Wind Energy

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Abstract

Electricity is perhaps the most versatile energy carrier in modern economies, and it is therefore fundamentally linked to human and economic development. Electricity growth has outpaced that of any other fuel, leading to ever-increasing shares in the overall mix. This trend is expected to continue throughout the following decades, with large – especially rural – segments of the world population in developing countries climbing the "energy ladder" and becoming connected to power grids (UNDP, World energy assessment: 2004 update. United Nations Development Programme, New York, 2004). Electricity therefore deserves particular attention with regard to its contribution to global greenhouse gas emissions, which is reflected in the ongoing development of low-carbon technologies for power generation. The main purpose of this chapter is to provide a bridge between detailed technical reports and broad resource and economic assessments on wind power. The following aspects of wind energy are covered: the global potential of the wind resource, technical principles of wind energy converters, capacity and load characteristics, life-cycle characteristics, current scale of deployment, contribution to global electricity supply, cost of electricity output, and future technical challenges. Wind power is the second-strongest-growing of renewable electricity technologies, with recent annual growth rates of about 34 %. The technology is mature and simple, and decades of experience exist in a few countries. Due to strong economies of scale, wind turbines have grown to several megawatts per device, and wind farms have now been deployed offshore. The wind energy industry is still small but competitive: 120 GW of installed wind power contributes only about 1.5 % or 260 TWh to global electricity generation at average capacity factors of around 25 % and levelized costs between 3 and 7 US¢/kWh, including additional costs brought about by the variability of the wind resource. The technical potential of wind is larger than current global electricity consumption, but the main barrier to widespread wind power deployment is wind variability, which poses limits to grid integration at penetration rates above 20 %. Life-cycle emissions for wind power alone are among the lowest for all technologies; however, in order to compare wind energy in a systems view, one needs to consider its low capacity credit: adding emissions from fossil-fuel balancing and peaking reserves that are required to maintain overall systems reliability places wind power at about 65 g/kWh. Wind power's contribution to twenty-first-century emission abatement is potentially large at 450–500 Gt CO_2.

Introduction

Electricity[1] is perhaps the most versatile energy carrier in modern economies, and it is therefore fundamentally linked to human and economic development. Electricity growth has outpaced that of any other fuel, leading to ever-increasing shares in the

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[1] Responsible for the section on technical principles of wind energy converters

overall mix. This trend is expected to continue throughout the following decades, with large – especially rural – segments of the population in developing countries climbing the "energy ladder" and becoming connected to power grids (UNDP 2004). Electricity therefore deserves particular attention with regard to its contribution to global greenhouse gas emissions, which is reflected in the ongoing development of low-carbon technologies for power generation.

Parts of this chapter are based on a report on the status of electricity-generating technologies (Lenzen and Badcock 2009; Lenzen 2010). That report was commissioned with the objective of providing an up-to-date snapshot of multiple criteria related to electricity generation, but not with the objective to provide a tool or a basis for multi-criteria decision analysis.

Why the need for a new assessment of the state of wind energy, or for that matter, electricity-generating technologies? This work does not aim to replace milestone reports such as the Energy Technology Perspectives (IEA 2008a) or the World Energy Assessment (UNDP 2004). Its main focus is twofold: (a) to provide more technical information than is usually found in global assessments on critical technical aspects, such as variability of wind power, and (b) to capture the most recent findings from the international literature.

The chapter unfolds by presenting an up-to-date summary reviews on the following aspects of wind energy:

1. Global potential of resource
2. Technical principles of wind energy converters
3. Capacity and load characteristics
4. Life-cycle characteristics
5. Current scale of deployment
6. Contribution to global electricity supply
7. Cost of electricity output
8. Future directions

The chapter concludes with a summary.

Global Potential of Resource

In 2008, the global capacity of wind energy converters was 121 GW, generating about 260 TWh of electricity or about 1.5 % of global electricity production (WWEA 2008). Most of the capacity (Fig. 1) is installed in the USA (25 GW) and in the EU (about 65 GW), followed by China (12 GW) and India (10 GW).

Wind energy deployment has been increasing rapidly throughout the past decade, recording growth rates of around 30 % since 1996 (Fig. 2). More than half of the 2008 additions occurred in the USA and in China (Fig. 3), with the USA overtaking Germany as the leader in installed wind capacity.

Measurements from numerous surface and balloon-launch monitoring stations suggest that the global technical potential from onshore wind energy exceeds current

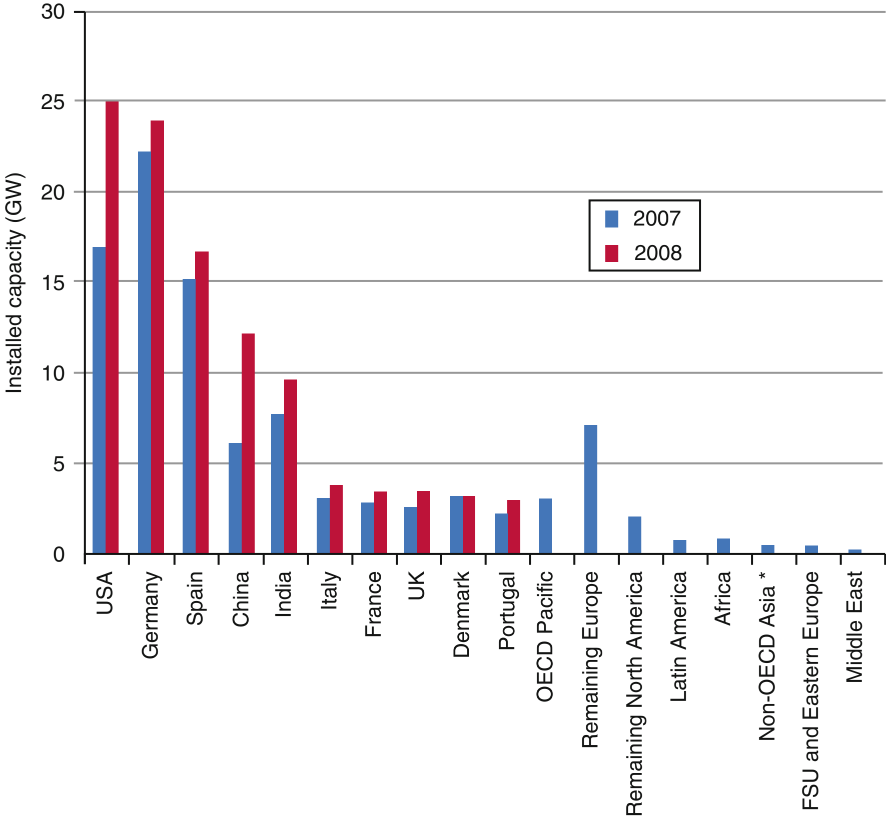


Fig. 1 Installed wind power capacity by region (Compiled from WWEA (2008), GWEC (2008)) (*Asia excludes China and India)

world electricity demand. Using global grid-cell data, Hoogwijk et al. (2004) undertake a detailed assessment of:

1. The theoretical potential (the energy content of global wind).
2. The geographical potential of onshore wind. Hoogwijk et al. assessment excludes land areas with wind speeds below 4 m/s (if the cutoff point had been 6 m/s, areas with current wind turbine installations would have been excluded). It also excludes areas unavailable for turbine installation, such as nature reserves and areas with other functions, and urban areas and high altitudes above 2,000 m with low air density. For further details, Table 1 in Hoogwijk et al. (2004) provides suitability factors, which shows the percentage of a land area available for wind turbine installation.
3. The technical potential (extrapolating wind data to hub height, considering wake effects and realistic power densities in MW/km^2, applying average capacity factors, subtracting downtime).

Fig. 2 Historical development of installed wind power capacity and annual growth rates (Compiled from WWEA (2008), GWEC (2008))

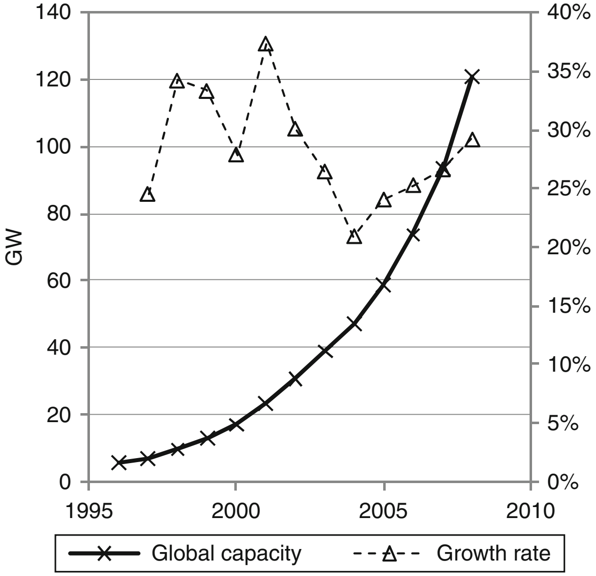
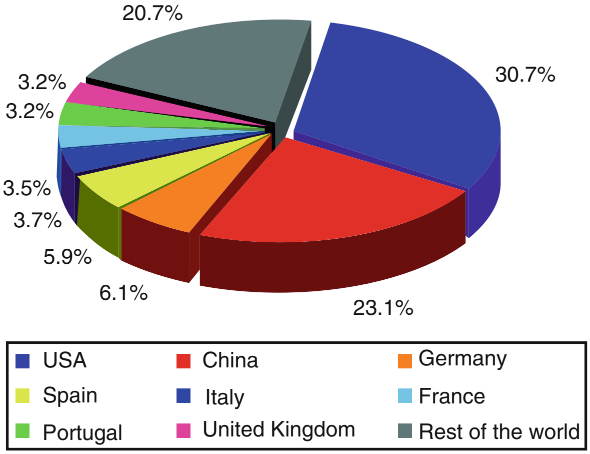


Fig. 3 Regional shares of added capacity in 2008 (After WWEA (2008))



4. The economic potential, given the cost of alternative sources (calculating rated turbine power optimized for grid-cell wind conditions, regressing capital cost and turbine output as a function of rated power and an economies-of-scale factor).

While the theoretical onshore potential exceeds humankind's energy consumption by a few 100-fold, Hoogwijk et al. (2004) estimate the technical potential to be about 100 PWh/year and the economic potential at cost below 7 US¢/kWh to be about 20 PWh/year, both of which still exceed current global electricity consumption. This is consistent with previous studies (Archer and Jacobson (2005) and

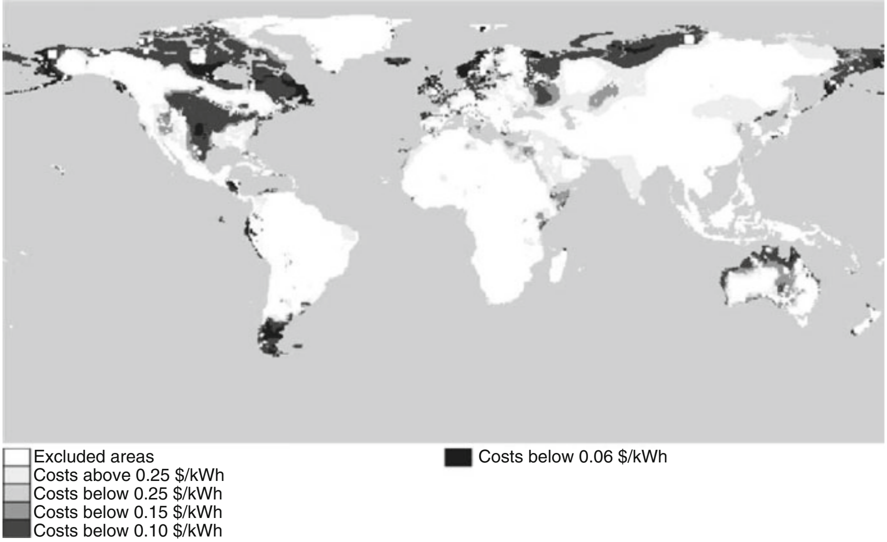


Fig. 4 The economic potential of onshore wind power (After Hoogwijk et al. (2004))

references listed by Hoogwijk et al. (2004) in their Sect. 7.2). However, most of the economic onshore potential – 15 PWh/year – is concentrated in a few remote regions (Fig. 4), namely, the north of Canada (8 PWh/year), Patagonia (4 PWh/year), Siberia (2 PWh/year), and the coastal regions of Australia (1 PWh/year). Only about 5 PWh/year overlaps with regions of significant electricity consumption, the Central USA (3 PWh/year), Western Europe (1 PWh/year), and Central America (1 PWh/year). Relatively small potential is found in Africa, South Asia, and Southeast Asia. The regional technical potentials given by Hoogwijk et al. (2004) are confirmed in studies on the USA (US Department of Energy et al. 2008), India (Carolin Mabel and Fernandez 2008), and China (Changliang and Zhanfeng 2009). Hoogwijk et al. (2004) do not include any grid integration, transmission, and distribution issues in their assessment, which is instead dealt within their later publication (Hoogwijk et al. 2007). The resolution of their global assessment is also such that it cannot account for specific circumstances at the small-region geographical level. In India, for example, the technical potential is further limited by transmission capacity of the grid (Carolin Mabel and Fernandez 2008).

Offshore potential is estimated to be even higher (see Kempton et al. (2007)), but reliable wind data are often lacking (Hoogwijk et al. 2004). Offshore wind power is currently seen as more expensive than onshore wind but at higher penetration rates in the longer term could offer more benefits than onshore because of its more level output and its proximity to large coastal cities (Snyder and Kaiser 2009).

The later assessment of wind by Hoogwijk et al. (2007) takes into account a whole range of effects occurring with increasing penetration, such as output smoothing and increasing interconnection, depletion of the wind resource, requirements of reliability backup and short-term spinning reserves, and increasingly discarded excess wind energy.

The potential of wind power is hence not limited by the resource potential but instead by how much can be integrated into existing power supply systems without causing major supply and demand imbalances and at acceptable costs (Holttinen 2008). At a given penetration rate, wind power's mitigation potential would depend on future electricity demand. Assuming steady increases in turbine size (from 1.5 MW in 2007 to 2 MW in 2030) and capacity factor (from 25 % in 2007 to 30 % in 2030), the GWEC (2008) projects a moderate growth scenario to lead to 1,400 GW capacity in 2030 (generating 3,500 TWh) and 1,800 GW in 2050 (4,800 TWh). Assuming a 2030 demand of 30 PWh, this scenario is equivalent to an average penetration rate of just over 11 % (compare GWEC (2008, p. 40)). 2050 annual CO_2 mitigation would then amount to about 4.4 Gt CO_2/year. Extrapolating this trend linearly to 2,100 yields a crude estimate of 350 Gt CO_2 total mitigation potential. In addition, the GWEC (2008) reference scenario yields about 1.7 Gt CO_2/year in 2050, or 150 Gt CO_2 until 2100, and the advanced scenario yields about 8.2 Gt CO_2/year in 2050, or 650 Gt CO_2 until 2100. These scenarios are consistent with estimates by the GWEC (2008, pp. 38, 45–46). A long-term global penetration rate of around 20 % is perhaps realistic (compare estimates of 15–20 % in Resch et al. (2008)) given that (a) large economic potential is not available in all world regions and (b) current research indicates substantial difficulties of integrating wind at penetration rates higher than 20 % (Hoogwijk et al. 2007). This corresponds to a total mitigation potential of about 450–500 Gt CO_2. For comparison, Hoogwijk et al. (2007) arrive at potentially avoided CO_2 emissions of 1 Gt CO_2/year, just in OECD Europe and the USA, at carbon prices of around US $30–50/t CO_2. This figure is in the ballpark of the estimate given above.

Technical Principles of Wind Energy Converters

This section discusses modern wind energy conversion systems. However, before setting forth the different types of wind turbines along with their design principles and characteristics, a reminder of the origin of winds, followed by a brief overview of the historical development of wind-powered devices, will first unfold.

Wind power is actually a form of solar power as winds result from solar radiation. Sunbeams entering the atmosphere heat the Earth's surface but not evenly across the surface and over time. Indeed, the equator receives more energy from the sun than the poles and dry land surfaces absorb, retain, and release heat at different rates than the oceans. Consequently, air masses surrounding the Earth's surface warm and cool at different rates. Since hot air masses are lighter than cold ones, they rise and reduce the atmospheric pressure below them drawing in cooler air masses. This creates a global atmospheric convection system that gives birth to winds. Since these air masses are in motion, they have kinetic energy. Wind energy converters capture this kinetic energy and then convert it into a useful form of energy such as electricity or mechanical power.

Sailboats and sailing ships have been using the power of the wind for at least the last 3,000 years. However, the first recorded use of (vertical-axis) windmills to operate irrigational and agricultural projects was in the seventh century BC in the Afghan highlands. The most ancient historical documents pertaining to horizontal-axis windmill technology date from about 1,000 AD and were found in the regions of Persia, Tibet, and China. From there, the technology spread westward to Europe where it was later, at the beginning of the twelfth century, extensively used to grind flour (Ackermann and Söder 2002).

Another seven centuries or so will pass before the first windmill designed for electricity production is built in Scotland in 1887 by Professor James Blyth. Set up in his holiday cottage, his 10-m-high wind turbine charged accumulators engineered by the Frenchman Camille Alphonse Faure to power the lighting of the cottage, thus making it the first residential area in the world to have electricity supplied by wind power (Shackleton 2009). A precursor of modern horizontal-axis wind generators was developed in Yalta, USSR, in 1931. This 100 kW generator mounted atop a 30-m tower was reported to have a capacity factor of 32 %, quite close to current wind machines (Wyatt 1986).

On the eve of the twenty-first century, rising concerns over energy security of supply and global warming paved the way to an expansion of interest in all available forms of renewable energy in general and in wind power in particular. Like this, and boosted in addition by readily available wind resources and economies of scale, worldwide grid-connected wind capacity doubled approximately every 3 years during the 1990s. After the 2003 surge in oil prices due to the geopolitical situation in the Middle East, interest in commercial wind power further expanded.

Modern Wind Energy Conversion Systems

Wind power is the conversion of the kinetic energy of winds into another form of energy, either mechanical or electricity. If the useful form of energy is mechanical (to, for instance, pump water or grind stones), the converter is generally referred to as a windmill. In contrast, if the useful form of energy is electricity, the converter is called a wind turbine or a wind energy converter. In the following section, focus will be on the latter technology, that is, to harness the kinetic energy of wind to produce electricity.

Before examining modern wind energy conversion systems, it is important to bear in mind that only a given fraction of the (kinetic) energy of wind can effectively be harnessed. If all the energy was to be extracted by a wind turbine, the air mass would come to a stop in the intercepting rotor area jamming the cross-sectional area for the following air masses. The theoretical limit of the kinetic energy of the wind that can be harnessed by a hypothetical ideal wind energy extraction machine (referred to as Betz's law and derived by combining the fundamental laws of conservation of mass and energy) is 16/27 (59.3 %).

Wind energy conversion systems can either depend on aerodynamic drag (force acting in a direction opposite to the oncoming flow velocity) or on aerodynamic lift.

Most of modern wind turbines are based on the aerodynamic lift. The resulting force stemming from the blades intercepting the air flow has two components: a (drag force) component in the direction of the flow and a (lift force) component perpendicular to the drag. The lift force is a multiple of the drag force and consequently the main driving power of the rotor, by means of which it produces the necessary driving torque.

The orientation of the spin axis of wind turbines based on aerodynamic lift (lift-type wind turbine) can be either vertical or horizontal. However, horizontal-axis machines are more commonly used for large-scale industrial applications (AWEA 2009).

Horizontal-Axis Wind Turbines

Horizontal-axis wind turbines (HAWTs) consist of a tower atop of which a nacelle containing the rotor, the generator, and an optional gearbox is mounted.

There exist diverse mechanisms to position the nacelle into or out of the wind. Small turbines are pointed by a wind vane, while large ones most of the time use a wind sensor coupled with a servomotor to electrically yaw (align) the nacelle toward or away from the wind depending on the signal sent by the wind sensor.

Since the power in the wind is a cube of the wind speed, the converted mechanical power must always be controlled at high wind speed. This power output control can be achieved by stall control (the blade position remains unchanged but natural turbulences occurring behind the blades in high wind speed reduce the aerodynamic forces and thus the power output), pitch control (the blade angle of attack is reduced at higher wind speed and so are consequently the aerodynamic forces and the power output), or a combination of the two, active stall regulation (the blade angle of attack is fine-tuned to create stall along the blade).

If the wind speed rises above the cutout wind speed threshold (usually varying between 20 and 30 m/s), the turbine is shut off and the rotor is turned out of the wind to avoid potential damage to the primary turbine structure. In so doing, a substantial quantity of energy is wittingly lost. However, equipment capital costs required to strengthen the primary structure to resist wind speeds over the cutout wind speed threshold will likely be larger than the value of the lost energy that could have had otherwise been harvested over the lifetime of the wind turbine.

The number of blades of a horizontal-axis wind turbine depends on its purpose. Turbines designed with two or three blades are usually more suited for electricity generation, while turbines designed with 20 or more blades are generally more suited for mechanical operations (e.g., water pumping).

While most generators are designed to run in the range of 1,200–1,800 rpm (revolutions per minute), large wind turbine rotors most of the time operate at speeds between 10 and 60 rpm. To convert the slow rotational speed of the blades to the higher speeds necessary to drive the electrical generators, gearboxes are therefore used on a majority of large turbines. However, direct mechanical connection (direct drive) can also be achieved with generators designed to run at very low rpm. Such generators usually consist of many poles (the required rpm of a generator depends on the number of pole pairs) and are very large (large diameter to accommodate the large number of poles) in comparison to generators attached to gearboxes (NREL 2001).

A fixed-speed turbine technology imposes the rotational rate of the turbine to that of the electric grid, whereas a variable-speed turbine technology allows the speed of the rotor to be proportional to the wind speed. In so doing, the former technology forgoes a substantial amount of wind potential, while the latter, in contrast, considerably improves the aerodynamic efficiency in high wind and allows to run at lower speeds so that, everything else being kept equal, a variable-speed technology collects more energy than its fixed-speed counterpart. However, this enhanced energy capture that comes at a high price because of the expensive embedded power electronics and control systems can be economically counterbalanced by fixed-speed wind turbines.

Drawbacks of HAWTs are that the tall towers and blades, up to 90 m long, are difficult to transport and to erect, necessitating tall and expensive cranes and skilled operators. In addition, their imposing structures make them pointedly visible across large areas, disrupting sceneries and landscapes, sometimes leading to local opposition.

In spite of turbulence issues, downwind HAWTs have also been engineered. First, because no additional mechanism for maintaining them aligned with the wind are necessary and second because in high winds, blades can bend, which decreases their swept area and subsequently their wind resistance. However, since turbulences ultimately lead to fatigue failures, horizontal-axis wind turbines are almost exclusively upwind machines.

Vertical-Axis Wind Turbines (VAWT)

The main advantage of this disposition, especially at sites where the wind direction is highly patchy, is that the turbine does not need to be pointed into the wind to be effective. In addition, the generating machinery and gearbox can be placed at ground level, easing maintenance and lowering material requirement.

However, drawbacks are that the driving torque of the rotor varies more noticeably within each turn, the static torque is rather low, and the rotor has to be started up by using the generator as a motor (Sesto and Casale 1998). In addition, it is difficult to erect vertical-axis turbines atop towers. Consequently they are most of the time erected close to the foundations upon which they rest (ground or building rooftop, for instance). It entails that, for a given installed capacity, less wind energy can be harnessed as wind blows slower at lower altitude. In addition, air masses flowing close to the ground are turbulent, potentially producing vibration, and subsequently noise and bearing wear, increasing the maintenance and/or shortening the equipment lifetime (Golding 1997). In contrast, the wind always strikes at a consistent angle the face of a horizontal-axis blade whatever the position in the rotation ensuring a consistent lateral wind loading during a revolution, reducing vibration and audible noise. Moreover, as opposed to HAWTs, blades, which are fixed to the shaft, cannot be adjusted (pitched), so that power output can be controlled only by aerodynamic stall.

Characteristics of a Wind Turbine

A wind turbine installation is made up of subsystems to harness the energy from the wind (rotor), to point the turbine into the wind (yaw mechanism), and to convert the mechanical rotation into electrical power (generator), as well as subsystems to start, stop, and control the turbine. Horizontal-axis medium to large size grid-connected wind turbines (>100 kW) currently occupy the biggest market share and are expected to principally account for wind deployment in the near future (Ackermann and Söder 2002). This section therefore specifically focuses on their designs that can be divided into three parts (NREL 2006):

- A tower on top of which the nacelle is mounted
- The rotor that includes blades
- The generator that includes an electrical generator, control electronics, and most of the time a gearbox

The Tower

The tower is an important part of a wind turbine primarily because it supports the nacelle and the rotor. The tubular steel tower design is the most widespread technological choice, even though there exist other alternatives like lattice towers or concrete towers. Towers are conical, with their diameter decreasing toward the nacelle, to enhance their strength on the one hand and reduce their material intensity on the other.

In areas with a high surface drag, it is better to erect tall towers since the wind blows faster farther away from the ground. More specifically, wind speed follows in daytime the wind profile power law, which foresees that wind speed rises proportionally to the seventh root of altitude (Peterson and Hennessey 1978). Consequently, doubling the altitude of a turbine theoretically increases the expected wind speeds by 10 % and the expected power by 34 %. However, to avoid buckling, increasing the tower height generally entails enlarging the diameter of the tower as well.

Rotor: Blade Design and Count

Turbine blades, sometimes slightly tilted up, are positioned significantly ahead of the tower and made rigid to prevent them from being shoved into the tower by high winds. Most modern large-scale wind turbine rotor blades are therefore made of glass fiber-reinforced plastics (e.g., epoxy), which, besides, allows for low rotational inertia and quick accelerations, should gusts of wind occur (variable-speed turbines). In contrast, previous generations of (fixed-speed) wind turbines whose rotational speed is imposed by the AC frequency of the power lines are manufactured with heavier steel blades and therefore higher inertia (Sahin 2004).

The determination of the number of blades depends on the purpose of the wind turbine as aforementioned. Wind turbines for electricity generation usually use either two or three blades even though two-bladed designs are more the exception than the norm for large-scale grid-connected horizontal-axis wind turbines.

The rotor moment of inertia of a three-bladed wind turbine is simpler to comprehend than that of a two-bladed one. In addition, three-bladed wind turbines are often better accepted for their visual aesthetics and are responsible for lower audible noise than their two-bladed counterparts (Thresher and Dodge 1998). Furthermore, during the yawing (alignment) of the nacelle in or out of the wind, a cyclic load is exercised on the root end of every blade and whose magnitude is function of the blade position. Three-bladed turbines see their cyclic load symmetrically balanced when combined at the turbine drivetrain shaft, contributing to smoother maneuvers during yawing.

On the flip side, two-bladed wind turbines, when equipped with a pivoting teetered hub, can also nearly filter out the cyclic loads into the turbine driveshaft and system during yawing. Moreover, the tower top weight is lighter and so consequently is the whole supporting structure, lowering associated costs. In addition, two-bladed turbines can have a higher rotational speed than their three-bladed counterparts. Indeed, the degree of rigidity necessary to avoid hindrance with the tower imposes a lower limit on the thinness of the blades and subsequently (a lower limit) on their mass. However, this is only true for upwind machines as bending of blades enhances tower clearance for downwind ones. Likewise, cheaper gearbox and generator costs can be achieved with two-bladed turbines as faster rotational speeds reduce peak torques in the turbine drivetrain. Lastly, the fewer the number of blades the higher the system reliability is, chiefly through the dynamic loading of the rotor into the tower and turbine drivetrain systems.

Electrical Generator

The energy captured by the blades is subsequently passed onto the generator via a transmission system consisting of a rotor shaft with bearings, brakes, an optional gearbox, as well as a generator.

Whereas the power generation industry resorts almost integrally to synchronous generators because of their variable reactive power production (voltage control), most wind turbines generate electricity through (six-pole induction) asynchronous generators that are directly connected with the electricity grid. However, some designs also use directly driven synchronous generators (Ackermann and Söder 2002).

Electrical generators produce AC (alternating current) power by definition. While the previous generations of (fixed-speed) wind turbines spin at a constant speed governed by the frequency of the grid they are connected onto, new (variable-speed) ones most of the time rotate at the speed that produces electricity most efficiently being given the actual wind conditions. This can be achieved either using direct AC-to-AC frequency converters (cycloconverters) or using DC current link converters (AC to DC to AC). Although variable-speed turbines require costly power electronics that in addition generate supplementary power loss, a substantially larger fraction of the wind energy can be harnessed by the rotor (NREL 2001).

Control Electronics

Wind conditions being highly variable across sites and over time, a wind turbine is designed to operate over a large range of wind speeds (usually between 12 and 16 m/s). Therefore, to avoid any potential damage to the primary turbine structure during operation in strong winds while ensuring an optimal aerodynamic efficiency of the rotor in light ones, the rotational speed and torque of the rotor must permanently be monitored and controlled. There are several approaches to successfully achieve this (power output) control.

Stall Regulation

This technique requires the rotor to spin at a constant speed (independent of the wind speed). When a wind stream is intercepted in the rotor area, it creates natural turbulences right behind the blades. This is called the stall effect. As a result, aerodynamic forces (induced drag or drag associated with lift) are reduced and so subsequently is the power output of the rotor (Ackermann and Söder 2002).

If the stall effect is a complicated dynamic process to comprehend, stalling is an easy power output control to practically implement as the faster the wind blows, the larger the stall effect is (passive regulation). However, stalling increases the (ordinary) drag by increasing the cross section of the blade facing the wind.

Pitch Control

Pitching the angle of attack of the blades into (respectively out of) the wind increases (respectively reduces) the aerodynamic forces and subsequently the power output of the rotor. One of the main technical challenges associated with designing pitch-controlled wind turbines is getting the blades to furl (to swing out of the wind) swiftly enough in case of a gust of wind. Seemingly, these systems must be able to adjust the pitch of the blades by a fraction of a degree at a time, depending on the wind speed, to control the power output.

The pitching system in medium and large size grid-connected wind turbines is usually based on a hydraulic system, controlled by a computer system. To prevent an eventual hydraulic power failure to furl the blades, pitch regulation systems are also spring-loaded.

By permanently fine-tuning at an optimum angle the rotor blades (even in low-wind conditions), pitch-controlled turbines achieve a better yield at low-wind sites than stall-regulated turbines. In addition, the thrust exercised by the rotor on both the tower and the foundation being significantly lower for pitch-controlled turbines than their stall-regulated counterparts, the primary structure of the former is less material intensive and likely incur lower costs. Moreover, stall-regulated (fixed-pitch) turbines must be shut down when the cutout wind speed threshold is reached, whereas pitch-controlled ones can progressively evolve toward a spinning mode as the rotor operates in a no-load mode at the maximum pitch angle (fully furled turbine).

On the flip side, once the stall effect becomes effective (in high wind conditions), the power oscillations occurring on stall-regulated turbines and stemming from the wind oscillations are smaller than those occurring on pitch-controlled turbines in a corresponding regulated mode (Ackermann and Söder 2002).

Active Stall Regulation

This regulation system is a combination between and a culmination of pitch and stall approaches. It is a combination because, to optimize the aerodynamic efficiency of the rotor and to ensure a torque large enough to create a turning force in light winds, the rotor blades are pitched like in a pitch-controlled wind turbine, whereas after the rated capacity is reached, they are pitched in the opposite direction (than that of a pitch-controlled turbine) in order to increase their angle of attack and install them into a deeper stall.

It is a culmination because active stall regulation achieves a power output control smoother than the jerky one associated with pitch-controlled turbines while still preserving at the same time the advantage of pitch-controlled turbines over stall-regulated ones to turn the blades parallel to the airflow (the so-called low-load feathering position) and subsequently reducing the thrust on the turbine structure (Ackermann and Söder 2002).

Wind Farms

Groups of turbines are often combined into wind farms whose installed capacity can range from a few to several 100 MW. The largest wind farm for commercial production of electric power, situated in Texas, USA, combines 421 turbines into a 735 MW plant. Such turbines are usually three bladed and have high tip speeds (the ratio between the rotational speed of the tip of a blade and the actual velocity of the wind) of 300 km/h. Their supporting structures tower from 60 to 90 m above ground, while their associated blades range from 20 to 40 m in length. Wind plants have short construction lead times, even compared to those of transmission infrastructure.

Trends

Variable-speed turbines with pitch control using either direct driven synchronous ring generator or double-fed asynchronous generators are likely to become the norm, not the exception. However, cost of energy is and will remain the key driving force of wind energy growth. Therefore, if variable-speed turbines are to become a sound economic winner, additional costs incurred by power electronics required by most variable-speed designs must clearly be counterbalanced by the enhanced energy capture.

Capacity and Load Characteristics

Wind energy converters are dependent on the wind, and hence turbine output varies over time, across all timescales ranging from seconds to up to years. Measuring, modeling, and understanding this variability are crucial for site selection and also for integration of wind power into electricity grids.

In 2008, the global capacity of wind energy converters was 121 GW, generating about 260 TWh of electricity (WWEA 2008). This yields a capacity factor of about 24.5 % (Fig. 5).

Plant outages are not as problematic with wind power as they are with fossil, nuclear, or large hydro, because numerous wind plants are usually distributed over a wide geographical area (Archer and Jacobson 2007). Such decentralization in a power supply system reduces the requirements for contingency reserve, since this type of reserve is mostly tied to the largest potential source of failure, which is the largest single generator in the system (Holttinen et al. 2008). Output from wind farms can be expected to be smoother than that of a single turbine, but smoothing effects on larger scales may not be so significant and may also vary between regions. While smoothing effects are discernible when comparing single turbines with wind farms and regions (Fig. 6, and also a similar figure for the UK in Oswald et al. (2008)), combining regions as such may not necessarily lead to much additional smoothing because of strong correlations in the wind regime over large distances (Fig. 7). Østergaard (2008) artificially combines the wind output of West and East Denmark (which are not connected into a common grid) and obtains only small averaging effects. Oswald et al. (2008) uses weather maps to demonstrate the correlation and variability of wind regimes across a large area combining Ireland, the UK, and Germany (Fig. 7). His findings (confirmed for Germany in Weigt (2008, Sect. 3.1 and Fig. 4)) cast doubt on the effectiveness of a trans-channel “supergrid” in smoothing out variations in wind load. Holttinen et al. (2009) present a detailed account of variability across geographical and temporal scales. Archer and Jacobson (2003) present wind speed data for a single site, and three and eight sites in Kansas, USA, and show how the frequency of low-wind events decreases as the number of included sites increases.

However, wind generators cannot – without storage – react to changes in demand because unlike hydropower they cannot follow a fluctuating demand (Fig. 8). Therefore, in the absence of supply matched end uses, they require a flexible electricity grid

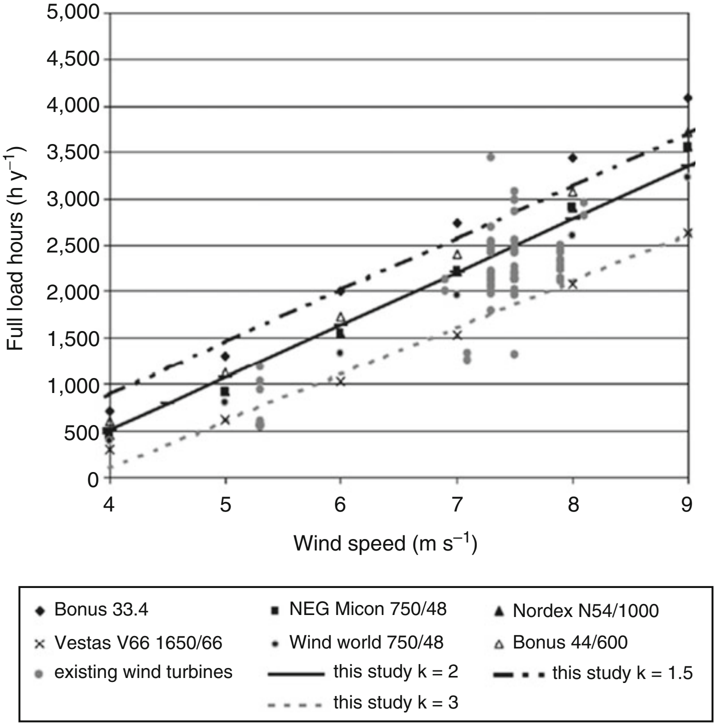


Fig. 5 Average capacity factor as a function of wind speed. Most turbines operate in a range between 2,000 and 3,000 full load hours, which is equivalent to capacity factors between 23 % and 34 % (After Hoogwijk et al. (2004); *k* is the Weibull wind speed distribution parameter). For wind farms at certain windy sites, average capacity factors of up to 45 % are reported (Archer and Jacobson 2007)

with a sufficient portion of technologies that can react quickly to demand changes, such as hydropower or natural-gas-fired plants (GWEC 2008; Söder 2004).

The *average capacity* factor of 24.5 % given above does not reflect the circumstance that electricity system planners must meet demand whenever it occurs and not on average. Where a technology is assessed with regard to its ability to supply peak load, the *capacity credit* describes the fraction of average capacity that is reliably available during peak demand. Capacity credit is also referred to in the literature as *demand capacity* (Pavlak 2008), *capacity value* (Milligan and Porter 2008), or *moderation factor* (Lund 2005). The difference between the average capacity and capacity credit is proportional to the time when wind power cannot meet (peak) demand because of a lack of wind. For example, provided a filled reservoir, the capacity credit of hydropower is virtually equal to its average capacity, but this is not the case for wind power because of its variability and uncertainty. Some generators assign zero capacity credit to wind; however, this is unrealistic (Diesendorf 2007). Wind can achieve up to 40 % capacity credit when penetration is low and times of

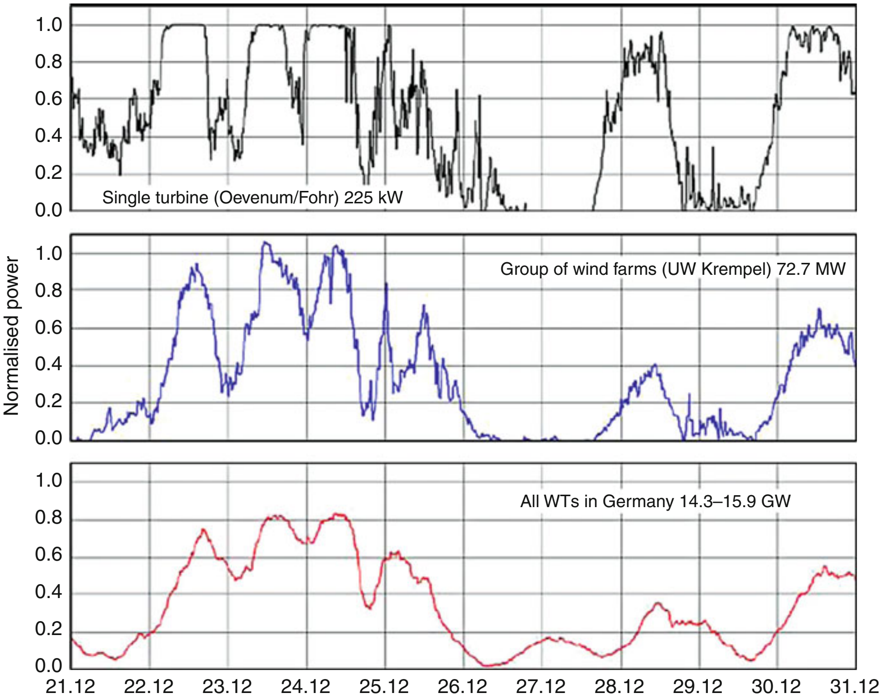


Fig. 6 Normalized power output from a single wind turbine (*top*), and group of turbines (*middle*), and all turbines in Germany (*bottom*; after Focken and Lange)

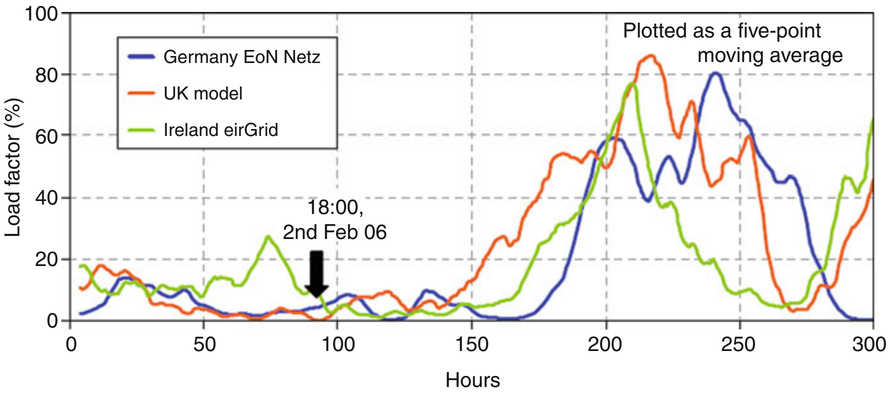


Fig. 7 Variability and correlation of wind loads across Ireland, the UK, and Germany (After Oswald et al. (2008)). On February 2, the electricity demand in Britain reached its peak for 2006

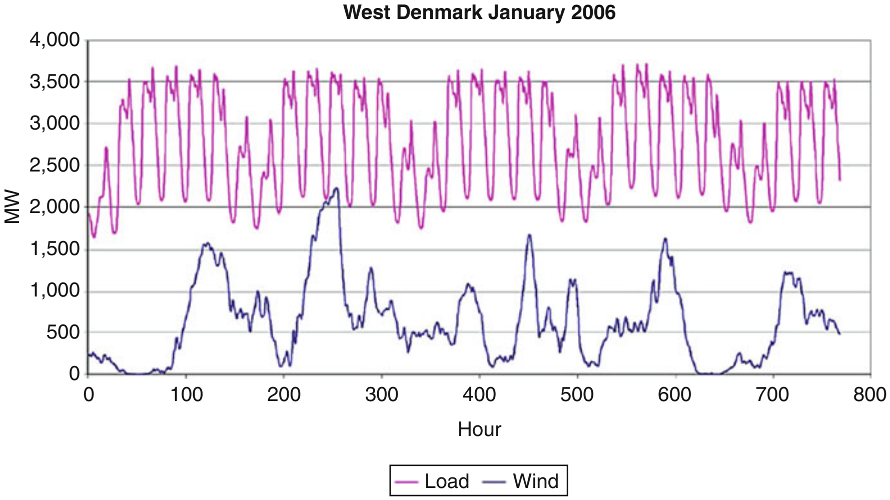


Fig. 8 Wind power output and load in West Denmark (After Söder et al. (2007), © 2007 IEEE)

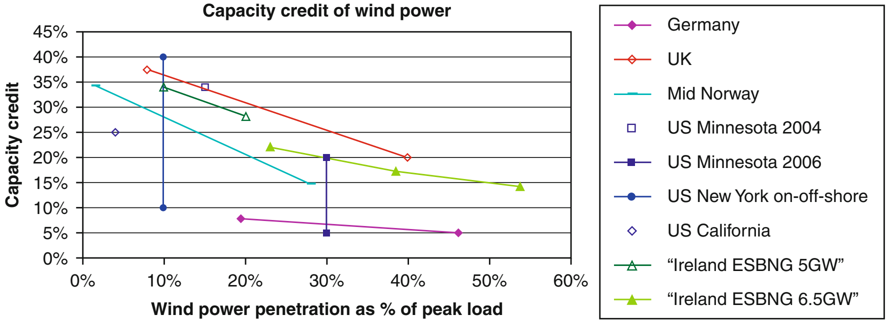


Fig. 9 Capacity credit of wind power as a function of wind penetration (After Holttinen et al. (2009)). Note that as penetration approaches 20 %, the capacity credit starts to fall consistently below wind power's average capacity factor. The results from Mid-Norway show that geographical dispersion improves capacity credit. Decreasing capacity credits have been confirmed theoretically, for example, by Martin and Diesendorf (1980)

ample wind coincide with times of high demand (Holttinen et al. 2009). In general, however, the higher the penetration of wind power in a system, and the more uncorrelated wind output with demand load, the lower its capacity credit (see Fig. 11 in Strbac et al. (2007) and Fig. 9).

Capacity credit is usually measured by applying probability calculus to hourly data on load, generation capacity, ramp rates, and planned or forced outages and applying merit orders in which technologies that avoid fuel costs are recruited first (Milligan and Porter 2008). The *loss-of-load probability*$\mathrm{LOLP}_i = \mathrm{Prob}(\sum_j C_j < L_i)$, with C_j being the capacity of generator j in the grid and L_i the load at hour i, is the probability that a supply system is not able to meet demand in hour i. Integrating

LOLP overall operating hours results in the*loss-of-load expectation* LOLE $= \sum_i$ LOLP_i, which is expressed in units of hours/year, or days/10 years, and provides a measure of system reliability. A common system LOLE target is 1 day/10 years, in which case the system has to import capacity from elsewhere. This corresponds to a $1 - 1/(10 \times 365) = 99.97$ % probability that the system will be able to meet demand without having to import capacity.

A power supply system is usually made up of a technology mix. A measure that allows characterizing the incremental contribution of any one component to the reliability of the system is the *effective load-carrying capability*ELCC, which is the new firm (i.e., zero-variance) load that can be added to the system including the incremental capacity increase, without deteriorating the system's reliability. Adding a new generator G as well as a hypothetical firm load ELCC to a system, hourly LOLP becomes $\mathrm{LOLP}_i = \mathrm{Prob}(\sum_j C_j + G < L_i + \mathrm{ELCC})$. ELCC is a hypothetical firm (i.e., zero-variance) load that can be added to a system as a result of the addition of a non-firm (i.e., variable) capacity G that would not change the system's LOLE. ELCC is hence calculated by solving $\sum_i \mathrm{Prob}(\sum_j C_j < L_i) = \sum_i \mathrm{Prob}(\sum_j C_j + G < L_i + \mathrm{ELCC})$.

ELCC depends critically on the ability of a generator to meet demand at top-ranking LOLP hours, which, in the case of wind, is determined by the correlation of wind output with top-ranking LOLP hours. *Capacity credit* is the ratio of ELCC and rated capacity. Defined as such, capacity credit values are around or lower than the average capacity (Fig. 9). However, capacity credit has at times been measured as the ratio of ELCC and average power (Martin and Diesendorf 1980), in which case it varies between 0 % and 100 %. As a result, where grid operators are required to meet demand at usual loss-of-load expectations, reserve load-carrying capacity or storage has to be secured (Pavlak 2008, Fig. 10).

Similarly, operators also strive to avoid having to curtail surplus wind power at times of high wind, raising different management issues again (Holttinen 2008). Geographical dispersion of wind turbines can help to reduce variability as well as increase predictability of output (Holttinen et al. 2008). Even during a rapidly passing storm front, power from dispersed capacity will take a few hours to change (Söder et al. 2007). Depending on the characteristics of the power system, that is, composition and diversity of technologies, demand management, size, demand profile, and degree of interconnection, low capacity credit poses barriers to the degree of integration of wind energy. In general, the more flexible, load-following capacity there is in the existing grid, the higher the potential penetration of wind power. However, operators run either the risk of not meeting demand by committing too much cheap slow-start capacity or the risk of overrunning cost by committing too much expensive fast-start capacity (DeCarolis and Keith 2006).

Grid integration issues have largely been studied theoretically, except for some European regions. For example, while Denmark receives on average more than 20 % of its electricity from wind, it sometimes receives much higher percentages and sometimes very little, in which case Denmark exports or imports electricity from the European grid and thus relies on other generation technology for load balancing (Pavlak 2008; Østergaard 2003), in particular Norwegian, Swedish, and Finnish hydro reservoirs and idle peaking plants in Denmark (Sovacool et al. 2008).

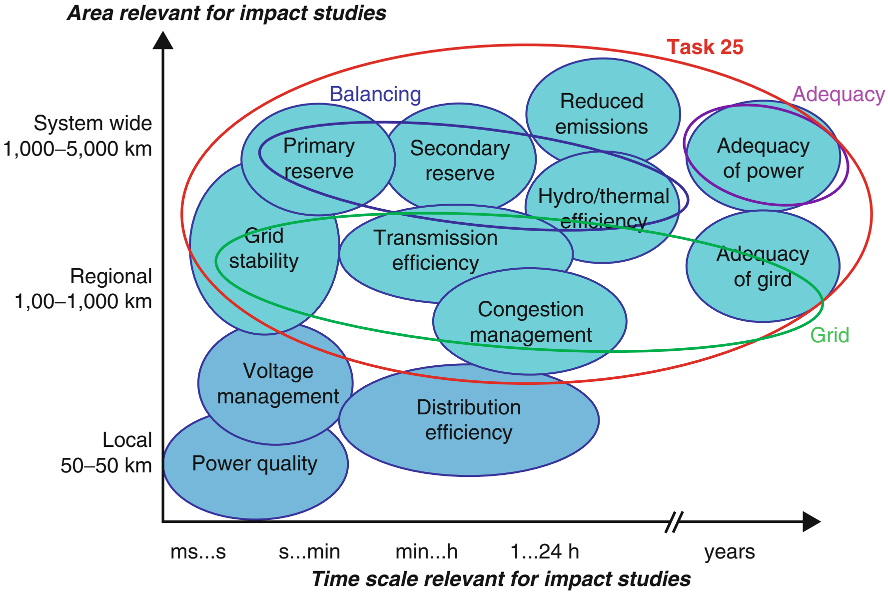


Fig. 10 Typology of grid impacts of wind power across temporal and spatial scales (After Holttinen et al. (2009)). *Balancing* reserves deal with short-term variability in the order of up to 24 h. *Adequacy* in peak-load situations (i.e., low LOLE) has to be secured long term and requires load-carrying reserves to compensate for shortfalls in capacity credit

For higher degrees of integration, the management and/or export of excess wind loads become(s) an issue (DeCarolis and Keith 2006). Söder et al. (2007) report results from four regional systems with high wind penetration, among which two are connected to a larger outside system, and two are not. Management of wind power variability involves the requirement for flexible interconnection capacity and the ability to curtail wind power production, respectively. Hoogwijk et al. (2007) (Fig. 9) find that – subject to supply and load correlation – the amount of electricity that has to be discarded grows strongly for penetrations in excess of 20–30 %. Lund (2005) investigates a scenario for expansion of wind power to cover 50 % of Danish demand and concludes that supply–demand balancing problems would become severe. Similarly, penetration of less than 20 % can lead to instabilities if a grid is not well interconnected with other grids, such as in the case of Spain (Hoogwijk et al. 2007).

Life-Cycle Characteristics

Lenzen and Munksgaard (2002) review and analyze a large body of literature on the life cycle of wind energy converters, comparing bottom-up component analyses with top-down input–output analyses. In their multiple regressions, these authors take into account not only technical features such as scale, vintage year, and load factor but also scope and methodology of the analysis (Fig. 11).

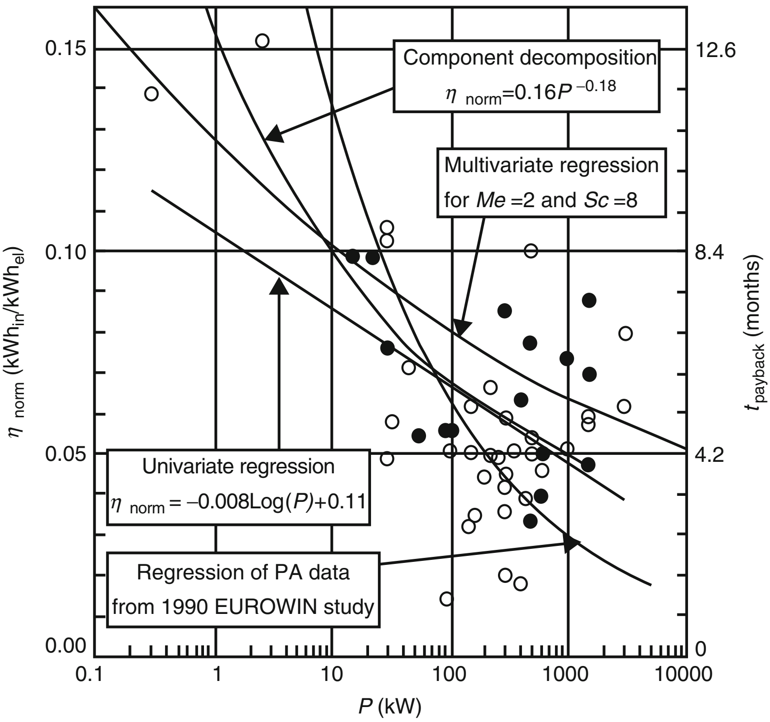


Fig. 11 Cumulative energy requirements of wind energy converters as a function of rated power (After Lenzen and Munksgaard (2002)). The multivariate regression line takes into account different scopes and methodologies adopted in case studies. 0.05 kWh$_{th}$/kWh$_{el}$ is found to be realistic for modern large turbines

A more recent study by Wagner and Pick (2004) confirms the energy payback times between 3 and 7 months, which – assuming a turbine lifetime of 20 years – corresponds to cumulative energy requirements between 0.035 and 0.075 kWh$_{th}$/kWh$_{el}$. The cumulative energy requirement η is related to the energy payback time, that is, the time it takes the wind turbine (lifetime T) to generate the primary-energy equivalent of its energy requirement, via $t_{payback} = \eta \cdot T \cdot \varepsilon_{fossil}$. ε_{fossil} is the conversion efficiency (assumed to be 35 %) of conventional power plants that are to be displaced by wind turbines.

Lenzen and Munksgaard (2002) found greenhouse gas intensities for the larger, modern turbines to be about 10 g/kWh$_{el}$, ranging among the lowest values for all electricity generation technologies. Lenzen and Wachsmann (2004) found large variations of specific life-cycle emissions of wind turbines between countries where turbine components were produced.

Roth et al. (2005) and Pehnt et al. (2008) take the reduced capacity credit of wind into account in their systems LCA and conclude that CO_2 emissions arising from the need of additional reserves add between 35 and 75 g CO_2/kWh, thus outweighing CO_2 emissions from the turbine life cycle. However, these values depend strongly on the technology mix of the overall power system.

Noise and impacts on birds are likely to be small from wind farms, compared to other impacts (GWEC 2008). Snyder and Kaiser (2009) provide a detailed account of possible ecological impacts from offshore wind farms.

The mitigation potential of wind in a power system represents an optimization problem, because the higher the penetration of wind power, the higher the emission reductions, and also the higher the variability cost.

Current Scale of Deployment

Due to large economies of scale, the scale of single wind energy converters has been increasing steadily (Fig. 12), featuring taller towers and larger rotors. Larger turbines with ratings above 3.5 MW are usually dedicated to offshore power generation, while onshore installations are usually rated between 1.5 and 3 MW (GWEC 2008). In early 2009, the French manufacturer Areva deployed 5 MW turbines for operation 45 km offshore of the German North Sea island of Borkum (Jha 2009). Five-megawatt turbines are also installed at the Beatrice site (40 m depth) off the Moray Firth east of Scotland (http://www.repower.de/index.php?id=369). In 2007, the average size of operating turbines was 1.5 MW.

Contribution to Global Electricity Supply

In 2008, the global capacity of wind energy converters was 121 GW, generating about 260 TWh of electricity or about 1.5 % of global electricity production (WWEA 2008). Most of the capacity (Fig. 1) is installed in the USA (25 GW, 1 % of electricity generation) and in the EU (about 65 GW, 3.7 %), followed by China

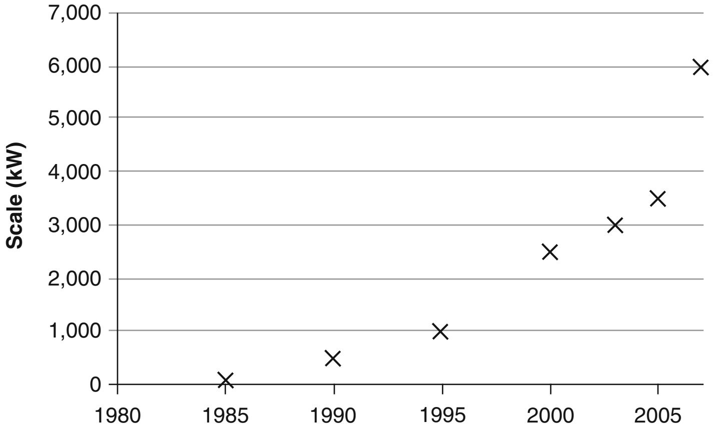


Fig. 12 Maximum scale of wind energy converters over time (Compiled after Hoogwijk et al. (2004), GWEC (2008), Joselin Herbert et al. (2007))

(12 GW) and India (10 GW). However, regional shares of wind power can be much higher in some countries: Denmark (21 %), Spain (12 %), Portugal (9 %), Ireland (8 %), and Germany (7 %). However, it is worth noting that Denmark at times receives much higher percentages of its electricity from wind and sometimes very little, in which case Denmark exports or imports electricity from the European grid and thus relies on other generation technology for load balancing (Pavlak 2008; Sovacool et al. 2008).

Wind energy deployment has been increasing rapidly throughout the past decade, recording growth rates of around 30 % since 1996 (Fig. 2). More than half of the 2008 additions occurred in the USA and in China (Fig. 3), with the USA overtaking Germany as the leader in installed wind capacity (WWEA 2008). In the USA, wind power has represented 40 % of 2007 national capacity growth (Bolinger and Wiser 2009).

Most of the wind generation is onshore; only about 1.1 GW is presently installed offshore, mainly located in Denmark (420 MW), the UK (300 MW), Sweden (135 MW), and the Netherlands (130 MW) (IEA 2008b, www.ieawind.org/Annex_XXIII.html). A further 8 GW were planned in early 2009 (Jha 2009).

Cost of Electricity Output

Capital costs make up about 80 % of total wind energy cost, with the remainder for operation and maintenance, since the wind turbine does not require any fuel input. Blanco (2008) presents a detailed breakdown of these costs; in onshore installations, the turbine covers 70 % of capital cost, with the remainder for grid connection, civil works, taxes, permits, etc. Within the turbine, the tower and blades make up for half of the costs. Electricity costs vary with site conditions: assuming a 20-year plant life, 5–10 % discount rate, and 23 % average capacity factor, Blanco (2008) states a levelized cost range for electricity from European 2 MW wind turbines between 6.5 and 13 US¢/kWh. Welch and Venkateswaran (2008) and Snyder and Kaiser (2009) report US cost estimate between 3 and 5 US¢/kWh and DeCarolis and Keith (2006) between 4 and 6 US¢/kWh.

Levelized electricity cost is the constant (discounted to present values) real wholesale price of electricity that recoups owners' and investors' capital costs, operating costs, fuel costs, income taxes, and associated cash flow constraints. They exclude costs for transmission and distribution. Levelized cost may differ from sales prices, because of profits or losses. The figures reported here are averages over plant types and vintages and over locations with varying resource endowments and demand profiles. Actual cost for particular plants may be different from the cost given here. Levelized electricity costs are strongly determined by the competitive landscape, in particular the extent and nature of regulation, subsidization and taxation, primary fuel (coal, gas, uranium) prices, and future carbon pricing. While under government regulation operators are able to transfer costs and risk to consumers and taxpayers, this is not the case in deregulated electricity markets, where high interest rates lead to investors favoring less capital-intensive and therefore less risk-prone power options. Electricity cost figures reported here refer to the financial and regulatory environment at the time of publication of the various references.

Civil works and especially the foundations are much more expensive in offshore installations, where they represent 20 % of capital cost, leading to higher levelized cost of 9–16 US¢/kWh. This is confirmed in an estimate of 10 US¢/kWh by Snyder and Kaiser (2009). However, technological learning can bring these costs down in the future (IEA 2008b; Smit et al. 2007).

Wind energy costs have increased during the past 3 years, mainly driven by supply tightness and price hikes of raw materials (IEA 2008b), which is difficult to control by government fiscal policy. Bolinger and Wiser (2009) provide a detailed analysis of most recent upward cost trends. Yet, the analysis of learning curves for the industry suggests that levelized costs will come down through increased efficiency, by about 10 % for every doubling of capacity (Blanco (2008); compare Fig. 14 in UNDP (2004)). As with other nonfossil electricity generation technologies, wind plant operators expect the competitive landscape to change in favor of wind power, once carbon is adequately priced (GWEC 2008; DeCarolis and Keith 2006). In the future, wind energy is also expected to benefit more from not being affected by fuel price volatility.

However, depending on the penetration of a power system with variable wind energy, additional indirect costs arise for maintaining LOLE, because wind energy will not be able to meet demand at its average capacity factor but at a generally reduced rate depending on its capacity credit (DeCarolis and Keith 2006). In addition, the presence of wind power in a power supply system introduces short-term variability and uncertainty and therefore requires balancing reserve scheduling and unit commitment. Grid operators need to meet peak demand to certain statistical reliability standards even when wind output falls relative to load. During these periods, which range from minutes to hours, electricity markets need to recruit demand-following units (such as gas, hydro, or storage), which at times of sufficient wind remain idle, so that costs arise essentially for two redundant systems (Pavlak 2008; Benitez et al. 2008) and for inefficient fuel use during frequent ramping (see p. 903 in Hoogwijk et al. (2007), Benitez et al. (2008), Smith et al. (2007)). Both adequacy and balancing cost (compare Fig. 10) are sometimes referred to as intermittency cost; however, in this chapter the term variability cost is used because strictly speaking wind energy is variable and not intermittent (Diesendorf 2007). Thus, wind energy reduces dependence on fuel inputs but does not eliminate the dependence on short-term balancing capacity and long-term reliable load-carrying capacity.

The impact of wind power on the power supply system is critically dependent on the technology mix in the remainder of the system, because the more flexible and load-following existing technologies, the less peak reserves are needed. It is also dependent on time characteristics of system procedures (frequency and duration of forecasts, etc.) and local market rules (Holttinen 2008). In general, the higher the wind penetration, the higher the variability in the supply system, and the more long-term reserve and short-term balancing capacity has to be committed (Fig. 13) on short-term balancing only. The corresponding cost increases are only partly offset by

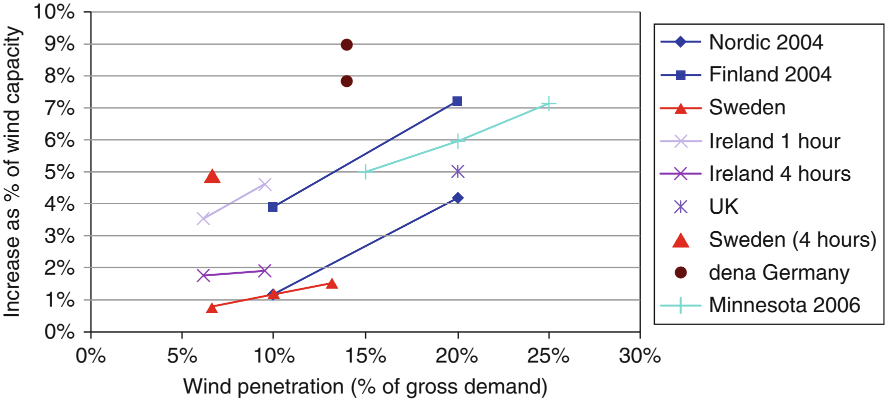


Fig. 13 Increase in short-term balancing requirement as a percentage of wind power as a function of wind penetration (After Holttinen et al. (2009))

a smoothing out of wind variability when many turbines are dispersed and interconnected over a wide geographical area (Hirst and Hild 2004), but they are more than offset by reduced fuel and operating cost. In specific applications, the cost of additional wind power also depends on the relative locations of turbines, load, and existing transmission lines and on whether sufficient load-carrying reserve exists in the grid or has to be built.

As expected, variability costs scatter significantly depending on a large array of parameters. They cannot be derived from capacity credit estimates, since these do not contain any information about to what extent cheap base load and expensive peak load are being displaced by wind (Martin and Diesendorf 1982). Variability costs are difficult to disentangle from overall cost in real-world grids (DeCarolis and Keith 2006), so that they have largely been estimated for theoretical settings, using statistical models for resource and load fluctuations and least-cost-optimizing generation and reserve scheduling under given output limits, startup and shutdown cost, ramp-rate restrictions, planned outages, fuel cost, and day-ahead forecasts (Holttinen et al. 2008; Hirst and Hild 2004). They have been quoted between 0.2 and 0.4 US¢/kWh for existing installations (Snyder and Kaiser 2009; GWEC 2008) and also higher at 1–1.8 US¢/kWh (DeCarolis and Keith 2006; Benitez et al. 2008; Ilex and Strbac 2002) for larger degrees of wind penetration. In a more up-to-date survey, Holttinen (2008), Strbac et al. (2007), and Smith et al. (2007) report on recent findings about increases in balancing requirements due to the presence of wind, ranging widely between 0.05 and 0.5 US¢/kWh (Fig. 14). Hence, at penetrations of up to 20 %, variability cost can be expected to be about equal or less than 10 % of generation cost.

Hoogwijk et al. (2007) (see Fig. 15) run numerical experiments at large-scale penetration rates of up to 45 % and find that beyond 30 % penetration the cost incurred by discarded excess electricity becomes comparable to base cost (6 US¢/kWh).

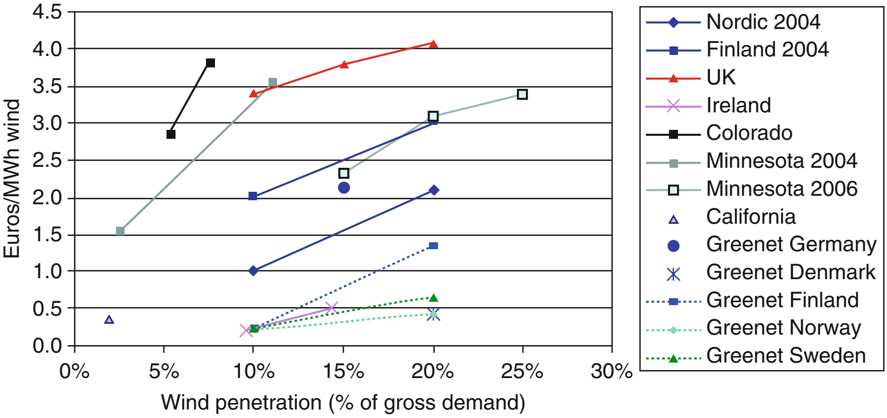


Fig. 14 Increase in balancing requirements per kWh of wind power as a function of wind penetration (After Holttinen et al. (2009))

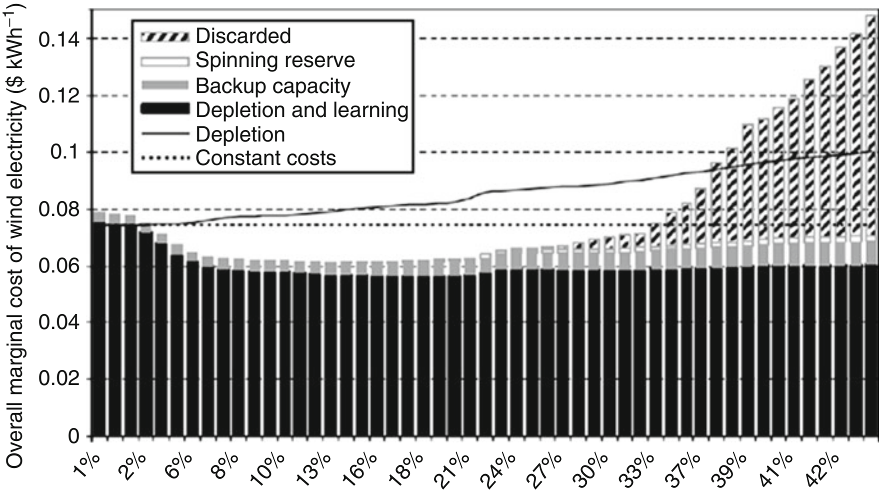


Fig. 15 Marginal cost of wind electricity at varying degrees of penetration (After Hoogwijk et al. (2007))

The market for wind turbine manufacturing is diverse and competitive, with manufacturers spread across many countries. However, large corporations are entering the market, sometimes assimilating smaller entities (GWEC 2008). During the recent wind market boom, and the shift to larger turbines, the industry faced a number of supply chain bottlenecks related to gearboxes and large bearings (Blanco 2008), leading to waiting times for turbines of up to 30 months (Sovacool et al. 2008).

Future Directions

Wind energy faces a number of technical future challenges. The variable and distributed nature of wind energy requires specific grid infrastructure in order to ensure grid stability, congestion management, and transmission efficiency. Significant investment in grid infrastructure has to occur in order to allow for substantial global penetration of wind energy (GWEC 2008). One of the most significant challenges is hence the integration of wind power into a large grid and the theoretical modeling of power system behavior at high penetration rates of wind. Recent efforts are also aimed at improving short-term forecasting of wind, which is still less accurate than forecasting of load (Holttinen et al. 2009). With increasing interconnection and geographical dispersion, forecasting errors are expected to decrease (see Fig. 16).

Some researchers suggest directing wind power to where it can be most competitive or where its variability does not create problems. Some industrial applications and also combined heat and power plants can – within limits – adjust their demand to supply (Østergaard 2003). Dedicated load-leveling applications such as desalination, aluminum smelting, space and water heating, or chargeable hybrid vehicle fleet can deal with hourly variations in wind power since they only require a certain amount of energy over a period of many hours (Kempton et al. 2007; Pavlak 2008). For example, large-scale vehicle-to-grid technologies can significantly reduce excess wind power at large wind penetration and replace a significant fraction of regulating capacity, but as Lund and Kempton (2008) show in a study for Denmark, electric vehicles would not nearly eliminate excess power and CO_2 emissions, even if they had long-range battery storage.

Tavner (2008) and Smith et al. (2007) list improvements in resource, turbine and systems modeling and forecasting, capital cost reduction, lifetime extension, transmission upgrading, and system integration as the main future research challenges for wind power. Joselin Herbert et al. (2007) review past developments and present

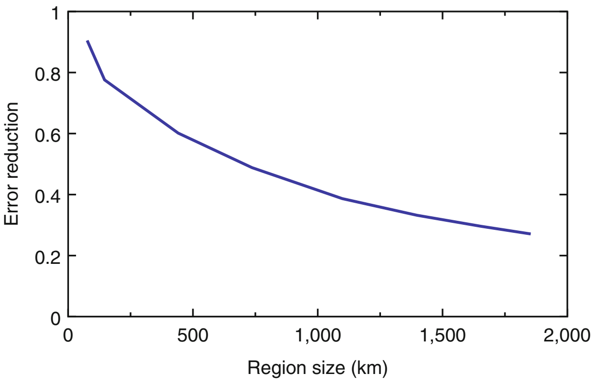


Fig. 16 Measured forecast error as a function of spatial range of interconnection (After Rohrig). The error reduction plotted on the y-axis is the ratio of the root-mean-square error (*RMSE*) of prediction at a regional scale and the single-site prediction RMSE

research needs for wind technologies, such as for resource assessment, site selection, turbine aerodynamics, wake effects, and turbine reliability. Offshore wind deployment faces technical challenges in the form of extreme wind conditions that exceed tolerances of current onshore turbines (Snyder and Kaiser 2009; Smit et al. 2007). The IEA Wind Offshore subgroup's tasks include research on ecological issues and deepwater installation. In order to reduce offshore wind costs, turbine concepts, submerged structures and cabling, and remote operation and maintenance will need to undergo further research (Blanco 2008). Many of the above issues are approached through theoretical modeling, be it turbine structure, system control and balancing, wind conditions, or reliability (Tavner 2008). Surprisingly, offshore wind power generation shares many of large hydropower and nuclear power's challenges regarding public opinion. Firestone and Kempton (2007) report a case study where the majority of survey respondents opposed offshore wind power development for environmental reasons and that many of the beliefs were "stunningly at odds" with the scientific literature. Perceived landscape changes also feature in a survey by Zoellner et al. (2008), but economic considerations more strongly influenced acceptance.

Summary

Wind energy deployment has witnessed a rapid increase throughout the past decade, with annual growth rates around 30 %, generating now about 1.5 % of global electricity. The technology is mature and simple, and decades of experience exist in a few countries. Due to strong economies of scale, wind turbines have grown to several megawatts per device, and wind farms have now been deployed offshore. In recent years, wind power has become competitive without subsidies, in markets without carbon pricing. The global technical potential of wind exceeds current global electricity consumption; however, taking into account the temporal mismatch and geographical dispersion of wind energy and demand loads and requirements for supply–load balance and grid stability, the maximum economic potential appears to be in the order of 20 % of electricity consumption. At such rates of wind energy penetration, and without storage and supply matched demand, the integration of wind power into electricity grids and long-distance transmission begins to present significant challenges for system reliability and loss-of-load expectation. The main issue for future deep penetrations of wind on a global scale is hence how wind plants can be integrated across very large geographical scales and with other variable power sources. For example, there are popular proposals for integrating parts of North African solar power for output smoothing of large wind supply in Europe. Some commentators remark that these proposals may be difficult to implement because of political and supply security issues; others are more optimistic. Finally, the life-cycle greenhouse gas emissions from wind power are some of the lowest among all electricity-generating technologies, but depending on the remainder of the power supply system, emissions arise because of the use of conventional technologies for supply–demand balancing.

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