CHAPTER 10

Wind Power Generation

Anselm Eicke, Laima Eicke, and Manfred Hafner

1 Introduction

Wind energy has been deployed for several thousand years. The kinetic energy of moving air was driving propeller boats in ancient Egypt, pumping water in ancient Persia and later employed to grind grains across the Eurasian continent. The first windmill for electricity production was built in Scotland in 1887. Pioneer projects followed in the US and several European countries. Wind turbines as known today were only developed in the second half of the twentieth century.

Since the early 2000's, global wind energy installations have experienced high growth rates. Globally installed wind capacity grew more than six-fold in the past decade from 100 GW in 2008 to more than 620 GW in 2019. Worldwide, wind power is the second largest deployed renewable energy

A. Eicke (✉)
Hertie School, Berlin, Germany
e-mail: anselm.eicke@daad-alumni.de

L. Eicke
Institute for Advanced Sustainability Studies (IASS), Potsdam, Germany

Harvard University - Harvard Kennedy School, Boston, MA, USA
e-mail: Laima.Eicke@iass-potsdam.de

M. Hafner
SciencesPo—Paris School of International Affairs, Paris, France

Johns Hopkins University SAIS Europe, Bologna, Italy

Fondazione Eni Enrico Mattei (FEEM), Milan, Italy
e-mail: mhafner@johnshopkins.it

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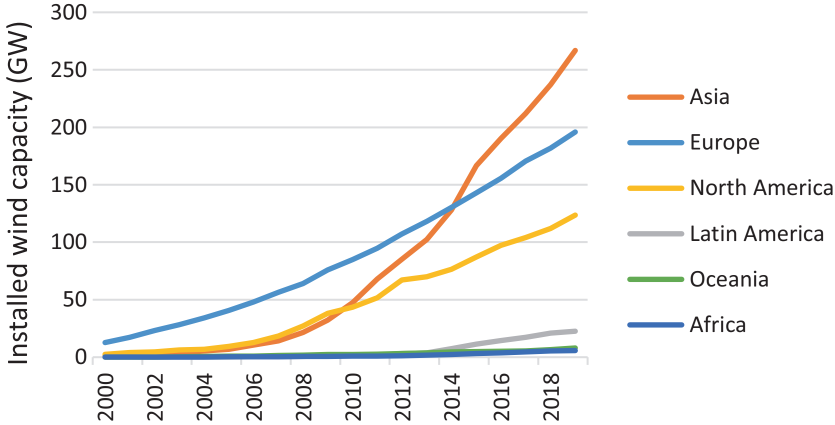

Fig. 10.1 Installed wind capacity per region (onshore and offshore combined). (Authors' own elaboration, data from IRENA 2020)

technology after hydropower, and is placed second in terms of capacity additions with 51 GW added in 2018, only surpased by solar energy (IEA 2020). Wind energy is distinguished between onshore and offshore depending on the location of turbines. Yet, as of 2018, offshore wind accounts for only 4.1% (24 GW) of the total installed wind capacity (IEA 2019).

The global wind energy market is dominated by Asia, where 41% of the global capacity is installed (Fig. 10.1). Asia overtook Europe in 2014, which was previouosly driving the expansion of wind power and accounted for 75% of global capacity in the early 2000's. North America ranks third with 112 GW installed in 2018. Despite huge potential, wind energy currently plays only a minor role in other continents (IRENA 2020). Wind energy makes up merely 6% of the world's electricity generation in 2018; yet, the international renewable energy agency (IRENA 2020) expects wind power to become the largest source of power generation in 2050, when about 35% of electricity supply may stem from wind energy (IRENA 2019).

Compared to onshore wind, offshore wind energy technologies had their technological break-through significantly later. The first larger-scale wind parks were installed along the coast lines of the North Sea and the Atlantic Ocean only in 2010. These two areas still encompass 90% of installed offshore wind capacity (IRENA 2020). Between 2010 and 2018, the global offshore wind market grew nearly 30% per year and it is expected to expand significantly in the upcoming years, with most capacity additions in 2018 located in China, North America, and Oceania (IEA 2019). IRENA projects the strongest growth of wind power in Asia where more than 50% of global wind energy capacity will be located in 2050. According to these projections, 23% of total installed onshore capacity will be located in North America and about 10% in Europe (IRENA 2019). For the offshore wind sector, projections also see Asia at the forefront in 2050, accounting for 60% of total installed capacity, followed by Europe (22%) and North America (16%).

2 Technical Characteristics

Wind turbines convert the kinetic energy of moving air into electricity. As the blades of a wind turbine are set in motion, their rotation turns a turbine. This rotational energy moves the shaft connected to the generator, producing electrical energy.

Modern wind turbines consist of three key components: the tower, the nacelle, and the rotor blades. The nacelle serves as the heart of the turbine. It encompasses the machine set, which includes the rotor hub, a generator, and the gearbox. The rotor blades are connected to the gearbox, or sometimes also directly to the generator, via a shaft. Electrical equipment allows adjusting the angle of the blades to limit electricity generation at high wind speeds and to optimize the output at changing wind speeds.

Abstracting from technical details, the power output of wind turbines mostly depends on two parameters: the wind speed and the length of the rotor blades. Because the electricity output of wind turbines is proportional to the swept area of the rotor blades, a doubling of the blade length squares the wind power potential. The energy output also raises proportionally to the third power of the wind speed. Doubling the wind speed thus leads to an increase in power potential by a factor of eight. This indicates that the hub height, that is, the length of the tower, is a crucial design parameter of wind turbines because wind speeds usually increase with height from the ground. In general, higher towers therefore improve the yield of wind turbines. Aside from height above the ground, wind speed also varies strongly across regions. The location of the installation is thus of key importance for the economics of wind energy. In general, coastal areas benefit from higher wind speeds compared to landlocked regions. This drives the deployment of offshore wind turbines despite the significantly higher technical complexity and costs. Offshore wind turbines are mostly fixed, and still rarely floating. Fixed turbines have their foundation on the ocean ground and they are therefore only deployed in shallow coastal areas. Floating offshore turbines are a less mature technology based on experiences made in the oil and gas sector. They allow harvesting wind energy farther offshore in deep waters. Only in 2017, the world's first commercial floating wind farm started operating in Scotland.

Technological improvements focus on increasing rotor diameters and the hub height to increase the power output of wind turbines. Yet, there is a trade-off between these two parameters: the higher the tower, the less weight it can hold due to turbulences caused by higher wind speeds. The firmness of construction materials sets limits to these efforts. The efforts to increase efficiency have been guiding technological development and led to significant cost reductions during the past decades: tower heights vary between 50 and 200 m, and average rotor diameters have more than doubled from 50 m in 2000 to 110 m in 2018. These improvements led to an increase in the average capacity by 250% (IRENA 2019). This trend is expected to continue: in the early 2020s, the largest windmills are expected to reach capacities of 12.5 MW and rotor diameters of up to 220 m. Nameplate capacities of future wind turbines are expected to further increase (GE Renewable Energy 2020).

The development of wind energy markets started in windy countries, including Denmark, Germany, and the UK. While the windiest locations are gradually filled by wind farms, renewable energy developers increasingly focus on locations with medium and low wind speeds (see below, the section on technical potential). Manufacturers have started developing new turbine designs specifically for these lower wind-speed sites. This is mostly achieved by increasing the height of towers. But the size of the generator also yields trade-offs: combining a small generator (with low rated capacity) with large blades, leads to a higher capacity utilization at low wind speeds, resulting in a more constant generation profile. This facilitates the integration of wind energy into the power system (see Sect. 10.5). The downside of such low wind-speed turbines is that not all the kinetic energy of wind is converted into electricity at high wind speeds. In turn, bigger (and more costly) generators produce significantly more electricity in times of high wind speeds, but are oftentimes underused. By now, wind turbine manufacturers offer a wide range of turbine sets, optimized for specific wind conditions.

Trends going beyond rising average tower heights and rotor diameters include new, aerodynamic profiles of blades and new materials, in order to increase durability and reduce maintenance costs also in demanding locations such as deserts or high seas (IRENA 2019). Digitalization drives predictive algorithms based on big data. These optimize the positioning of turbines in the wind and improve monitoring and control systems, further reducing maintenance costs (Wood Mackenzie 2019). Improvements in terms of sustainability and cost reductions could be achieved by recycling various materials. Pioneer projects have shown promising results for example, by recycling expensive fiberglass components of wind turbines (IRENA 2019).

3 Technical Potential of Wind Energy

Wind energy potential, often expressed as the mean wind speed of a location, is unequally distributed around the globe (Fig. 10.2). The power output of wind turbines thus varies strongly between locations. Generally, wind resources of higher quality for energy production are close to the poles; the lowest potential is close to the equator. The most promising areas in Europe are in the north, for example, in the North and Baltic Seas; the coasts of South America and New Zealand equally bear large potentials (Fig. 10.2).

Today's wind installations are far from tapping this huge theoretical potential. In theory, the most lucrative sites could provide more than today's total electricity consumption worldwide (IEA 2019). In practice, land usage conflicts, citizens' opposition, and environmental regulations limit deployable

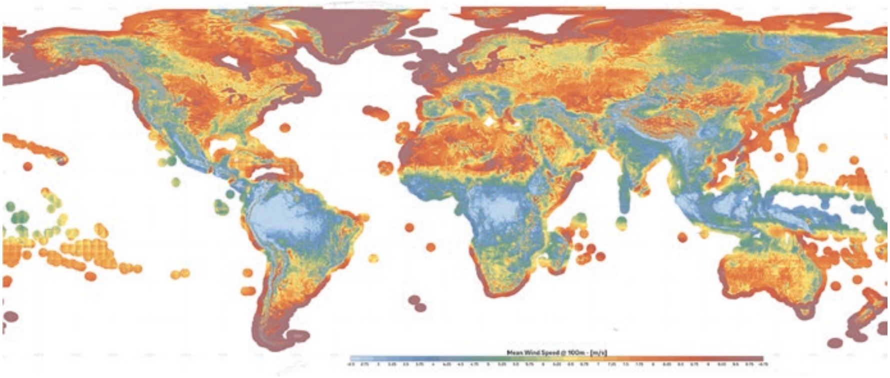

Fig. 10.2 The global wind energy potential shown as mean wind speeds 100 m above ground. (Source: Global Wind Energy Atlas 2019)

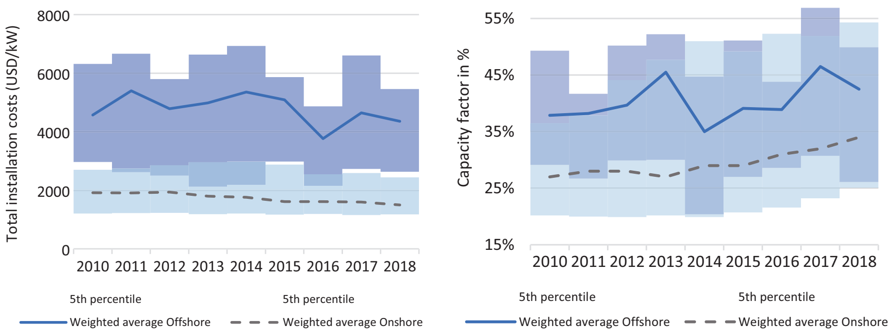

Fig. 10.3 Global average installation cost and capacity factors of onshore and offshore wind energy between 2010 and 2018. The shaded areas show the 5% to 95% quantiles in each year. (Authors' own elaboration, data from IRENA 2020)

land. These limitations are in particular hindering the rapid deployment of onshore wind and are often less relevant for offshore wind.

Wind speeds vary not only by region but also over time. Most of the time, wind farms do not generate electricity at full capacity. The capacity factor indicates how much electricity a wind turbine generates on average per year. It is defined as the actual electricity generation divided by the maximum theoretical electricity generation, that is, the power output if the turbine always generated at nameplate capacity. The higher the capacity factor, the more electricity a wind turbine produces. Typical capacity factors of onshore wind power range between 30% and 40%, with an average of 34% in 2018 (Fig. 10.3). The highest values are achieved in favorable sites and with newer wind turbine designs. In particular, coastal areas feature higher levels of wind speeds than landlocked regions, and offshore wind power's electricity generation is usually significantly higher per unit of capacity installed. Capacity factors of offshore wind farms range between 35% and 65% with an average of 43% in 2018. Some of the highest levels are reached in the North and Baltic seas in Europe (IEA 2019). Next to sites, also the turbine's design affects the capacity factor as we have discussed in the previous subsection.

4 Costs of Wind Energy

In comparison to electricity generation from fossil fuels, wind power is much more capital-intensive. Because wind power has no fuel cost and has comparatively low cost for operation and maintenance, the largest cost-components of wind turbines are investment and finance costs. This makes wind power plants particularly dependent on good financing conditions and low cost of capital.

The installation cost of wind energy varies strongly between countries. For example, the average total installation costs for onshore wind farms ranged between USD 1170 per kW in China and USD 2030 kW in the UK in 2018 (IRENA 2019). The main reason for this difference is the market structure of wind energy components. Blades and towers of wind turbines are bulky and difficult to transport; they are therefore usually produced locally. Consequently, their prices vary strongly among countries. By contrast, electrical equipment such as the nacelle, including generator and transformers, is shipped around the world and cost differences for these parts are smaller. The most expensive component of wind power plants is the turbine, followed by grid connection and the foundation (EWEA 2009).

On average, installation costs of onshore wind projects have been falling by 22% between 2010 and 2018 (Fig. 10.3, left) and are expected to further decline. The cost decline for onshore wind was mainly driven by technological advancement in turbine technologies, measured by high learning rates (IRENA 2017; Williams et al. 2017). These were fostered by public investment in research, development, and demonstration in several key markets (Klaassen et al. 2005; Zhou and GU 2019). Especially larger generators and longer blades increased power output and led to a decline in the specific (per capacity) costs. At the same time, average capacity factors of onshore wind turbines increased from 27% to 34% (Fig. 10.3, right). This is due to better-informed selection of sites and to developments of new turbine designs, better adapted to lower wind speeds.

Offshore wind parks are much more costly to construct than onshore installations. Grounding wind turbines on the sea requires expensive equipment, including for example specialized ships. Similarly, maintenance throughout the turbine's lifetime is more complex than for onshore installations due to the challenging accessibility. In terms of installation costs, the average cost of offshore energy is about three times higher than for onshore energy (USD 4360 per kW compared to USD 1500 per kW, Fig. 10.3, left panel) (IRENA 2019). But the costs of offshore wind projects have also been decreasing in recent years, for reasons similar to onshore wind. Particularly strong improvements were achieved in reducing operation and maintenance costs. Further cost decreases of offshore wind energy are expected due to high investment plans in China, likely to result in further technological improvements.

The levelized cost of electricity (LCOE) is a metric for the average cost of power generation. The LCOE is the ratio of all costs divided by the generated electricity produced over the lifetime of the plant. It therefore captures declines in costs and also technological improvements in the form of higher capacity factors. Note that LCOE is a useful metric for the cost improvements within a technology, but it should not be used to compare different generation technologies because it neglects the time-value of electricity, that is, the value that wind power offers to the electricity sector in terms of offsetting other electricity costs. LCOE of wind energy declined as technological improvements had a decreasing effect on cost (in the denominator) and increasing capacity factors improved the electricity yield (in the nominator). IRENA expects a continued decline of onshore LCOE from USD 60 per MWh in 2018 to USD 40 per MWh by 2030 (IRENA 2019). Due to the different generation profiles, a cost-benefit comparison between the two technologies exceeds the comparison of LCOE, which are significantly lower for onshore than for offshore wind (55 USD/MWh compared to 186 USD/MWh, IRENA (2020)). As discussed in the previous section, offshore wind power has significantly higher capacity factors than onshore (Fig. 10.3, right) and thereby, steadier generation profiles. This implies offshore wind also generates electricity when onshore wind does not. Because wind generation often has a depressing effect on wholesale prices, their steadier generation profile allows offshore wind to produce electricity when the wholesale electricity price is higher, which generally leads to higher market values.

As more and more wind parks that have been installed 20 to 30 years ago reach their technical lifetime, repowering old wind farms entails further cost-saving potential. Full repowering describes the replacement of entire wind parks whereas partial repowering implies that single components, such as rotors or gearboxes, are replaced while foundations and towers remain in place. The replacement or upgrading of older components with more advanced technologies can enhance the power output of wind parks and increase their operating time. This strategy allows installing the most advanced technologies at locations with best wind resources, which often had already been covered by installations. Higher rates of social acceptance by local communities, already accustomed to wind power, and existing environmental assessments decrease risks and costs in comparison to new sites. Repowering may also require grid extension due to more powerful turbines (IRENA 2019).

The installation costs of onshore and offshore wind projects are expected to continue their past decline during the next decades (IRENA 2019). Further technological advancement, more competitive supply chains, and economies of scale in production are the main drivers of these developments. Limitations to further reductions in cost are cost of materials, transportation, and the costs deriving from regulatory processes.

5 System Integration

The rapid expansion of wind power imposes new challenges on power systems. The four main characteristics of wind power hindering its system integration are the temporal variability, rapid changes in generation, difficult predictability, and regionally diverging wind energy potentials. These characteristics impose additional costs on the power system.

Changing wind speeds cause wind generation to vary over time. The replacement of dispatchable energy sources with variable wind energy raises the question of generation adequacy. Will there always be sufficient generation capacity to meet electricity demand? The contribution of wind energy to the system's generation adequacy is called "capacity value", that is, the amount of dispatchable generation capacity that it can replace without reducing security of supply. The capacity value of wind energy depends on how much wind resource is available during times of peak loads. As a rule of thumb, the capacity value is close to the average power produced by wind power when the share of wind power in the system is small (Milligan et al. 2017). This implies that offshore wind power tends to have higher capacity values than onshore wind due to its higher capacity factors. With an increasing share of wind in the system, its capacity value declines. The capacity factor can become higher if wind conditions systematically correlate with electricity demand, for example, when high wind speeds in winter time cause higher electricity consumption for heating.

High shares of wind power may cause rapid changes in electricity generation, for example, due to a weather front rapidly changing wind speed. This requires dispatchable generators to quickly adapt power output, and it imposes steep ramping gradients. Most conventional generators in today's power systems are not designed and optimized for such operational mode, in particular nuclear and coal plants. But simultaneity in wind generation is also a problem for wind power plant operators. An oversupply of electricity leads to a declining value of wind energy, reflected in low prices in liberalized markets (known as merit order effect).

The difficult predictability of wind generation has raised concerns about increasing balancing costs due to the deployment of wind energy. Yet, practical experience has shown decreasing balancing costs despite growing shares of wind power (e.g. Hirth and Ziegenhagen 2015). In several countries in Europe and the United States, wind power provides frequency support services (IEA Wind Task 25 2017). Measures to enhance flexibility with high shares of wind power include the introduction of new electricity markets, demand-side flexibility, and storage. Electricity markets that have cross-border trades of intraday and balancing resources and emerging ancillary services markets are supporting the integration of wind power.

All three issues (variability, rapid changes, and difficult predictability of wind power) are strongly reduced through interconnecting multiple power systems. Such geographical smoothing reduces extreme variations. For example, all wind plants in Europe generated less than 5% of their installed capacity in 2017 only in two consecutive hours. The maximum duration of less than 10% of capacity was 38 hours (IEA Wind Task 25 2017).

The fourth major challenge for integrating wind power into power systems are regionally diverging wind energy potentials. Wind farms, usually in remote lowly populated areas or offshore, require a grid connection to load centers. Aggravating the challenge, wind turbines are typically built in large wind farms to benefit from economies of scales. A large wind farm may consist of several hundred individual wind turbines, ranging up to a total of 1.5 GW, equivalent to a large conventional power plant. The construction of additional transmission infrastructure is a time-consuming process in many countries. A lack of grid infrastructure implies that electricity from wind cannot be transmitted and is consequently curtailed. The required network reinforcement for wind power significantly varies between regions, depending on where wind power plants are located relative to load and existing grid infrastructure. Grid connection is often a major component of the integration cost of wind energy. Yet, in most countries, these costs are usually not paid by wind plant operators (Eicke et al. 2020), also because the network costs are difficult to attribute to individual assets.

6 Policies Supporting Wind Energy

In this chapter, we have discussed various barriers hindering wind energy. Technological challenges include harsh environmental conditions, variability, and uncertainty of generation and infrastructure needs. Economic barriers are the high upfront capital costs and long payback periods which impede the access to finance in many countries. In addition, wind turbines are often confronted with limited social acceptance, increasing investment risks and prolonged installation processes. To address these challenges and to advance the deployment of renewable and domestic energy sources, countries around the world introduced support policies for wind energy, which can be grouped into deployment policies, integration policies, and enabling policies (IRENA 2019).

Deployment policies address economic barriers. They are based on fiscal and financial/economic instruments: in Europe, several countries introduced feed-in tariffs in the early 2000s, while the US and India deployed renewable portfolio standards, and introduced tax incentives. Since the late 2010s, renewable auctions have been increasingly introduced across the globe (IRENA 2019). Competitive auctions brought down installation costs and are meant to create incentives for technological advancements. This even led to extremely low auction results with bids for offshore wind energy without guaranteed feed-in tariffs in the Netherlands, Germany, and the UK (IRENA 2019). In technology neutral auction designs, wind energy often won; many countries therefore started using technology specific auction designs (Steinhilber 2016; Mitchell and Connor 2004). Furthermore, the deployment of offshore wind energy is often supported through financing grid connections and redeveloping sites.

Technical integration policies for wind energy tackle technological challenges by improving the flexibility of power systems. These comprise the enhancement of existing grid infrastructure, and promoting research and development of sector coupling and electricity storage. Several countries with high shares of wind energy generation, including Denmark and Germany, encourage the transformation into hydrogen of electricity at peak wind generation. The EU is supporting the strategic build-up of battery cells and hydrogen solutions within its Green Deal (Eicke and Petri 2020). Social integration policies improve public acceptance for wind energy. They include participatory processes in the planning stage of projects, and the engagement of local communities via ownership models or the provision of local services. Policies fostering local co-ownership or financial benefits for nearby communities have been shown to increase the acceptance of wind parks in the population (Wolf 2019).

Enabling policies address several of the above-mentioned challenges in an integrated manner, taking the whole economy into account. Examples are climate targets and industrial strategies that provide medium and long-term guidance and investment security. They foster the development of wind projects and the build-up of domestic wind industries. Such industrial policies for the wind energy sector have been part of recovery packages in response to the COVID-19 pandemic, for example in China and Germany (Weko et al. 2020). These measures are based on strong economic growth prospects and job creation potentials (Helgenberger et al. 2019). Enabling policies also encompass labor market measures, research programs and education policies to build up well-trained and skilled personnel for wind energy. Economic/financial policies might change the cost of electricity from wind generation in relation to fossil fuels significantly, for example, by introducing carbon pricing (IRENA 2019).

The design of supporting policies differs significantly by country context and policy objectives. In combination, development, integration, and enabling policies aim to tackle the technological, economic, and social challenges we discussed in this chapter. This helps further improving wind energy technologies and taping their huge potentials across the globe.

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