Introduction, trends and key messages

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Utilizing wind for energy has a long history, but the oil crisis of the 1970s led to what we now understand as modern wind energy. The development started along two separate routes [1]: a highly technological approach involving large wind turbines (1-5 MW), developed by aerospace and engineering construction companies; and a more trial-and-error approach driven by pioneering companies and individuals in Denmark, starting with smaller wind turbines (10-50 kW). The first failed commercially and to some extent also technically, leaving the second to lay the foundations of the modern wind-energy industry. The evolution of the wind energy sector has been remarkable in respect of its technological advances, cost reductions and deployment. The latter has been facilitated by a combination of technology-push and market-pull incentives and mechanisms in a triple-helix approach involving collaboration between industry, knowledge institutions and policy-makers.

Wind energy today is an integral part of the electricity system and thereby subject to requirements regarding power quality and reliable operation. The technology is cost-competitive while still rapidly developing. The scale is constantly increasing, with higher hub heights, larger rotors and operation at little-known heights and in unfamiliar waters and climates. In a scenario envisaging 100% renewable energy, the value of wind energy goes beyond the electric power sector to become the energy source for green fuels and gases for use in sectors that are otherwise difficult to decarbonize. Wind energy taps directly into the mission to reach net-zero emissions by 2050: it is thus a key instrument for the Paris Agreement in seeking to keep the future global temperature increase well below 2°C.

This chapter addresses the need to scale up zero-emission energy technologies, technology trends and markets for wind energy. It introduces the four parts into which the report is divided: wind-energy systems, turbine technologies, materials and components, and cross-cutting issues. It concludes with a number of key messages to accelerate the development of wind energy further, including its value to the energy system and to society at large.

**Need to scale up zero-emission energy technologies**

The recent report by the UN Intergovernmental Panel on Climate Change (IPCC) is a wake-up call on climate change, which is happening much faster than originally anticipated [1]. Unless there are immediate, rapid and large-scale reductions in greenhouse gas (GHG) emissions, limiting global warming close to 1.5°C or even 2°C will be beyond our reach. What countries are currently doing is far from enough. According to the UNEP Gap 2020 report, 127 countries, representing 63% of global GHG emissions, have adopted, announced or are considering adopting net-zero goals, but there is a huge gap between these goals and the National Determined Contributions (NDC) that have been issued [2]. Emissions in 2030 will put the world on the path to a 3.2°C increase this century, even if all unconditional NDCs are fully implemented. Therefore, ambitions must be roughly tripled for the 2°C pathway and increased at least fivefold for the 1.5°C pathway.

How to reach net-zero emissions by 2050, and in particular the role of the energy sector in this goal, has been thoroughly analysed [3]. The pathway
should be technically feasible, cost-effective and socially acceptable and combine short and longer-term actions. Up to 2030, this includes strong incentives for and the deployment of clean energy technologies and disincentives for fossil-fuel technologies. Net-zero emissions by 2050 will also require massive new energy technologies and innovation in critical areas such as electrification, hydrogen, bioenergy and carbon capture, utilisation and storage (CCUS).

Wind energy is playing a key role in accelerating the global energy transition. The general trend reflects the fact that the share of wind energy must increase from roughly 6% of the global power mix now to more than 30% by 2050 to come near to achieving a pathway to well below 2°C [4]. The IEA’s Net-Zero by 2050 report foresees a renewable share of 61% in 2030 and 88% in 2050, corresponding to annual installations of wind power of 390 GW/year in 2030 and 350 GW/year in 2050 [3].

Long-term energy scenarios differ when it comes to the scale of electrification needed for a net-zero emissions pathway. In scenarios with higher shares of electricity generation, wind power and other renewables, when combined with indirect electrification (green hydrogen and other Power-to-X fuels (PtX)1), are the cornerstone of the transition. DNV has projected the share of wind energy in total electricity generation by 2050 by region and distinguishes between onshore wind, fixed offshore wind and floating wind energy [5]. By 2050, wind energy is expected to provide 50% in Europe, 44% in North America and more than 30% of electricity in Greater China, Latin America and South East Asia, as shown in Figure 1.

A similar forecast for the EU has been made by ETIPWind and WindEurope, which predicts 50% of wind power in the electricity mix by 2050 [6]. Likewise, the Nordic Clean Energy Scenarios 2050 by Nordic Energy Research predicts wind power to grow from 15% of total generation in 2020 to almost 50% in 2050 in the Nordic region [7].

**Technological trends**

Turbines continue to increase in height and capacity. The average size of newly installed wind turbines in the period 1994-2021 is shown in Figure 2, increasing from 0.5 MW in 1995 to 6.5 MW in 2020 [8]. In Europe in 2020, the average size for onshore wind in this period was 3.3 MW and for offshore wind 7 MW. New offshore sites announced 13 and 14 MW turbine sizes in 2020, which will be delivered by GE 13 MW Haliade-X and Siemens Gamesa 14-222 DD turbines. Recently, MingYang has announced that they will run a pilot for a 16 MW turbine in 2023.2

Rotor diameters are also increasing for wind turbines in general. In the EU, the rotor size for onshore wind had an average size of 108 m in 2018,

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1 PtX refers to electricity conversion and reconversion processes used to produce and store fuels, with the ‘X’ denoting the resulting fuel. Options include ‘power-to-’ hydrogen, ammonia, chemicals, fuel, gas, liquid, methane, food and syn-gas.

the majority of rotors being between 75 and 150 m. For offshore wind, the rotor size in 2018 averaged 149 m, the majority of rotors being above 150 m [9]. The largest offshore turbines so far announced have a rotor size of 220 for GE, 222 m for SGRE, 236 m for Vestas and 242 m for MingYang.

Capacity factors are also increasing over time, as shown in Figure 3 for offshore globally, from 38% in 2010 to 43% in 2018. The projection is to have a factor of up to 58% in 2030 and 60% in 2050 [10].

The capacity factors for onshore wind have an average of 25%. The highest capacity factor for land-based wind in 2020 was reached in Norway (37%), the UK and Finland (35%), followed by the US, Sweden, Canada, Denmark and Ireland at more than 30% [8].
Development of levelized cost of energy (LCoE) has been remarkable in recent years. The growth in wind-energy capacity has been accompanied by decreasing costs of wind energy, not least from 2014 to 2019, as shown in Figure 4.

Historically the LCoE has been driven by energy production, capital costs (CapEx), operating costs (OpEx), the cost of financing and the lifetime of the technology [9]. Energy production is the outcome of site-specific wind resources and the choice of turbine technology.

Capital costs cover the turbine, the balance of system (such as foundation, electrical infrastructure and access infrastructure) and soft costs (construction financing and contingency funds). They also depend on commodity prices for, e.g., steel and cement, as well as labour costs, but also the economies of scale of large wind-energy projects. Operating costs include the costs of management, maintenance and repair, as well as insurance and lease payments for land or ocean. Financing costs depend on the market, the perceived risk of the investment, the type of investor and national (jurisdiction-specific) policies and tax structures. In OECD countries, discount rates typically vary by 3-11% for onshore projects and 6-13% for offshore projects. For non-OECD countries, the rate may be ~3% higher for onshore wind [11]. Finally, the lifetime of the wind turbine matters. It is typically 20 years, but may be extended to 25 years or even beyond 30 years.

The CapEx and OpEx cost components of onshore and fixed-bottom offshore wind are shown in Figure 5. For onshore wind energy, the turbine represents half the costs, and operation and maintenance (O&M) account for approximately 29%. For offshore wind, O&M represents 34% of the costs, and the balance of system 37% due to expenditures for sub-structures, array cables and export cables; the turbine costs, by contrast, only represent 19%. Financing costs vary widely across countries and with time.

The potential for further cost reductions is considerable. A recent study shows that experts judge future onshore and offshore wind costs to decline by 37-49% by 2050, as shown in Figure 6 [12]. In comparison, DNV expects cost reductions for onshore and offshore wind to be 42-80% by 2050, meaning that cost reductions are predicted to be higher for both fixed offshore (44%) and floating offshore (80%) [5]. WindEurope predicts cost reductions for wind energy in Europe to be 45% for onshore, 57% for bottom-fixed and 78% for floating offshore wind by 2050 [6]. In the case of onshore wind, this is due to more rapid approvals, larger turbines and repowering at the best sites. For bottom-fixed offshore, economies of scale, bigger turbines and improvements in O&M matter, as do industrialization, knowledge transfers from offshore installations and economies of scale.

The factors influencing LCoE reductions are better site characteristics and growth in turbine size. Onshore turbines are expected to have a capacity of 5.5 MW by 2035, a hub height of 130 m and a rotor diameter of 174 m. Offshore turbines are expected to have a capacity of 17 MW by 2035, with a hub height of 151 m and a rotor diameter of 250 m, as shown in Table 1.
Markets

The historical development of new installations (GW) shows that the annual growth rate was +22% from 2001-2010, of which only 1% was offshore. From 2010-2015 the annual growth rate was +10%, but with ~3% offshore. Since 2015 the annual growth rate has been 8%, but with offshore shares of 5-10% [4]. 2020 added ~90 GW, bringing the total turbine capacity to 743 GW. This growth was led by China. In terms of cumulated installations, the top five markets in 2020 therefore continue to be China, the US, Germany, India and Spain, which between them account for 73% of all wind power installations [4].

In 2020³ the top ten wind-turbine manufacturers acquired a new leader: US manufacturer GE Renewable Energy benefited from a strong domestic


Table 1. Expected relative turbine size 2035 for on- and offshore wind compared to 2019 [12]

<table>
<thead>
<tr>
<th></th>
<th>Onshore</th>
<th>Offshore</th>
</tr>
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<tbody>
<tr>
<td>Capacity MW</td>
<td>2.5</td>
<td>6.0</td>
</tr>
<tr>
<td>Rotor diameter m</td>
<td>120</td>
<td>150</td>
</tr>
<tr>
<td>Hub height m</td>
<td>89</td>
<td>103</td>
</tr>
<tr>
<td>Total height m</td>
<td>149</td>
<td>178</td>
</tr>
<tr>
<td>Specific power W/m²</td>
<td>221</td>
<td>340</td>
</tr>
</tbody>
</table>
Next is Goldwind, which was successful primarily in its home country of China. In the third place is the former leader Vestas, followed by Envision and Siemens Gamesa. However, the difference between the top three manufacturers is small. Together the top ten accounted for over 75% of the total global installed capacity of 96.36 GW in 2020.

Markets for wind turbine technologies are one thing, the share of wind energy in the electricity system quite another. In 2020, Denmark had the highest share of wind (56.34%), followed by Lithuania (36.8%) and Ireland (35.13%). Next came the UK (24.15%), Germany (23.71%) and Spain (20.91%). The US, China and India had 8.31%, 6.12% and 4.5% respectively of wind power in their electricity systems (see Figure 7).

Perspectives on wind energy

Confronted with the tremendous challenges that lie ahead in reaching net-zero emissions by 2050, and taking into account the technology and market trends for wind energy, this report presents DTU Wind Energy’s multifaceted, comprehensive contributions to this mission. As a starting point, it summarizes the RD&D challenges as described by the international wind energy communities and describes the wind energy eco-system and the key characteristics of the evolving wind energy RD&D in general and DTU in particular.

The report structure follows the organization of DTU Wind Energy into three divisions, but also covers some cross-cutting activities:

Part I. Wind energy systems provides new knowledge and research that aim to maximize the value of wind energy systems combining wind characteristics, socio-economics, and system integration and optimization.

Part II. Wind energy technologies describes developments in the technical-scientific foundation for larger, more cost-effective and reliable wind turbines in the future, together with their development and validation.

Part III. Materials and components focuses on the development of the next generations of sustainable materials, components and structures to minimize the footprint left by wind energy technology.

Part IV. Cross-cutting issues describes efforts to integrate sustainability in all aspects of wind energy, as well as two important pillars of DTU, namely research-based education and scientific advice.

Key messages
Wind energy has a decisive role to play in the transition to net-zero energy. First and foremost, it is central to the direct electrification of all end-use sectors, covering transport, housing and industry. Indirect electrification in terms of PtX fuels for hard-to-abate sectors such as heavy-duty transport and heavy industries will increase the demand for cheap wind energy, as 50-70% of green hydrogen costs are associated with the price of power [13]. The history of modern wind energy has demonstrated the impressive development in cost reduction, scale, capacity and deployment driven by an intelligent combination of technology-push and market-pull mechanisms. The future development will be even more dramatic and will need ambitious and continuous public and private investment in RD&D, as well as strong engagement and cooperation in the further development of wind energy technologies and systems.

The key messages from this report are to prioritize the mission-driven RD&D across the whole wind-energy value chain, covering cumulative research, uncertain research and collaborative research.

Cumulative research into wind energy technologies and systems should add to the existing body of knowledge and succeed in driving down the costs of energy, increase the social value of wind energy and address the sustainability challenges:

- Easing the siting of wind farms by means of advanced wind atlases with data layers such as extreme winds, turbulence intensities and flow inclinations to determine wind turbine design requirements.
- Although the LCoE continues to be an important driver for improvements to wind energy, the social value of wind energy requires flexible orientation allowing for a broader scope of optimization variables, such as the technology mix, the development of the whole energy system, the supporting regulatory and market framework and citizen engagement.
- Facilitating co-existence between wind energy and other activities.
- Transforming the [offshore] infrastructure by combining transmission with storage and/or local demand, and moving from grid-following to grid-forming converters.
- Further developing advanced systems engineering and optimization of the wind energy system with high levels of coupling of the individual wind-turbine level and at the wind-farm level.
- Upscaling wind turbines through further improvements in aerodynamic performance, loads, dynamic response and stability. Combining sensors, data and digitalization to help the design process, as well as the wind farm’s cost-effective, safe operation and efficient through-life management and maintenance. More intelligent adaptive rotors and more durable and safer solutions to combat leading-edge erosion.
- Further improving floating offshore wind farms with cost-efficient floater designs, including continued validation of models, test methods and innovations in rotor design, mooring systems, cables and installation methods, logistics and weather-window planning.
- Providing advanced structural testing as a foundation for our in-depth understanding of complex structural behaviour, based on which reliable, efficient numerical models will be developed and validated.
- Developing the entire wind energy conversion process further, supported by well-validated IT programmes and model experiments, as well as full-scale tests of components and entire wind turbines.
- Better understanding of the behaviour of materials in order to develop better materials models for the future design of wind turbine components (blades), as well as to understand the basic materials properties to develop new composite materials with improved properties.
- Developing metrics, methods and solutions to integrate sustainability into all aspects of wind energy, including e.g. life extension, 100% recycled wind turbines, reduction or substitution of materials and resources, and the social aspects.
- Providing research-based education of wind energy engineers to global markets.
- Collaborating with industry and end-users to develop reliable international standards for renewable energy.
- Transferring and adapting knowledge of wind energy to new settings and actors while balancing conflicting geopolitical interests and the need to accelerate technological development.
There is also a need for uncertain research, that is, basic research the outcome of which is far from assured. It may also bring high risk/high rewards to the field. This would not necessarily duplicate previous trial and error procedures in the wind energy sector, but rather be based on scientific methods of exploring the unknowns and taking advantage of advanced models and key enabling technologies such as digitalization, artificial intelligence, advanced sensors and autonomous systems.

There is no doubt that the collaborative capability of the Danish wind energy sector has helped advance the technology and positioned Danish knowledge producers (OEMs) and users (developers and utilities) on very competitive global markets. With the launch of the energy islands in Danish waters by 2033, collaborative efforts will be further tested in terms of planning, designing, constructing and operating this large type of wind energy infrastructure in the future. Likewise, cooperation across borders is needed with neighbouring countries in respect of planning, grids and market mechanisms. Finally, and in line with previous practice, international RD&D will contribute to avoiding overlaps, filling in gaps and bringing the best minds on board to solve the unknowns.

References