the turbines at Goodnoe Hills failed after eleven days of operation, causing severe damage to the turbine. Structural fatigue and bearing failures plagued the MOD-2 turbines until operational tests ended in 1987. The mean time between failures for the PG&E turbine was less than forty hours and its average availability reached only 37 percent. All Mod-2 turbines were later dismantled. According to the engineers, the problems were due to design limitations and simplified models of wind and would be resolved after modifications and repairs. Although there have been major operating and maintenance results from the five wind turbine prototypes, it has been proofed that large scale wind turbines could compete successfully for utility companies operating funds.

Plans to develop the Mod-3 and Mod-4 turbines were never carried out.

Two new development programs followed: a large-scale Mod-5 HAWT program that was canceled in 1983, as well as a medium-scale Mod-6 HAWT and VAWT program. Two contractors were chosen to design and develop what became known as the General Electric Mod-5A (7.3 MW) and the Boeing Mod-5B (7.0 MW) HAWTs.

MOD-5B was cut back to a 3.2-megawatt turbine. In 1988, the two-blade MOD-5B (with a 98-meter rotor diameter) was erected for the Hawaiian Electric Company in Oahu, Hawaii. In use over the next five years, its availability reached 67 percent.

Even though the Mod-5B was the first large-scale wind turbine to operate successfully at a variable speed, it was shut down in 1992 because of its poor economic performance and chronic malfunctions.

Following the failure of the MOD-5B design, the federal wind power program quietly ran down, having achieved no commercial impact. NASA and its subcontractors largely retreated from wind technology development.

At that point, energy and fuel costs decreased and energy was no longer a major national priority. As a result, and perhaps due to the failures that had already happened, the Mod-6 program (whose contractors had not yet been selected) was canceled.

Thus, only one third-generation turbine, the Mod-5B, was completed under the Federal Wind Energy Program.

According to Sovacool,[42] "*the development of wind turbines in the U.S. were characterized by a closed style subscribing to centralized management with a focus on rapid increases in turbine size and a strong belief in sequential stages of development. Wind researchers and government regulators undertook little product development between steps, evaluated technologies selectively and encouraged competition while discouraging information sharing. Further, corporate ownership was incentivized and government policy episodic*."

The US federal wind energy program could be described as a failure, since the program objectives have only partially been achieved.

3.5 Wind Farms

As stated in the introduction, wind turbine scale-up is bidirectional. Horizontal scale-up is brought about by the formation of wind farms. These come in two kinds: onshore and offshore, based on the location where the turbines are installed. Any wind farm typically includes wind turbines, generators, power transformers and a connection to the power grid (see Figure 19).

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[42] Sovacool K. Benjamin; The importance of open and closed styles of energy research; Social Studies of Science, Vol. 40, No. 6 (December 2010), pp. 903-930, Sage Publications, Ltd.

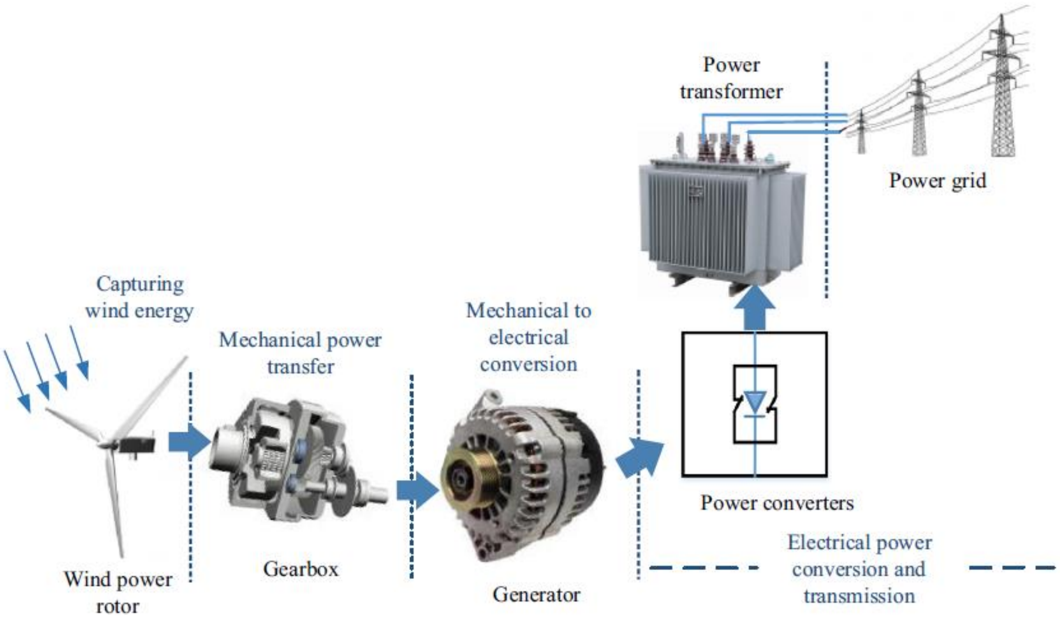

Figure 19: Main components of a Wind Power Production Configuration (WPPC). [43]

Offshore wind farms usually consist of wind turbines that are bigger than the onshore ones, generating up to about 6 MW each or more. There are also small-size wind farms that may deliver electricity to a small town, a community or a utility company. A large wind farm might spread over hundreds of square kilometers. Advocates of wind technology argue that about 95% of the land they require can be concurrently used by farmers for agricultural activities.

Wind turbines are placed so that interference of airflow among them is minimized. Their exact position matters, because even small differences of 30 meters could potentially double output. This careful placement is called 'micro-siting'.

Their location—site selection—is critical for the economic feasibility of wind farms. The have to be near transmission lines that have enough capacity to accept additional power. They also need to overcome local opposition. Wind farm siting can be controversial when neighboring communities raise objections. Of course, onshore wind farm installations are located where there are optimum wind conditions, in hilly or mountain regions. In the case of offshore wind farms, these are situated near the shoreline in order to minimize transmission costs.

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[43] Kumar Jogesh et al.; Wind energy: Trends and enabling technologies, Renewable and Sustainable Energy Reviews 53(2016)209-224

The faster the average wind speed, the more electricity the wind turbine will generate. Thus, faster winds are generally economically superior for the development of wind farms. The ideal wind conditions would be strong but consistent winds of low turbulence, coming from a single direction. Mountain passes are ideal locations for wind farms under these conditions as they channel the wind blocked by mountains through a tunnel-like pass, towards areas of lower pressure and flatter land.

To an electric utility, a wind farm acts as a power plant that burns fossil fuel. Yet, due to the variability of wind speed, the amount of electricity a wind farm generates can vary. Therefore, their integration into a utility electrical system or into the grid should be carefully planned. Even if scientific research has provided methods of short-term wind energy forecasting, the variability of the wind speed remains an issue.

Spacing and sitting of the wind turbines of a wind farm are decisive factors for the success of a wind project, since they may increase the installation and operation costs.

Finally, other factors (not only technical, but also environmental and socioeconomic) should be taken into account.

Current wind farms or parks usually range in size from 20 MW to 200 MW, but they can be much larger—even in the range of thousands of MW production capacity. They consist of dozens or even hundreds of large turbines (each more than 1 MW in capacity) located in the same area and controlled either on-site or remotely.

The following table shows the biggest onshore wind farm installations:

Table 1: The world's largest onshore wind farms.[44]

Wind farm	**Current capacity (MW)**	**Country**
Gansu Wind Farm	6,800	China
Zhang Jiakou	3,000	China
Urat Zhongqi, Bayannur City	2,100	China
Hami Wind Farm	2,000	China

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[44] https://en.wikipedia.org/wiki/Wind_farm

Wind farm	Current capacity (MW)	Country
Damao Qi, Baotou City	1,600	China
Alta (Oak Creek-Mojave)	1,320	United States
Muppandal Wind farm	1,500	India
Hongshagang, Town, Minqin County	1,000	China
Kailu, Tongliao	1,000	China
Chengde	1,000	China
Shepherds Flat Wind Farm	845	United States
Roscoe Wind Farm	781.5	United States
Horse Hollow Wind Energy Center	735.5	United States
Capricorn Ridge Wind Farm	662.5	United States
Fântânele-Cogealac Wind Farm	600	Romania
Fowler Ridge Wind Farm	599.8	United States
Sweetwater Wind Farm	585.3	United States
Zarafara Wind Farm	545	Egypt
Whitelee Wind Farm	539	Scotland, U.K
Buffalo Gap Wind Farm	523.3	United States
Meadow Lake Wind Farm	500	United States
Dabancheng Wind Farm	500	China
Panther Creek Wind Farm	458	United States

The world's ten biggest offshore wind farms are shown in the following table:

Table 2: The world's ten largest offshore windfarms.[45]

Wind farm	Capacity (MW)	Country	Turbines & model	Commissioned
Walney	659	United Kingdom	47 x Siemens Gamesa 7 MW, 40 x MHI Vestas V164 8.25MW	2012
London Array	630	United Kingdom	175 × Siemens SWT-3.6	2013
Gemini Wind Farm	600	Netherlands	150 × Siemens SWT-4.0	2017
Greater Gabbard wind farm	504	United Kingdom	140 × Siemens SWT-3.6	2012
Anholt	400	Denmark	111 × Siemens 3.6-120	2013
BARD Offshore 1	400	Germany	80 × BARD 5.0	2013
Rampion Wind Farm	400	United Kingdom	116 x Vestas V112-3.45MW	2018
Thorntonbank	325	Belgium	6 × REpower 5MW and 48 × REpower 6.15MW	2013
Sheringham Shoal	315	United Kingdom	88 × Siemens 3.6-107	2012
Thanet	300	United Kingdom	100 × Vestas V90-3MW	2010

Europe is the leader in offshore wind energy, with the first offshore wind farm (Vindeby) installed in Denmark in 1991. Offshore wind turbines present several advantages compared to the onshore ones, like the noise being diminished by distance, higher wind speeds and social acceptance. Nevertheless, they have bigger operation and maintenance costs.

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[45] https://en.wikipedia.org/wiki/Wind_farm

Figure 20: An aerial view of Whitelee Wind Farm, the largest onshore wind farm in the UK and second-largest in Europe. [46]

As of 2010, there are 39 offshore wind farms in the waters off of Belgium, Denmark, Finland, Germany, Ireland, the Netherlands, Norway, Sweden and the United Kingdom, with a combined operating capacity of 2,396 MW. More than 100 GW (or 100,000 MW) of offshore projects are proposed or under development in Europe. The European Wind Energy Association has set a target of 40 GW installed by 2020 and 150 GW by 2030.

Figure 21: Offshore wind turbines near Copenhagen, Denmark [47]

As of 2017, the Walney Wind Farm in the United Kingdom is the largest offshore wind farm in the world at 659 MW, followed by the London Array (630 MW), also in the UK. In 2010, there were no offshore wind farms in the United

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[46] https://en.wikipedia.org/wiki/Whitelee_Wind_Farm

[47] https://en.wikipedia.org/wiki/Middelgrunden

States, but projects were under development in wind-rich areas in the East Coast, the Great Lakes and the Pacific coast. In late 2016, the Block Island Wind Farm was commissioned.

3.6 Manufacturing Wind Turbines: Engineering vs. Craft Approach

As stated in the previous sections, the most commercially successful wind turbines were developed independently of government R&D programs.

Through the last century of wind technology development, we can distinguish two types of wind turbine design and manufacturing. The first one implemented mainly in Denmark (the Danish style) and the 'scientific' one, implemented in other countries but, mainly, in Germany and the USA. The latter relies primarily on planning tools and formal mathematical and scientific models, rather than input from potential users.

The Danish style of research was deeply influenced by the political and economic structure of Denmark. Danish political institutions are based on cooperative and egalitarian ideals. They can be traced to the country's foundation as an agricultural society consisting mainly of medium and small farms and a rather educated rural population. Windmills have been used for the production of electricity in local communes and small villages. Wind technology's advancement in the late 1960s and early 1970s was not an initiative of the industrial sector or of R&D funded by the government, but addressed the needs of municipalities and small farming communities that wanted to build and operate their own windmills. According to Sovacool[48], "*these actors viewed wind energy not as a means to make money, but as a mechanism that provided a community service*."

In the mid-1970s, there was a wave of enthusiastic amateurs and skilled artisans committed to the development of wind turbines based on simplified designs of Juul's Gedser turbine—although using inexpensive, off-the-shelf parts. Despite their limited scientific background and experience, they nonetheless produced surprisingly reliable turbines.

By the late 1970s, about a dozen small Danish manufacturers were building small wind turbines. By 1978, some 50 turbines had been installed in Denmark and, by 1979, their number had increased to about 120. But small manufacturers lacked the ability and capital to construct larger turbines, allowing small agricultural machinery companies such as Bonus or Vestas but, also, the oil-tank

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[48] Sovacool K. Benjamin; The importance of open and closed styles of energy research; Social Studies of Science, Vol. 40, No. 6 (December 2010), pp. 903-930, Sage Publications, Ltd

producer Nordtank to enter the market. After they bought the patents of the pioneering wind turbines, they hired the technicians who empirically knew how to produce commercial wind turbines. In addition, the government established a test station for small wind turbines in 1978 at the Riso research center near Copenhagen. The station tested and licensed wind turbines, while test engineers provided technical and scientific support to the producers. Only after the approval of the Riso Test Station would turbine manufacturers be subsided by the government.

Commercial wind turbine production in Denmark remained an affair of skilled workers and non-academic technicians until 1980, when the first academic engineers were employed.

As stated by M. Heymann [49]"*it is worth mentioning that another important factor in Danish wind turbine development was the Danish association of wind turbine owners, Vindkraftvaerker, with its monthly journal, Naturlig Energi (Natural Energy), facilitating the information and data sharing among designers*."

In the 1970s, Danish researchers disagreed with the large-scale turbines vision developed by the Department of Energy (DOE) in the USA. They preferred to remain focused on incremental improvements to small-scale turbines.

Skilled workers also built small turbines in the United States and Germany, but their efforts were negligible, because the socioeconomic environment was hostile for small-scale development and use. However, due to insufficient financing most of these companies had to develop the turbines quickly with little operational testing, which resulted in a big number of failures when operating in California.

In Germany too, the socioeconomic environment was not favorable for the creation of a wind turbine market, because of the opposition of utilities and the government preference for large scale wind turbines. In addition, the technical solutions adopted and the companies involved in both the German and the American research programs originated from aircraft engineering and the aerospace industrial sector—in contrast to the Danish experimental practice of Juul. Furthermore, while Danish manufacturers steadily managed to reduce the weight and increase the size and sophistication of their turbines, producers in Germany and the United States (with the exception of the US Department of Energy research program) tended to reduce the sophistication and increase the structural stability and weight.

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[49] Heymann Matthias; Signs of Hubris: The Shaping of Wind Technology Styles in Germany, Denmark, and the United States, 1940-1990; Technology and Culture, Vol. 39, No. 4 (Oct., 1998), pp. 641-670.

By 1981 until the late 1980s, during the California wind power boom, Danish producers like Vestas offered thousands of mature and reliable 55-kilowatt turbines. Thus, the Danish wind industry prospered and could gradually improve the efficiency, size, power output and specific cost of wind turbines. Between 1981 and 1989, turbine capacity increased incrementally from 55 to 65, 75, 95, 150, 225, 400, and finally 500 kilowatts.

In the late 1980s, major features of the Danish concept have been globally adopted. Most manufacturers came to prefer three-blade upwind turbines. Companies such as Mitsubishi in Japan, the Husumer Schiffswerft (HSW) in Germany and even Windpower in the US (with its new 300-kilowatt turbine, developed in the early 1990s) copied major features of the Danish design with considerable success.

By 1985, Danish wind turbine manufacturers held 50 percent of the world market and, by 2006, the industry had a turnover of more than US$4 billion and constituted up to 85 percent of Danish exports. Before consolidation in 2001, four of the world's largest six wind turbine manufacturers were Danish, and in 2008 the largest wind turbine manufacturer (Vestas) and the largest independent blade manufacturer (LM Glasfiber) were Danish.

The USA did emerge to become the world leader in terms of total installed wind capacity in 2008, but most of this technology was not based on those earlier designs and US firms had to license patents from other countries, notably from companies in Denmark, Germany and Spain.

4 Wind Energy Technology Impacts[50]

Nowadays, utility-scale wind turbines have little in common apart from their main working principles and their common windmill ancestry. Nevertheless, the latter were perfectly ‘embedded’ in their environment and all of its aspects—e.g. socially, physically etc.

Although both windmills and modern wind turbines use the same primary energy resource, it seems that wind energy technology scaling disproportionately impacts its social and physical environment, at he the expense of its “renewable” character. The emerging implications are overlapping: for instance, wind turbine sitting is both a technical and an environmental issue that depends upon physical (aerial) conditions, logistics (e.g. accessibility) or legislative frameworks. Parameters such as these can complicate project economics.

In the 1980s, wind energy was being discussed as part of a soft energy path—i.e., a way to abandon fossil fuels and reverse the greenhouse effect. Renewable energy commercialization led to an increasing industrialization of wind power, with severe impacts that can occur at the various stages of planning, site development, construction, operation and decommissioning or abandonment (if applicable). However, different phases tend to be associated with different impacts. Any or all of the impacts have the potential to accumulate over time and with the installation of additional generators. The relationships between incremental changes in wind powered electricity generation and other environmental impacts (such as those on wildlife or landscape) are generally not known and are unlikely to be proportional.

Subsequently, we summarize the main issues that may arise due to the wind technology scaling process.

- Technical issues (e.g. siting, connection to grid, project logistics, operation and maintenance, waste management etc.)

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[50] Information for this chapter has been obtained from the following resources:

- WWF-Norway; Environmental Impacts of Offshore Wind Power Production in the North Sea; 2014.
- https://www.bloomberg.com/news/, 2020-02-05.
- Agarwal T., Verma S., Gaurh A,; Issues and Challenges of Wind Energy; International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT) – 2016.
- Pierpont N., Wind Turbine Syndrome: A Report on a Natural Experiment: K-Selected Books, 2009.
- Committee on Environmental Impacts of Wind-Energy Projects; NRC of the National Academies, The National Academies Press, 2007.
- Brittan Jr. G Gordon; Wind, Energy, Landscape; Philosophy & Geography, 4: 2, 169 — 184, 2001.

- Socio-environmental issues (e.g. climate change, visual and aural impact, wildlife impact, landscape aesthetics, economic and fiscal issues etc.)

These issues are mostly overlapping and cannot be examined in isolation: for instance, the construction and maintenance of wind-energy facilities may alter an ecosystem through vegetation clearing, soil disruption, potential erosion and/or noise. Furthermore, forest clearing represents perhaps the most significant potential change through fragmentation and loss of habitat for some species.

4.1 Technical Issues

4.1.1 Siting

The selection of the suitable location to place either isolated wind turbines or wind farms (siting) is of great importance for the economics of an installation. Yet, at the same time, we should note that the construction of wind energy farms (or isolated wind turbines) requires large areas at sufficient heights or near the coastline in the case of offshore wind farms, to ensure the availability of wind energy. As stated in previous sections, their advocates argue that wind energy farms that are usually located in rural areas (where there is availability of land) use only 95% of the total wind farm area, leaving space for agricultural activities such as farming, livestock operations etc.

Although a location may satisfy the requirements above, actual supply of wind will never be consistent, as wind variability is an issue. Thus, the generating system cannot provide steady electricity, thereby affecting the power system operations. To resolve this, power system regulators can be used to make detailed schedule plans and set reserve capacity for wind energy systems. However, it is a costly supplement to ensure consistency. Furthermore, to reduce the requirement of reserve capacity and increase the wind power penetration, accurate forecasting methods are necessary.

Currently, offshore wind farms seem to be advantageous due to the energy potential associated with vast offshore areas, since increased wind potential, less turbulence and space availability promise great productivity of energy and make this form of energy more competitive. Offshore wind facilities require larger amounts of space because the turbines and blades are bigger than their land-based counterparts. Depending on their location, such offshore installations may compete with a variety of other ocean activities, such as fishing, recreational activities, sand and gravel extraction, oil and gas extraction, navigation and aquaculture.

4.1.2 Wind Energy Projects Implementation

As mentioned above, wind turbines (either solitary or in terms of wind farms) are mostly situated on rural areas. Therefore, their installation projects—but, also, their operation and maintenance process—require the construction of a supporting infrastructure: namely, access roads, ancillary structures etc. These may alter habitats and irreparably fragment any type of landscape—whether sylvan, rocky or other. Such internal fragmentation, apart from the aesthetic impact, may subdivide populations of some species. The magnitude and importance of these effects are determined by the natural history of the individual taxa and the scale of the fragmentation. There are several effects of forest roads on aquatic and terrestrial communities. These include the destruction of corps, the disruption of the physical environment, the alteration of the chemical environment of the road bed and its edge, the direct mortality of species, the mortality of animals from collision with vehicles using roads, the modification of animal behavior and an increase in the spread of invasive species. Additionally, there can be changes in the human uses of land and water (due to an increased access to said resources or by providing access where none was previously available). Increased hunting, fishing, recreational driving and other (formerly irregular) activities are also possible. All of these can culminate in radical transformations.

As far as offshore wind farm construction and operation is concerned, there are still large knowledge gaps regarding the environmental impacts of offshore wind. The considerable lack of baseline data is a significant impediment to the evaluation of impacts. Their potential effects differ among species, depending on their likelihood of interaction with the structures and cables, sensitivities and avoidance responses. Studies have generally focused on marine mammals and seabirds because of stakeholder concerns and legal protection for these species and their habitats.

In the case of wind farms, it seems that their construction phase is likely to have the greatest impact on marine mammals. The activities of greatest concern are pile driving and increased vessel traffic. The loud sounds emitted during pile driving could potentially cause hearing damage, masking of calls or spatial displacement, as animals move out of the area to avoid the noise.

Underwater sound levels are unlikely to reach dangerous levels or mask acoustic communication of marine mammals. However, this phase of the development is of greatest concern for seabirds. Mortality can be caused by collision with the moving turbine blades, while avoidance responses may result in displacement from key habitat or increase energetic costs.

During offshore wind farm operation, cables transmitting the produced electricity will also emit electromagnetic fields that could affect the movement and navigation of species that are sensitive to electric or magnetic fields. Commercial fish species may potentially be positively affected if fishing is prohibited in the vicinity of the wind farm.

In order to access the environmental impacts of both onshore and offshore wind farm projects, we need to apply a holistic research approach, taking into account the way species behave together, the physical environment and the economic and social activities of the location.

4.1.3 Grid connection issues

Since wind turbines are usually installed in rural areas, there are two main problems in wind energy generation with respect to the electricity grid. Firstly, in many of the rural areas there is no or limited access to grid infrastructure, resulting in energy waste. Secondly, even if there is a stable grid present, the integration of the wind turbines into the grid is problematic because of the wind speed variability, resulting in either voltage fluctuations or in a variability of power supply. This gap between supply and demand (due to produced power losses or variability) can be overcome by using batteries, power regulators etc. Yet, this is a costly supplement, especially in many developing countries. Hence, an effective grid infrastructure is essential for wind energy.

To confront future wind power grid integration, new design and operation approaches are introduced, such as demand side management and energy storage techniques, grid infrastructure upgrade, power electronics components etc. The problem of grid integration can also be solved by using power electronics concepts.

4.1.4 Waste Management

Although the number of decommissioned turbines so far is low (given the overall number of installed wind turbines), taking into account the short history of industrial scale turbines and their lifespan of about 20-30 years, the high installation rate suggests that a similarly high decommissioning rate can be expected at some point in the near future. There are numerous wind turbines approaching decommission age and, if the waste material from these turbines is not handled sustainably, the whole concept of wind power as a clean energy alternative will be challenged.

Although modern wind turbines already have a recyclability rate of 85% to 90% (as they are built to withstand hurricane-force winds), blades cannot be easily crushed, recycled or repurposed, while it is very difficult and costly to transport them. It is unclear exactly how decommissioned wind turbines will be managed in the future. For parts that are worn out or weakened in strength, material recycling or energy recovery will probably be the most likely option. However, some parts could possibly be re-used directly or, after possible refurbishment, indirectly in other turbines or for other purposes.

According to Bloomberg[51], "*tens of thousands of aging blades are coming down from steel towers around the world. Most have nowhere to go but in landfills. In the USA alone, about 8,000 will be removed in each of the next four years. Europe, which has been dealing with the problem for longer, has about 3,800 coming down annually through at least 2022. While most of a turbine can be recycled or find a second life on another wind farm, researchers estimate the US will have more than 720,000 tons of blade material to dispose over the next 20 years—a figure that does not include newer, taller, higher-capacity versions"*.

Thus, it seems like industrial scale wind turbines may cause even more environmental challenges.

4.2 Impacts on the environment

The environmental impact of wind power is relatively minor when compared to that of fossil fuel power. Compared to other low-carbon power sources, wind turbines have one of the lowest global warming potentials per unit of electrical energy generated by any power source.

4.2.1 Impacts on wildlife

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[51] https://www.bloomberg.com/news/, 2020-02-05

Wind turbines, like many other human activities and buildings, also increase the death rate of avian creatures such as birds and bats. Some species (e.g. migrating bats and songbirds) are known to be harmed more than others and factors such as turbine siting can be crucial for that. However, many details (as well as the overall impact from the growing number of turbines) remain unclear.

According to the proponents of wind turbines, impacts on wildlife are smaller when compared to other sources of energy. It is estimated that conventional (fossil-fueled) power stations killed twenty times as many birds than wind turbines per GWh Other sources kill many more birds than wind turbines, even though precise data on total bird deaths caused by most of these anthropogenic sources are sparser and less reliable than one would wish for.

Researchers and industry experts are trying to find possible protective or preventative solutions when it comes to accidents due to wind turbines. On the basis of several studies, it has been found that turbines with lower hub heights, shorter rotor diameter (higher revolution rate) and tighter turbine spacing lead to the killing of a larger number of birds. Possible solutions include new wind turbine designs, like tubular steel towers.

Furthermore, the overall importance of turbine-related deaths for bird populations is still unclear. An assessment of the importance of wind turbines for bird mortality requires more information and a better understanding of the species affected and the likely consequences for the local populations of those species. There are many research initiatives that suggest ‘scientific’ solutions to the problem: e.g. modeling the spatiotemporal patterns of migratory and residential wildlife with respect to geographic features and weather, in order to provide a basis for science-based decisions about where to site new wind projects. For instance, in states like Texas, avian radars are used to detect birds in an area. If there is any risk to the passing birds, the system will stop the wind turbines immediately and start them again after the birds have crossed the wind farm safely.

4.2.2 Weather and Climate Change

Wind farms may affect weather in their immediate vicinity. Turbulence from spinning wind turbine rotors increases the vertical mixing of heat and water vapor that affects the meteorological conditions downwind (including rainfall). In general, wind farms lead to a slight warming at night and a slight cooling during the day. A proposed technical solution is the use of more efficient rotors or the placement of wind farms in regions with high natural turbulence.

A number of studies have used climate models to study the effect of extremely large wind farms (e.g. detectable changes in global the climate) and reported some rather pessimistic results. Using wind turbines to meet 10 percent of global energy demands in 2100 could actually have a warming effect, causing temperatures to rise by 1 °C in the regions (on land) where the wind farms are installed, including a smaller increase in areas beyond those regions. This is due to the effect of wind turbines on both horizontal and vertical atmospheric circulation. Turbines installed in water would have a cooling effect, while the net impact on global surface temperatures would be an increase of 0.15 °.

4.2.3 Noise impact

Noise pollution is one of the most critical environmental issues in implementing wind energy. That noise can be either aerodynamic or mechanical. Aerodynamic noise is developed due to the flow of air over and past the blades of a turbine and increases with the speed of the rotor. This can be reduced by a careful blade design. Mechanical noise is produced by moving components such as the gearbox, the generator, bearings etc. This noise pollution can even lead to lower property values within a certain radius from the construction and is also hazardous for humans—for instance, some scientists have proposed a "*wind turbine syndrome*"[52]. This is a psychosomatic disorder that pertains to the belief that low frequency wind turbine noise (either directly or through annoyance) causes or contributes to various measurable health effects related to anxiety.

The noise effect due to wind turbines has been extensively researched in the USA and Europe. Several technical design solutions have been proposed in order to overcome it. Mechanical noise can be minimized by proper design & selection, maintenance etc. It can also be reduced by using anti-vibration support footings and acoustic insulation curtains.

4.2.4 Visual impacts

Visual impacts are mainly influenced by the shape, color and layout of the wind turbines. The extent of this problem often depends upon individual perceptions, which are almost impossible to measure. Several methods have been applied to analyze visual impacts of the wind turbines and several technical measures have been proposed. Wind turbines require aircraft warning lights, which may create

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[52] Pierpont N., Wind Turbine Syndrome: A Report on a Natural Experiment: K-Selected Books, 2009

light pollution. Residents near turbines may complain of a "shadow flicker" caused by rotating turbine blades, when the sun passes behind the turbine. This can be avoided by locating the wind farm in a way that prevents unacceptable shadow flicker or by turning the turbine off for the time of the day when the sun is at the angle that causes flicker.

4.2.5 Landscape Impacts and Aesthetics

Onshore wind farms spread over wild and rural areas or isolated wind turbines can have significant impact on the landscape. This can lead to its industrialization and affect especially scenic and culturally important landscapes or historical sites. This is one the main reasons why wind power projects cause strong local opposition around the world. It is worth mentioning that research has shown strong support for wind energy in general but substantially less support for projects close to one's home—namely, the phenomenon of NIBYism ("Not in my backyard!").

The impact of wind turbines is primarily visual, as they are only rarely in balance with other landscape elements due to their industrial aerodynamic design being in disharmony with other elements of the physical environment—e.g. rocks, trees etc. The latter accommodate the winds by bending to them, but windmills can capture their energy only by resisting them.

There is also a conflict of scales. According to Brittan Jr. G.[53] "*it is not impossible to reconcile contemporary wind turbines with the classical landscape aesthetic or the "scenic" ideal. They dominate rather than harmonize; they upset rather than balance; they are not in scale. In a word, they are "ugly"*".

Public perceptions of wind-energy projects vary widely. To some, wind turbines appear visually pleasing, while others view them as intrusive industrial machines. According to the proponents of utility-scale wind energy, aesthetic issues are subjective. Some people find wind farms pleasant or see them as symbols of energy independence and local prosperity. In some cases, wind farms have been reported and promoted as tourist attractions. This the case with enormous wind farms (where tourists are attracted by the magnitude of the technical artifact) or modern wind turbines with an innovative design. Arguably, in these cases it seems like the object of attraction is the artifact in isolation and not as a part of the physical environment. The evaluation of the aesthetic impacts

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[53] Brittan Jr. G Gordon; Wind, Energy, Landscape; Philosophy & Geography, 4: 2, 169 — 184, 2001.

of wind energy projects needs to focus on the relationship of the proposed project to any scenic landscape features and the surrounding context.

As stated by Brittan Jr. G.,[54]"*in order to assess the visual and aesthetic impacts of wind energy installations, several methods (e.g. best practices and guidelines) have been proposed, but there is no immediately available aesthetic norm that would single-handedly remodel wind turbines as "landscape-beautiful"—i.e., there is no immediately available and adequate conception of the "landscape" on which they "fit in*".

It seems like any aesthetic violations are due to the size of contemporary industrial scale wind turbines. Old traditional windmills, fashioned locally and in compliance with the place and its history, where (as a part of it) perfectly in balance with the landscape and the life of local communities.

4.3 Local Control – Locality

Apart from the purely aesthetic aspects, local acceptance of wind turbine installations (or the lack thereof) gives rise to the issue of the character of contemporary technology, as defined by Albert Borgmann—namely, the device paradigm. *According to it, technology has to do with "devices" (also known as "black boxes"—i.e., out-of-view commodity-producing or other machinery) as opposed to a "thing".*[55] It is not necessary to get inside them either, since in principle it is always possible to replace the three-termed function that includes input, "black box," and output with a two-termed function that links input to output directly. In the case of wind turbines, except for the blades, virtually everything is shielded—including the towers of many turbines, which are hidden from view behind the same sort of stainless steel that sheathes many electronic devices. For the most of us, wind turbines are strange, hermetically sealed artifacts that we are unable to control and repair. Moreover, the machinery is located a great distance, away from anyone, behind chain-link fences and locked gates.

There is one more reason for the strong resistance to their placing. For locals, there are no important differences between industrial scale wind turbines and other energy-generating technologies. Wind turbines are merely producers of a commodity, electrical energy, and interchangeable in this respect with any other technology that produces the same commodity as cheaply and as reliably.

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[54] Brittan Jr. G Gordon; Wind, Energy, Landscape; Philosophy & Geography, 4: 2, 169 — 184, 2001.

[55] Brittan Jr. G Gordon; Wind, Energy, Landscape; Philosophy & Geography, 4: 2, 169 — 184, 2001.

Furthermore, the fact that these wind turbines installation are owned and operated by large companies (whose investors and boards of directors live and work far away from the site) diminishes any sense of local connection and, more importantly, of local responsibility and control.

4.4 Local Economic and Fiscal Issues

When assessing the economic and fiscal impacts of a wind-energy project, the main issues that arise include: (1) the fair treatment of both the landowners who lease land for the project and the other affected but uncompensated owners and occupants; (2) a fine-grained understanding of how wind-energy facilities may affect property values; (3) a realistic appraisal of the net economic effects of the wind-energy facility during its construction and over its lifetime; and (4) a similarly realistic assessment of the revenues the local community can expect and the costs it will have to assume.

5 Conclusions and Suggestions for Further Research[56]

5.1 Conclusions

In recent years, the renewable power sector experienced record-high increases in installed capacity, outpacing net installations in fossil fuel and nuclear power combined. Among all possible renewable sources of electricity wind, power has proven the fastest growing energy resource.

After over a century of intermittent wind power technology development and policy support, the wind power industry entered the twenty-first century with strong tailwinds. The technology itself matured to the point where megawatt-scale turbines had high reliability and wind power became increasingly economic. European policy makers laid a solid foundation to support wind power growth and wind power grew rapidly in Spain, Denmark, and Germany. Escalating federal and state-level policy support in the United States rekindled wind power growth there and positioned it favorably for the twenty-first century. Additionally, India and China's wind markets were showing signs of life as well. It had been a long uphill battle over the course of the twentieth century, but wind power was finally established as a legitimate player in the global electricity landscape.

The global wind power market in 2020 especially saw its second largest annual increase, with offshore wind accounting for a record 10% of new installations. The global wind power market expanded 19% in 2019 to 60 GW, the second largest annual increase, for a total of 650 GW (621 GW onshore and the rest offshore). Nowadays, wind power has become a global multi-billion-euro industry and nearly all countries in the world have developed its utilization politically, legally, and technically. Industry experts predict that if this pace of growth continues, by 2050 one third of the world's electricity needs will be fulfilled by wind power.

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[56] Information for this chapter has been obtained from the following resources:

- Owens N. Brandon, The Wind Power Story; A Century of Innovation that Reshaped the Global Energy Landscape; 2019 IEEE, John Wiley & Sons, Inc.
- REN21; Renewables 2020 Global Status Report, 2020.B.
- Heymann Matthias; Signs of Hubris: The Shaping of Wind Technology Styles in Germany, Denmark, and the United States, 1940-1990; Technology and Culture, Vol. 39, No. 4 (Oct., 1998), pp. 641-670.
- Brittan Jr. G Gordon; Wind, Energy, Landscape; Philosophy & Geography, 4: 2, 169 — 184, 2001.
- Geels W. Frank.; Multi-Level Perspective on System Innovation: Relevance for Industrial Transformation in Xand R. Olshoorn E. and Anna J. Wieczorek, Understanding Industrial Transformation: Views from Different Disciplines; 163-186; 2006 Springer Verlag.

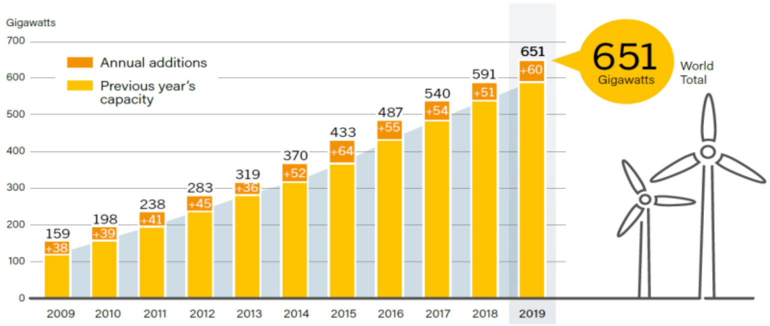

Figure 22: Wind Power Global Capacity and Annual Additions, 2009-2019.[57]

As stated in the previous chapters the history of wind energy technology installations is a continuous attempt for size scale-up either vertically or horizontally (as in the case of wind parks). Scaling of wind technology means extrapolation to larger sizes than those produced so far. It is particularly in that context that empirical models (which may effectively describe data from a historical perspective due to design variations and technology advances) are anchored to physical models of components and fundamental rules of scaling (similarity rules). Scaling trends need to be interpreted with great care. The analysis of commercial data on turbine dimensions, component mass and so on is fraught with difficulties. Historically, considering designs that appeared throughout the twentieth century, the growth of turbine size has been quite irregular. This, however, took place mostly when wind technology was a fringe research interest, based mainly on experimental expertise.

The development of modern electricity-generating horizontal-axis wind turbines is obvious descended from the far-reaching European windmill and the small, DC-generating wind turbines of the 1930s.

The initial use of wind power for generating electricity appeared toward the end of the 19th Century in Europe (principally in Denmark, and later in Germany and France) and the USA. Danish wind technology grew out of the agricultural sector as a natural byproduct of the Danish economy, craftsmanship culture and the long history the Danes had with the wind. This development has been supported by the state since the beginning of the 20th century. In the USA, wind energy technology development has been based on the business accumen of entrepreneurs like the Jacobs brothers. In the USA, just like in Denmark, the farmers and ranchers were the main users of wind turbines. At the same time, engineers and entrepreneurs were committed to the central power system and the creation of a grid of transmission lines to carry the electricity. Thus, the idea of individual power units was an anathema to those who thought in terms of large,

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[57] REN21; Renewables 2020 Global Status Report, 2020.B

centrally controlled systems that serve large populations from a central generating source. The Rural Electrification Act (REA), which was passed in 1936, subsidized local farmers to establish cooperatives with the authority to get loans to bring electrical power to farms within their designated region resulting to the death of the early wind energy technology industry.

By the end of World War I, more than one-fourth of all rural power stations in Denmark used wind turbines. In Germany, like in the USA, wind power had lost its economic importance after the electrification of rural areas. As a result, thousands of windmills disappeared in the first three decades of the twentieth century.

This early phase of development was followed by the pioneering attempts of American, German and Dutch engineers like Putnam, Juul, Huette and others. **The research style of Dutch engineers was based merely on the input from potential users and empirical models, in contrast to the German and US engineers' heavy reliance on formal mathematical and scientific models.** Commercial wind turbine production in Denmark remained a business of skilled workers and non-academic technicians until 1980, when the first academically trained engineers were employed.

This transition from the windmill and small scale wind turbines to utility scale wind energy production installations signals the transition from the traditional "old Dutch craft approach" to the 'academic' one.

After World War II, there is a growing interest in the potential use of wind energy, mainly due to fuel shortages, the increasing demand for electricity and the realization that fossil fuel reserves were finite. Nevertheless, before 1973, experience indicated that electricity derived from the wind would be more expensive than that obtained from the combustion of coal, town gas or oil.

It was the oil crisis of the 1970s and the fact that (due to economic and safety reasons) nuclear power was no longer seen as the only solution to energy problems that rekindled interest in renewable energy technologies and led to the commercial adoption of grid-integrated wind energy systems. More money than ever before have been invested in wind energy technology.

In **Denmark, prompted by a government program**, researchers followed the traditional Dutch craftsmanship style and started with low-tech windmill designs, took small steps in scaling up technologies and engaged continually in product development.

In the USA, in contrast to the Danish paradigm, big technology consortia (based mainly on the airspace industry) have been formed with government intervention, to implement the task of building large utility scale wind turbines capable to participate seamlessly in the national electricity grid. The USA research programs were highly concentrated within a few large firms rather than a large and broad base, as in Denmark. Researchers from institutes or companies that participated in these programs did not collaborate with other designers, producers and suppliers. Information-sharing and distribution of knowledge among researchers was indirect, with efforts further limited by the small number of users and the very few feedback mechanisms. Furthermore, the extent of interaction between producers and suppliers was poor, since most relationships were one-off, short-term contracts motivated by profits at the expense of efforts to foster knowledge sharing and interactive learning. Engineers became insulated from the hands-on problems encountered in construction, operation and maintenance.

In Germany, there also was strong support by the Ministry for Research and Technology (Bundesministerium für Forschung und Technologie, BMFT). Efforts have been based on the initial plans of Huetter. Most projects in both countries were not successful in terms of reliably producing wind energy for a long time. There have been only partial contributions to the understanding of the functioning of wind turbines (e.g. connection to the grid for a short time).

Most of the programs implemented in the western world (USA, Canada and Europe) produced poor results or have been used as proof of concepts of some specific functionality (e.g. grid integration). All of them were focused on the development of large-scale turbines, which were unanimously considered feasible within a development time of a few years. Despite the poor track record of large wind turbines, the EC continued to support the development of megawatt-size turbines across Europe in the late 1980s and early 1990s. These 'next generation' turbines of the early 1990s have since proved technically successful, but specific costs are four times those of existing commercial turbines.

A 'bigger-is-better' ideology and a strong belief in technical efficiency characterized most government-supported R&D efforts. The search for expected economies of scale produced a sort of gigantism that aptly matched the prevailing tradition of economic and technological thinking. The close correlation between technical efficiency and economic performance did not hold true for wind technology. The very low operating expenses of more technically sophisticated wind turbines did not compensate for higher construction costs and more frequent and more serious performance failures. In wind technology, the superiority of bigger and more technically efficient designs remained a largely *undisputed article of faith, even seeming to evolve from an engineering strategy to an engineering paradigm*.[58]

From 1981 to the late 1980s, during the California wind power boom, Danish producers (e.g. Vestas) conquered the global wind turbine market. The USA did emerge to become the world leader in terms of total installed wind capacity in 2008, but most of this technology was not based on those earlier designs. Hence, US firms had to license patents from other countries—notably from companies in Denmark, Germany and Spain.

With each new generation of wind turbine evolution, there have been questions about whether the technology has hit its limits: whether physical scaling laws, regulation issues, transportation or other logistical challenges meant that the 'optimal' turbine size has been reached and that additional size will just add costs. It seems that, at some size, the cost of building a larger turbine will grow faster than the resulting energy output and revenue, making further size increases uneconomic.

Although both windmills and modern wind turbines use the same primary energy resource, wind energy technology scaling impacts disproportionally its operating social and physical environment, at the expense of its "renewable" character. In the last chapter, we discussed the most important of these issues, either technical or socio-environmental, like siting, connection to a grid, visual and noise impact, landscape aesthetics, etc., which are the main issues of the public debate about the implementation of wind technology projects. These issues cannot be examined in isolation and the solutions cannot be purely technical. It seems that the growing size of current wind turbines resulted to their transformation from windmills to modern utility scale power production plants and to their physical and economic integration into the modern electricity markets.

Following their 'scientific' design and manufacturing process, their continuous scale-up in size, their production capacity, their integration to the centrally controlled grid or the absence of any direct positive connection to local interests, wind turbines and wind farms cannot any longer be considered technical artefacts of a human scale, designed to serve local community needs. Rather, they have been transformed into RES based power production plants—i.e., "*mechanized weeds*"[59] that do not conform to landscape aesthetics.

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[58] Heymann Matthias; Signs of Hubris: The Shaping of Wind Technology Styles in Germany, Denmark, and the United States, 1940-1990; Technology and Culture, Vol. 39, No. 4 (Oct., 1998), pp. 641-670.

[59] Brittan Jr. G Gordon; Wind, Energy, Landscape; Philosophy & Geography, 4: 2, 169 — 184, 2001.

5.2 Suggestions for Further Research

Since the scaling process affects the whole life cycle of wind energy technology (from its design to operation and maintenance), in terms of this work we only summarily touched upon some of its aspects.

In order to examine 'wind power technology scaling', emphasis has been put on the 'wind power technology' part of the statement—namely, the 'artefact' scaling—and not on the 'scaling' process per se. Some scholars prefer to replace the imagery of 'sizes' and 'levels' with the flat surfaces of 'networks' and try to reinterpret the issue of size and level as a problem of 'connections'—scale-free descriptions—in order to bypass this dualism.

Since scale is a critical concept for the contemporary scientific literature (especially in complexity theory), this remains an open research issue for the STS community (according to S. Woolgar as scalography).

As stated in the previous chapters, during the last decades the continuous wind turbine scale-up process resulted in wind energy's rising contribution to total global electricity production.

Despite its economic and environmental benefits, this augmentation in scale has generated heated opposition from communities around the world, which are often successful in delaying or halting proposed wind farms altogether. Landscapes once devoid of industrial facilities are significantly transformed when they become 'planted' with the highly visible whirling towers, substations and transmission lines that comprise a wind farm.

Understandably, wind energy development remains a highly controversial energy topic. As discussed in Chapter 4, due to the scale of contemporary industrial wind turbine installations and their impacts on the social and physical environment, nearby communities express their concern and often react spiritedly and massively. Wind turbine installation opposition has become a worldwide phenomenon. Taking into account the environmental benefits and the enormous development of this industrial sector (as well as local interests, politics, alliances and particularities), there is a need to investigate the limitations of contemporary industrial scaling alongside its user-friendly attributes within the frameworks of STS and political ecology.

Scaling up wind energy technology is not only a matter of size magnification but, rather, a radical transformation of the way technological artefacts are used and operate. The scale of the economic and social environment in which they are manufactured and operate is also significant, causing the imbalances stated above (impacts). Hence, there is a need and opportunity to enrich existing policy frameworks (cf. Geel's multilevel perspective), by taking into account the effects of scale-up technology on governance.

Finally, there are further questions regarding the process of technological scaling. The radical transformation of "things" into "devices", as stated previously, should be further elaborated upon within the framework of the philosophy of technology.

6 Appendix: Wind Turbines Evolution[60]

1887: The first known wind turbine used to produce electricity is built in Scotland. The wind turbine is created by Professor James Blyth of Anderson's College, Glasgow (now known as Strathclyde University). "Blyth's 10 m high, cloth-sailed wind turbine was installed in the garden of his holiday cottage at Marykirk in Kincardineshire and was used to charge accumulators developed by the Frenchman Camille Alphonse Faure, to power the lighting in the cottage, thus making it the first house in the world to have its electricity supplied by wind power. Blyth offered the surplus electricity to the people of Marykirk for lighting the main street, however, they turned down the offer as they thought electricity was 'the work of the devil.'"

1888: The first known US wind turbine created for electricity production is built by inventor Charles Brush to provide electricity for his mansion in Ohio.

1891: A Danish scientist, Poul la Cour, develops an electricity-generating wind turbine and later figures out how to supply a steady stream of power from the wind turbine by use of a regulator, a Kratostate.

1895: Poul la Cour converts his windmill into a prototype electrical power plant. It is then used to provide electricity for lighting for the village of Askov.

By 1900: Approximately 2,500 windmills with a combined peak power capacity of 30 megawatts are being used across Denmark for mechanical purposes, such as grinding grains and pumping water.

1903: Poul la Cour starts the Society of Wind Electricians. He is also the first known person to discover that wind turbines with fewer blades that spin faster are more efficient than turbines with many blades spinning slowly.

1904: The Society of Wind Electricians holds its first course on wind electricity.

By 1908: 72 electricity-generating wind power systems are running across Denmark. The windmills range from 5 kW to 25 kW in size.

1927: Joe Jacobs and Marcellus Jacobs open a "Jacobs Wind" factory in Minneapolis, Minnesota. They produce wind turbines for use on farms, since farms often don't have access to the grid. The wind turbines are generally used to charge batteries and to power lights.

1931: A vertical-axis wind turbine design called the Darrieus wind turbine is patented by Georges Jean Marie Darrieus, a French aeronautical engineer. This

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[60] https://www.renewableenergyworld.com

type of wind turbine is still used today, but for more niche applications like on boats, not nearly as widely as horizontal-axis wind turbines.

1931: A horizontal-axis wind turbine similar to the ones we use today is built in Yalta. The wind turbine has 100 kW of capacity, a 32-meter-high tower, and a 32% load factor (which is actually similar to what today's wind turbines get).

1941: The first megawatt-size wind turbine is connected to a local electrical distribution grid. The 1.25-MW Smith-Putnam wind turbine is erected in Castletown, Vermont. It has blades 75 feet in length.

During World War II: Small wind turbines are used on German U-boats to recharge submarine batteries and save fuel.

1957: Jacobs Wind has now produced and sold approximately 30,000 wind turbines, including to customers in Africa and Antarctica.

1957: Johannes Juul, a former student of Poul la Cour, builds a horizontal-axis wind turbine with a diameter of 24 meters and 3 blades very similar in design to wind turbines still used today. The wind turbine has a capacity of 200 kW and it employs a new invention, emergency aerodynamic tip breaks, which is still used in wind turbines today.

1975: A NASA wind turbine program to develop utility-scale wind turbines starts. "This research and development program pioneered many of the multi-megawatt turbine technologies in use today, including: steel tube towers, variable-speed generators, composite blade materials, partial-span pitch control, as well as aerodynamic, structural, and acoustic engineering design capabilities. The large wind turbines developed under this effort set several world records for diameter and power output."

1975: The first US wind farm is put online, producing enough power for up to 4,149 homes.

1978: The world's first multi-megawatt wind turbine is produced by Tvind school teachers and students. The 2-megawatt wind turbine "pioneered many technologies used in modern wind turbines and allowed Vestas, Siemens and others to get the parts they needed. Especially important was the novel wing construction using help from German aeronautics specialists." (This wind turbine is still running today.)

1978: Danish wind turbine manufacturer Vestas produces its first wind turbine.

1978: The Public Utility Regulatory Policies Act (PURPA P.L. 95-617) is enacted in the US. PURPA requires that utilities interconnect renewable energy projects to the grid. It also requires that utilities purchase equal to “avoided cost,” the cost it would cost a utility to build its own power plant.

1980: Wind developer Zond is founded (eventually becomes GE Wind Energy).

1980: Wind turbine manufacturer Danregn Vindkraft is founded, spinning off from a Danish manufacturer of irrigation systems. It later becomes Bonus Energy and then Siemens Wind Power.

1980: The levelized cost of wind power is now $0.38/kWh in the United States.

1980: The world’s first wind farm including 20 wind turbines is put online

1980s: Denmark starts siting offshore wind turbines.

1980s: Enertech begins building 1.8 kW wind turbines that can connect to the grid.

1980s: Commercial wind turbine rotors get up to a diameter of 17 meters and a capacity of 75 kilowatts.

1981: A second wind farm goes up in the US. Total US installed wind power capacity is now approximately 10 megawatts, enough for approximately 8,575 homes.

1981: California implements tax credits for wind turbines.

1982: Four wind farms are online in the US, double the number from the year before, producing enough power for up to 13,500 homes.

1983: Danregn Vindkraft changes its name to Bonus Energy to better appeal to the US market it focused on.

1983: Eight wind farms are online in the US, double the number from the year before, producing enough power for up to 109,000 homes, over a dozen times more than two years prior.

1984: Fifteen wind farms are online in the US, almost double the year before, producing enough power for up to 146,000 homes.

Enercon is founded. It eventually becomes Germany’s largest wind turbine manufacturer, and it remains in that position today.

1986: California tax credits for wind turbines expire.

1986: Vestas, which had previously focused on other types of machines (dating back to 1898), decides to focus 100% on the wind turbine market. It forms Vestas Wind Systems A/S and sells off its other business arms.

1987: A 3.2-megawatt wind turbine is developed by the NASA wind turbine program. It has “the first large-scale variable speed drive train and a sectioned, two-blade rotor,” which allows for easier transport.

1990: The Solar, Wind, Waste, and Geothermal Power Production Incentives Act of 1990 is enacted to amend PURPA and remove size limitations on renewable energy power plants qualifying for PURPA benefits.

1990: 46 wind farms are online in the US, providing enough power for up to nearly 300,000 homes.

1990s: Durability and performance become more important for customers, so tubular steel and reinforced concrete towers are used underneath wind turbines.

1991: Vestas sells its 1,000th wind turbine.

1991: The first offshore wind farm in the world is constructed in southern Denmark. It includes 11 wind turbines manufactured by Bonus Energy, each with a capacity of 450 kW.

1991: The UK's first onshore wind farm is constructed in Cornwall. The wind farm includes 10 wind farms that together produce enough electricity for approximately 2,700 homes.

1992: The United States implements the Production Tax Credit (PTC) for wind power. The PTC incentives electricity production rather than simply incentivizing installation (which resulted in problems with performance and reliability). In the initial years, wind power producers get paid 1.5¢ per kWh for electricity they produce for the first 10 years of operation. The PTC is a key incentive, probably the most important incentive, driving wind power growth across the US in the coming years. Though, Congress lets it expire before reinstating it several times, leading to a boom-bust cycle and limiting its overall effect.

1994: Vestas rolls out OptiSlip with a new wind turbine. OptiSlip allows the wind turbine to supply a constant current of electricity to the electric grid.

1994: Gamesa Eólica, a subsidiary of Spain-based Gamesa Corporación Tecnológica (which was formed in 1976 to develop new technologies and apply them to emerging activities), is formed in order to manufacture wind turbines. The next year, it also starts developing wind power projects.

1995: Vestas produces its first offshore wind turbine.

1995: Suzlon Energy is founded in India to manufacture, install, and operate wind turbines.

1995-2000: Commercial wind turbine rotors get up to a diameter of 50 meters and wind turbines get up to a capacity of 750 kilowatts, 10 times more than approximately 10 years ago.

1996: Global wind power capacity reaches 6,100 megawatts.

1997: Enron acquires Zond and German wind turbine manufacturer Tackle.

1998: Global wind power capacity reaches 10,200 megawatts.

1998: China-based Goldwind is formed to manufacture wind turbines.

1998: Vestas goes public, putting out an initial public offering (IPO) on the Copenhagen Stock Exchange.

1999: Vestas launches a wind turbine with "OptiSpeed," which makes it suitable for low-wind sites.

2000: 97 wind farms are online in the US, providing enough power for up to 592,000 homes. US installed wind power capacity is up to 2,554 megawatts.

2000: An order for 1,800 Vestas wind turbines, the largest wind turbine order in the world, is made by Spain's Gamesa.

2000: Gamesa goes public with an initial public offering (IPO) on the Bolsa de Madrid.

2000: Global wind power capacity reaches 17,400 megawatts.

2002: GE acquires Enron Wind during Enron's bankruptcy proceedings. (GE Wind Energy eventually becomes the #1 wind turbine manufacturer in the world in 2012.)

2002: 149 wind farms are online in the US, providing enough power for up to 1.1 million homes.

2002: Global wind power capacity reaches 31,100 megawatts.

2003: The UK's first offshore wind farm opens in north Wales. It includes 30 wind turbines, each with a power capacity of 2 megawatts.

2004: Vestas and NEG Micon merge. Afterwards, Vestas commands 34% of the wind turbine market, far more than any other country.

2004: Siemens acquires Bonus Energy (originally called Danregn Vindkraft). ("Between 2004 and 2011, Siemens grew wind power from 0.5% to 5% of the combined Siemens turnover, with employees growing from 800 to 7,800.")

2005: 226 wind farms are online in the US, providing enough power for up to 2.2 million homes.

2005: Global wind power capacity reaches 59,091 megawatts.

2007: The UK announces plans to install thousands of offshore wind turbines, enough to provide electricity for every home in Britain by 2020.

2007: Global wind power capacity reaches 93,820 megawatts.

2008: 416 wind farms are online in the US, providing enough power for up to 6.5 million homes.

2008: Nearly 2000 wind farms are in operation across the UK, producing enough electricity for over 1.5 million British homes.

2008: Global wind power capacity reaches 120,291 megawatts.

2009: The first large-capacity floating wind turbine in the world begins operating off the coast of Norway. It uses a Siemens wind turbine and is developed by Statoil.

2009: The Roscoe Wind Farm in Texas becomes the largest wind farm in the world. It has a power capacity of 781.5 megawatts and includes 634 wind turbines. (Part of the Roscoe Wind Farm pictured above.)

2009: An investment tax credit is implemented for manufacturers of wind power products. The 30% tax credit is part of the American Recovery and Reinvestment Act of 2009.

2009: Under the American Recovery and Reinvestment Act of 2009, $93 million is dedicated to wind power research and development. “$45 million will go towards wind turbine drivetrain R&D and testing, $14 million for technology development, $24 million for wind power research and development, and $10 million for the National Wind Technology Center. Along with this funding the National Renewable Energy Laboratory (NREL) will receive more than $100 million from ARRA.”

2009: New wind power projects in the US are eligible for a 30% grant from the US Treasury Department to help cover the cost of the projects and stimulate economic activity. The grant program is part of the American Recovery and Reinvestment Act of 2009, and is only available for projects placed in service by the end of 2010.

2009: New wind power projects in the US are eligible for a 30% Investment Tax Credit (ITC) in place of the PTC if they prefer. The grant program is part of the American Recovery and Reinvestment Act of 2009, and is only available for projects placed in service by the end of 2013.

2010: 581 wind farms are online in the US, providing enough power for up to 10 million homes.

2010: The median levelized cost of wind power is now $0.08/kWh in the United States, approximately 21% what it was in the 1980s. (The minimum is $0.06/kWh.)

2010: The US Department of the Interior signs the first lease for an offshore wind energy project, Cape Wind.

2010: China passes US to become the country with the most cumulative installed wind power capacity in the world. Charts of new and cumulative wind power capacity by country are as follows:

2010: Global wind power capacity reaches 197,039 megawatts.

2011: The Siemens Wind Power division is formed.

2011: The median levelized cost of wind power is now $0.07/kWh in the United States. (The minimum is $0.05/kWh.)

2011: Commercial wind turbine rotors get up to a diameter of 126 meters and wind turbines get up to a capacity of 7500 kilowatts, approximately 100 times more than in the 1980s.

2011: Japan plans a multiple-unit floating wind farm (6 wind turbines, each with 2 megawatts of capacity). By 2020, Japan intends to have up to 80 floating wind turbines off its coast near Fukushima.

2012: The Alta Wind Energy Center in California becomes the largest wind farm in the world. It has a power capacity of 1,320 megawatts, with plans to increase that to 3,000 megawatts. It includes 440 wind turbines at the end of 2012.

2012: 815 wind farms are in operation in the US, with a total power capacity of about 60 gigawatts, enough to power up to 15 million US homes.

2012: Wind power becomes the #1 source of new power capacity in the US. 45,100 wind turbines are installed in the US this year, accounting for 42% of all new US power capacity.

2012: The US again becomes the world's largest wind power market.

2012: Installed wind power capacity in China reaches 75 gigawatts, the most in the world for a single country.

2012: The UK has over 3 gigawatts of offshore wind power capacity installed, the most in the world and over three times more than Denmark, which comes in second.

2012: Global wind power capacity reaches 282,587 megawatts.

2012: Wind power now producing over 30% of Denmark's electricity needs.

2012: Vestas produces its 50,000th wind turbine, and its wind turbines installed around the world reach 50,000 megawatts of power capacity.

2013: The median levelized cost of wind power is now \$0.06/kWh in the United States, approximately 15% what it was in the 1980s. At \$0.06/kWh, the price of electricity.

2013: The world's first hybrid wind/current-powered turbine is installed off the coast of Japan.

2013: The London Array wind farm is completed in the UK. The London Array becomes the largest offshore wind farm in the world. It includes 175 wind turbines for a total capacity of 630 megawatts of power capacity, enough to cover the annual electricity consumption of 480,000 British homes.

2013: GE produces wind turbines that incorporate energy storage.

2013: 54% of Spain's electricity comes from renewable energy, mostly wind energy, in one month (April).

2013: China again passes the US to become the world's largest wind power market.

2013: Wind power becomes China's third-largest source of power, passing nuclear power.

2013: Wind power produces more electricity than any other source in Spain for three months in a row, is now providing the country with approximately 25% of its electricity.

2013: The first offshore wind turbine in the US is launched.

2020: 8 models, either offshore or onshore from 10 – 15 MW are currently offered in the market by the following manufacturers, SCD technology, BEWIND, GE General Electric, MingYang and Siemens Gamesa.

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