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Chapter 7

Wind Power

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Author(s):	CLAs:	Ryan Wiser, Zhenbin Yang			
	LAs:	Maureen Hand, Olav Hohmeyer, David Infield, Peter Hjuler Jensen, Vladimir Nikolaev, Mark O'Malley, Graham Sinden, Arthouros Zervos			
	CAs:	Naim Darghouth, Dennis Elliott, Hannele Holttinen, Jason Jonkman, Andrew Mills, Patrick Moriarty, Sara Pryor, Charles Smith			
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All monetary values provided in this document either have been or will be adjusted for inflation/deflation and then converted to USD for the base year 2005.

Chapter 7: Wind energy

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EXECUTIVE SUMMARY

Wind energy offers significant potential for near- and long-term carbon emissions reduction. Though there are a number of different wind energy technologies available within a range of applications, the primary use of wind energy of relevance to climate change mitigation is to generate electricity from larger, grid-connected wind turbines, deployed either on- or off-shore. Focusing on these technologies, the wind power capacity installed by the end of 2009 was capable of meeting roughly 1.8% of worldwide electricity demand, and that contribution could grow to in excess of 20% by 2050 if ambitious efforts are made to reduce carbon emissions and to mitigate the other barriers to increased wind energy deployment. On-shore wind energy is already being deployed at a rapid pace in many countries, and no insurmountable technical barriers exist that preclude increased levels of wind energy penetration into electricity supply systems. Moreover, though average wind speeds vary considerably by location, ample technical potential exists in most regions of the world to enable significant wind energy development. In areas with particularly good wind resources, the cost of wind energy can be competitive with fossil generation but, in most regions of the world, policy measures are required to make wind energy economically attractive. Nonetheless, continued advancements in both on- and off-shore wind energy technology are expected, further reducing the cost of wind energy and improving wind energy’s carbon emissions mitigation potential.

The wind energy market has expanded rapidly. Modern wind turbines have evolved from small, simple machines to large, highly sophisticated devices, driven in part by more than three decades of basic and applied R&D. The resulting cost reductions, along with government policies to expand RE supply, have led to rapid market development, demonstrating the commercial and economic viability of the technology. From a cumulative capacity of 14 GW by the end of 1999, the global installed wind power capacity increased twelve-fold in ten years to reach almost 160 GW by the end of 2009. Most additions have been on-shore, but 2.1 GW of off-shore wind power capacity was installed by the end of 2009, with European countries embarking on ambitious programmes of off-shore wind energy deployment. From 2000 through 2009, roughly 11% of global net electric capacity additions came from new wind power plants; in 2009 alone, that figure was likely more than 20%. Total investment in wind power installations in 2009 equaled roughly US$57 billion, while direct employment in the wind energy sector has been estimated at 500,000. Nonetheless, wind electricity remains a relatively small fraction of worldwide electricity supply, and growth has been concentrated in Europe, Asia, and North America (Latin America, Africa and the Middle East, and the Pacific regions have installed relatively little wind power capacity). The top five countries in cumulative installed capacity by the end of 2009 were the U.S., China, Germany, Spain, and India; the top five countries in terms of wind electricity supply as a proportion of total electricity consumption were Denmark, Portugal, Spain, Ireland, and Germany. In the late 2000s, the U.S. and then China became the locations for the greatest annual capacity additions. Policy frameworks continue to play a significant role in wind energy utilization, and expansion of wind energy, especially in regions of the world with little wind energy development to date and in off-shore locations, is likely to require additional policy measures.

The global wind energy resource is sizable. A growing number of global wind resource assessments have demonstrated that the world’s technical potential for wind energy exceeds global electricity demand. Estimates of global technical potential range from a low of 70 EJ/y (excluding off-shore) to a high of 1,000 EJ/y (including on- and off-shore); estimates of the potential for off-shore wind energy alone range from 15 EJ/y to 130 EJ/y. Although the global potential for wind energy is not fixed (but is instead related to the status of the technology, the economics of wind energy, and subjective judgments on other constraints to wind energy development) and further

advancements in wind resource assessment methods are needed, the technical potential for the resource itself is unlikely to be a limiting factor on global wind energy development. Instead, economic constraints associated with the cost of wind energy, the institutional constraints and costs associated with transmission grid access and operational integration, and issues associated with social acceptance and environmental impacts are likely to restrict growth well before any absolute global technical resource limits are encountered. Ample potential also exists in most regions of the world to enable significant wind energy development. That said, the wind resource is not evenly distributed across the globe, and wind energy will therefore not contribute equally in meeting the needs of every country. Additionally, the wind resource is not uniformly located near population centres – some of the resource is therefore economically less feasible. Research into the effects of global climate change on the geographic distribution and variability of the wind resource is nascent, as is research on the possible impacts of climate change on extreme weather events and therefore wind turbine operating environments. Research to date, however, suggests that global climate change will alter the geographic distribution of the wind resource, but that those effects are unlikely to be of a magnitude to greatly impact the global potential for wind energy to reduce carbon emissions.

Analysis and experience demonstrate that successful integration of wind energy is achievable. Wind energy has characteristics that pose new challenges to electric system planners and operators, such as variable electrical output, reduced predictability, and locational dependence. Nonetheless, wind electricity has been successfully integrated into existing electricity supply systems without compromising system security and reliability; in some countries, wind energy supplies in excess of 10% of aggregate annual electricity demand. Because the characteristics of the existing electric system determine the ease of integrating wind energy, acceptable wind electricity penetration limits and the operational costs of integration are system-specific. Nevertheless, theoretical analyses and practical experience suggest that, at low to medium levels of wind electricity penetration (under 20% of total electricity demand), the operational integration of wind energy generally poses no insurmountable technical barriers and is economically manageable. That said, concerns about (and the costs of) wind energy integration will grow with wind energy deployment and, even at medium penetration levels, integration issues must be addressed both at the local and system levels through stability and balancing requirements. Active management through a broad range of strategies is anticipated, including the use of flexible power generation technologies, wind energy forecasting and output curtailment, and increased coordination and interconnection between electric systems; demand-side management, energy storage technologies, and geographic diversification of wind power plant siting will also become increasingly beneficial as wind electricity penetration rises. Finally, significant new transmission infrastructure, both on-shore and off-shore, would be required to access areas with the best wind resource conditions. Both cost and institutional barriers would need to be overcome to develop this infrastructure. At low to medium levels of wind electricity penetration, the available literature suggests that the additional costs of managing electric system variability and uncertainty, ensuring resource adequacy, and adding new transmission to accommodate wind energy will generally not exceed 30% of the generation cost of wind energy.

Environmental and social issues will affect wind energy deployment opportunities. Wind energy has significant potential to reduce (and is already reducing) GHG emissions, together with the emissions of other air pollutants. The energy used and emissions produced in the manufacture and installation of wind turbines are small compared to the energy generated and emissions avoided over the lifetime of wind power plants (the carbon intensity of wind energy is estimated to range from 4.6 to 27 gCO_2/kWh, whereas energy payback times are between 3 to 9 months). In addition, managing the variability of wind power production has not been found to significantly degrade the carbon emissions benefits of wind energy. Alongside these benefits, however, wind energy also has the potential to produce some negative impacts on the environment and on human beings.

Prominent environmental concerns about wind energy include bird and bat collision fatalities and habitat and ecosystem modifications, while prominent social concerns include visibility and landscape impacts as well various nuisance effects and radar interference. Modern wind energy technology involves large structures, so wind turbines are unavoidably visible in the landscape, and planning wind power plants often creates local public concern. Appropriate siting of wind turbines is important in minimizing the impact of wind energy development on local communities, and engaging local residents in consultation during the planning stage is often an integral aspect of the development process. The construction and operation of both on- and off-shore wind power plants also impacts wildlife through bird and bat collisions and through habitat and ecosystem modifications, with the nature and magnitude of those impacts being site- and species-specific. Attempts to measure the relative impacts of various electricity supply technologies suggest that wind energy generally has a comparatively small environmental footprint, but impacts do exist, and techniques for assessing, minimizing, and mitigating those concerns could be improved. Though community and scientific concerns should be addressed, streamlined planning, siting, and permitting procedures may be required to enable more-rapid growth in wind energy utilization.

Technology innovation and underpinning research can further reduce the cost of wind energy. Current wind turbine technology has been developed largely for on-shore applications, and has converged to three-bladed upwind rotors, with variable speed operation. Though on-shore wind energy technology is reasonably mature, continued incremental advancements are expected to yield improved design procedures, increased reliability and energy capture, reduced O&M costs, and longer component life. In addition, as off-shore wind energy gains more attention, new technology challenges arise, and more-radical technology innovations are possible (e.g., floating turbines). Advancements can also be gained through more-fundamental research to better understand the operating environment in which wind turbines must operate. The cost of wind energy is affected by five fundamental factors: annual energy production, installation costs, operating and maintenance costs, financing costs, and the assumed economic life of the power plant. Though the cost of wind energy has declined significantly since the beginnings of the modern wind energy industry in the 1980s, in most regions of the world, policy measures are required to make wind energy economically attractive. In areas with particularly good wind resources or particularly costly alternative forms of energy supply, however, the cost of wind energy can be competitive with fossil generation. For on-shore wind power plants built in 2009, levelized costs in good to excellent wind resource regimes averaged US$50-100/MWh; levelized costs can reach US$150/MWh in lower resource areas. Off-shore wind energy had typical levelized costs that ranged from US$100/MWh to US$200/MWh. It is estimated that continued R&D, testing, and operational experience could yield reductions in the levelized cost of on-shore wind energy, relative to these 2009 levels, of 7.5-25% by 2020, and 15-35% by 2050. The available literature suggests that off-shore wind energy has greater potential for cost reductions: 10-30% by 2020 and 20-45% by 2050.

Wind energy offers significant potential for near- and long-term carbon emissions reduction. Given the commercial maturity and cost of on-shore wind energy technology, increased utilization of wind energy offers the potential for significant near-term carbon emissions reductions: this potential is not conditioned on technology breakthroughs, and related systems integration challenges are manageable. As technology advancements continue, especially for off-shore wind energy, greater contributions to carbon emissions reduction are possible in the longer term. Based on a review of the carbon and energy scenarios literature, wind energy’s contribution to global electricity supply could rise from 1.8% by the end of 2009 to 13% by 2050 in the median scenario, and to 21-26% by 2050 at the 75th percentile of scenarios, if ambitious efforts are made to reduce carbon emissions. Achieving the higher end of this range of global wind energy utilization would likely require not only economic support policies of adequate size and predictability, but also an expansion of wind energy utilization regionally, increased reliance on off-shore wind energy in some regions, technical and institutional solutions to transmission constraints and operational integration concerns, and proactive efforts to mitigate and manage social and environmental concerns associated with wind energy deployment. Though R&D is expected to lead to incremental cost reductions for on-shore wind energy technology, enhanced R&D expenditures may be especially important for off-shore wind energy technology. Finally, for those markets with good wind resource potential but that are new to wind energy deployment, both knowledge (e.g., wind resource mapping expertise) and technology (e.g., to develop local wind turbine manufacturers and to ease grid integration) transfer may help facilitate early wind power installations.

7.1 Introduction

This chapter addresses the potential role of wind energy in reducing GHG emissions. Wind energy (in many applications) is a mature renewable energy (RE) source that has been successfully deployed in many countries, is technically and economically capable of significant continued expansion, and its further exploitation may be a crucial aspect of global GHG reduction strategies. Though average wind speeds vary considerably by location, the world's technical potential for wind energy exceeds global electricity demand, and ample potential exists in most regions of the world to enable significant wind energy development.

Wind energy relies, indirectly, on the energy of the sun. A small proportion of the solar radiation received by the earth is converted into kinetic energy (Hubbert, 1971), the main cause of which is the imbalance between the net outgoing radiation at high latitudes and the net incoming radiation at low latitudes. The earth's rotation, geographic features, and temperature gradients affect the location and nature of the resulting winds (Burton *et al.*, 2001). The use of wind energy requires that the kinetic energy of moving air be converted to useful energy. Because the theoretically-extractable kinetic energy in the wind is proportional to the cube of wind speed, the economics of using wind for electricity supply are highly sensitive to local wind conditions.

Wind energy has been used for millennia (for historical overviews, see, e.g., Gipe, 1995; Ackermann and Soder, 2002; Pasqualetti *et al.*, 2004). Sailing vessels relied on the wind from at least 3,100 BC, with mechanical applications of wind energy in grinding grain, pumping water, and powering factory machinery following, first with vertical axis devices and subsequently with horizontal axis turbines. By 200 B.C., for example, simple windmills in China were pumping water, while vertical-axis windmills were grinding grain in Persia and the Middle East. By the 11th century, windmills were used in food production in the Middle East; returning merchants and crusaders carried this idea back to Europe. The Dutch refined the windmill and adapted it for draining lakes and marshes in the Rhine River Delta. When settlers took this technology to the New World in the late 19th century, they began using windmills to pump water for farms and ranches. Industrialization and rural electrification, first in Europe and later in America, led to a gradual decline in the use of windmills for mechanical applications. The first successful experiments with the use of wind to generate electricity are often credited to Charles Brush (1887) and Poul la Cour (1891). Use of wind electricity in rural areas and, experimentally, in larger-scale applications, continued throughout the mid-1900s. However, the use of wind to generate electricity on a commercial scale began in earnest only in the 1970s, first in Denmark on a relatively small scale, then on a much larger scale in California (1980s), and then in Europe more broadly (1990s).

The primary use of wind energy of relevance to climate change mitigation is to generate electricity from larger, grid-connected wind turbines, deployed either in a great number of smaller wind power plants or a smaller number of much larger plants. As of 2010, such turbines typically stand on tubular towers of 50-100 meters in height, with three-bladed rotors of 50-100 meters in diameter; machines with rotor diameters and tower heights of 130 meters were operating, and even larger machines are under development. Wind power plants are commonly sited on land: by the end of

2009, wind power plants sited in shallow and deeper water off-shore were a relatively small proportion of global wind power installations. Nonetheless, as wind energy deployment expands and as the technology becomes more mature, off-shore wind energy is expected to become a more significant source of overall wind energy supply.

Due to their potential importance to climate change mitigation, this chapter emphasizes grid-connected on- and off-shore wind turbines for electricity production. Notwithstanding this focus, wind energy has served and will continue to meet other energy service needs. In remote areas of the world that lack centrally provided electricity supplies, smaller wind turbines can be deployed alone or alongside other technologies to meet individual household or community electricity demands; small turbines of this nature also serve marine energy needs. Small-island or remote electricity grids can also employ wind energy, along with other energy sources. Even in urban settings that already have ready access to electricity, smaller wind turbines can, with careful siting, be used to meet a portion of building energy needs. New concepts for higher-altitude wind energy machines are also under consideration and, in addition to electricity supply, wind energy can meet mechanical and propulsion needs in specific applications. Though not the focus of this chapter, these additional wind energy applications and technologies are briefly summarized in Text Box 7.1.

Drawing on available literature, this chapter begins by describing the size of the global wind energy resource, the regional distribution of that resource, and the possible impacts of climate change on the resource (Section 7.2). The chapter then reviews the status of and trends in modern on-shore and off-shore wind energy technology (Section 7.3). Following that, the chapter discusses the status of the wind energy market and industry developments, both globally and regionally, and the impact of policies on those developments (Section 7.4). Near-term issues associated with the integration of wind energy into electricity supply systems are addressed (Section 7.5), as is available evidence on the environmental and social impacts of wind energy (Section 7.6). The prospects for further technology improvement and innovation are summarized (Section 7.7), and historical, current, and potential future cost trends are reviewed (Section 7.8). The chapter concludes with an examination of the potential future deployment of wind energy, focusing on the carbon mitigation and energy scenarios literature (Section 7.9).

Box 7.1. Alternative wind energy applications and technologies.

Beyond the use of large, modern wind turbines for electricity supply, a number of additional wind energy applications and technologies are currently employed or are under consideration. Though these technologies and applications are at different phases of market development, and each holds a certain level of promise for scaled deployment, none are likely to compete with traditional large on- and off-shore wind energy technology from the perspective of carbon emissions reduction, at least in the near- to medium-term.

Small wind turbines for electricity supply. Smaller-scale wind turbines are used in a wide range of applications. Though wind turbines from hundreds of watts to tens of kilowatts in size do not benefit from the economies of scale that have helped reduce the cost of larger wind turbines, they can be economically competitive with other supply alternatives in areas that do not have access to centrally provided electricity supply (Byrne *et al.*, 2007). For rural electrification or isolated areas, small wind turbines can be used on a stand-alone basis for battery charging or can be combined with other supply options (e.g., solar and/or diesel) in hybrid systems. As an example, China had 57 MW of cumulative small (<100 kW) wind power capacity installed by the end of 2008 (Li and Ma, 2009); 33 MW were reportedly installed in China in 2009. Small wind turbines are also employed in grid-connected applications for both residential and commercial electricity customers. Though the use of wind energy in these disparate applications can provide economic and social development benefits, the current and future size of this market makes it an unlikely source of significant long-term carbon emissions reductions; AWEA (2009b) estimates annual global installations of <100 kW wind turbines from leading manufacturers at under 40 MW in 2008. In addition, in urban settings where the wind resource is highly site-specific and can be poor, the carbon emissions savings associated with the displacement of grid electricity can be low or even zero once the manufacture and installation of the turbines are taken into account (Carbon Trust 2008a; Allen *et al.*, 2008).

Wind energy to meet mechanical and propulsion needs. Among the first technologies to harness the energy from the wind are those that directly used the kinetic energy of the wind as a means of marine propulsion, grinding of grain, and water pumping. Though these technologies were first developed long ago, there remain opportunities for the expanded use of wind energy to meet mechanical and propulsion needs (e.g., Purohit, 2007). New concepts to harness the energy of the wind for propulsion are also under development, such as using large kites to complement diesel engines for marine transport. Demonstration projects and analytic studies have found that these systems may yield fuel savings of up to 50%, though this depends heavily on the technology and wind conditions (O'Rourke, 2006; Naaijen and Koster, 2007).

Higher-altitude wind electricity. Higher-altitude wind energy systems have recently received some attention as an alternative approach to generating electricity from the wind (Roberts *et al.*, 2007; Argatov *et al.*, 2009; Archer and Caldeira, 2009; Kim and Park, 2010; Argatov and Silvennoinen, 2010). A principal motivation for the development of this technology is the sizable wind resource present at higher altitudes. There are two main approaches to higher-altitude wind energy that have been proposed: (1) tethered wind turbines that transmit electricity to earth via cables, and (2) base stations that convert the kinetic energy from the wind collected via kites to electricity at ground level. A variety of concepts are under consideration, operating at altitudes of less than 500 meters to more than 10,000 meters. Though some research has been conducted on these technologies and on the size of the potential resource, the technology remains in its infancy, and scientific, economic, institutional challenges must be overcome before a realistic estimate of the carbon emissions reduction potential of higher-altitude wind energy can be developed.

7.2 Resource potential

The global resource potential for wind energy is not fixed, but is instead related to the status of the technology, the economics of wind energy, and the assumptions made regarding other constraints to wind energy development. Nonetheless, a growing number of global wind resource assessments have demonstrated that the world's technical potential for wind energy exceeds global electricity demand, and that ample potential exists in most regions of the world to enable significant wind energy development. However, the wind resource is not evenly distributed across the globe, and wind energy will therefore not contribute equally in meeting the needs of every country. This section summarizes available evidence on the size of the global technical resource potential for wind energy (7.2.1), the regional distribution of that resource (7.2.2), and the possible impacts of climate change on wind energy resources (7.2.3). This section focuses on long-term average annual technical resource potential; for a discussion of seasonal and diurnal patterns, as well as shorter-term wind power variability, see Section 7.5.

7.2.1 Global technical resource potential

A number of studies have estimated the global technical resource potential for wind energy. In general, two methods can be used to make these estimates: first, available wind speed measurements can be interpolated to construct a surface wind distribution; and second, physics-based numerical weather prediction models can be applied. Studies of the global wind energy resource have used varying combinations of these two approaches, and have typically used relatively simple analytical techniques with coarse spatial and temporal resolution.[1] Additionally, it is important to recognize that estimates of the resource potential for wind energy should not be viewed as fixed – they will change as wind energy technology develops and as more is learned about technical, environmental, and social concerns that may influence development.

Synthesizing the available literature, the IPCC's Fourth Assessment Report identified 600 EJ/y of on-shore wind energy technical resource potential (IPCC, 2007), just 0.95 EJ (0.2%) of which was being used for wind energy supply in 2005. The IPCC (2007) estimate appears to derive from a study authored by Grubb and Meyer (1993). Using the direct equivalent method of deriving primary energy equivalence (where electricity supply, in TWh, is translated directly to primary energy, in EJ; see Chapter 1), the IPCC (2007) estimate of on-shore wind energy potential is 180 EJ/y (50,000 TWh/y), almost three times greater than global electricity demand in 2007 (19,800 TWh).[2]

Since the Grubb and Meyer (1993) study, a number of analyses have been undertaken to estimate the global technical potential for wind energy. The methods and results of these assessments are summarized in Table 7.1.

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[1] Wind power plant developers may rely upon global and regional wind resource estimates to obtain a general sense for the locations of potentially promising development prospects. However, on-site collection of actual wind speed data at or near turbine hub heights remains essential for most wind power plants of significant scale.

[2] The IPCC (2007) cites Johansson *et al.* (2004), which obtains its data from Goldemberg (2000), which in turn references WEC (1994) and Grubb and Meyer (1993). To convert from TWh to EJ, the documents cited by IPCC (2007) use the standard conversion, and then divide by 0.3 (i.e.., the "substitution" method of energy accounting in which RE supply is assumed to substitute the primary energy of fossil fuel inputs into conventional power plants, accounting for plant conversion efficiencies). The direct equivalent method does not take this last step, and instead counts the electricity itself as primary energy (see Chapter 1), so this chapter reports the IPCC (2007) figure at 180 EJ/y, or roughly 50,000 TWh/y. This figure is close to that estimated by Grubb and Meyer (1993).

Table 7.1. Global assessments of technical wind energy resource potential.

Study	**Scope**	**Methods and Assumptions***	**Results****
Krewitt *et al.* (2009)	On-shore & Off-shore	Updated Hoogwijk and Graus (2008), itself based on Hoogwijk *et al.* (2004), by revising off-shore wind power plant spacing by 2050 to 16 MW/km^2	*Technical:* 121,000 TWh/y 440 EJ/y
Lu *et al.* (2009)	On-shore & Off-shore	>20% capacity factor (Class 1); 100m hub height; 9 MW/km^2 spacing; based on coarse simulated model dataset; exclusions for urban and developed areas, forests, inland water, permanent snow/ice; off-shore assumes 100m hub height, 6 MW/km^2, <92.6 km from shore, <200m depth, no other exclusions	*Technical (limited constraints):* 840,000 TWh/y 3,050 EJ/y
Hoogwijk and Graus (2008)	On-shore & Off-shore	Updated Hoogwijk *et al.* (2004) by incorporating off-shore wind energy, assuming 100m hub height for on-shore, and altering cost assumptions; for off-shore, study updates and adds to earlier analysis by Fellows (2000); other assumptions as listed below under Hoogwijk *et al.* (2004); technical potential defined in economic terms separately for on-shore and off-shore	*Technical/Economic:* 110,000 TWh/y 400 EJ/y
Archer and Jacobson (2005)	On-shore & Near-Shore	>Class 3; 80m hub height; 9 MW/km^2 spacing; 48% average capacity factor; based on wind speeds from surface stations and balloon-launch monitoring stations; constrained technical potential = 20% of total potential	*Technical (limited constraints):* 627,000 TWh/y 2,260 EJ/y *Technical (more constraints):* 125,000 TWh/y 450 EJ/y
WBGU (2004)	On-shore & Off-shore	Multi-MW turbines; based on interpolation of wind speeds from meteorological towers; exclusions for urban areas, forest areas, wetlands, nature reserves, glaciers, and sand dunes; local exclusions accounted for through corrections related to population density; off-shore to 40m depth, with sea ice and minimum distance to shore considered regionally; sustainable potential = 14% of technical potential	*Technical:* 278,000 TWh/y 1,000 EJ/y *Sustainable:* 39,000 TWh/y 140 EJ/y
Hoogwijk *et al.* (2004)	On-shore	>4 m/s at 10m (some less than Class 2); 69m hub height; 4 MW/km^2 spacing; assumptions for availability / array efficiency; based on interpolation of wind speeds from meteorological towers; exclusions for elevations >2000m, urban areas, nature reserves, certain forests; reductions in use for many other land-uses; economic potential defined here as <US$100/MWh (2005$)	*Technical:* 96,000 TWh/y 350 EJ/y *Economic:* 53,000 TWh/y 190 EJ/y
Fellows (2000)	On-shore & Off-shore	50m hub height; 6 MW/km^2 spacing; based on upper-air model dataset; exclusions for urban areas, forest areas, nature areas, water bodies, and steep slopes; additional maximum density criterion; off-shore assumes 60m hub height, 8 MW/km^2 spacing, to 40m depth, 5-40 km from shore, with 75% exclusion; technical potential defined here in economic terms: <US$230/MWh (2005$) in 2020; focus on four regions, with extrapolations to others; some countries omitted altogether	*Technical/Economic:* 46,000 TWh/y 170 EJ/y
WEC (1994)	On-shore	>Class 3; 8 MW/km^2 spacing; 23% average capacity factor; based on an early global wind resource map;	*Technical (limited constraints):*

		constrained technical potential = 4% of total potential	484,000 TWh/y 1,740 EJ/y *Technical (more constraints):* 19,400 TWh/y 70 EJ/y
Grubb and Meyer (1993)	On-shore	>Class 3; 50m hub height; assumptions for conversion efficiency and turbine spacing; based on an early global wind resource map; exclusions for cities, forests, and unreachable mountain areas, as well as for social, environmental, and land use constraints, differentiated by region (results in constrained technical potential = ~10% of total potential, globally)	*Technical (limited constraints):* 498,000 TWh/y 1,800 EJ/y *Technical (more constraints):* 53,000 TWh/y 190 EJ/y

* Where used, wind resource classes refer to the following wind densities at a 50 meter hub height: Class 1 (<200 W/m2), Class 2 (200-300 W/m2), Class 3 (300-400 W/m2), Class 4 (400-500 W/m2), Class 5 (500-600 W/m2), Class 6 (600-800 W/m2), and Class 7 (>800 W/m2).

** Reporting of resource potential and conversion between EJ and TWh are based on the direct equivalent method (see Chapter 1). Definitions for theoretical, technical, economic, and sustainable potential are provided in the glossary of terms, though individual authors cited in Table 7.1 often use different definitions of these terms.

Among all of these studies, the global (constrained) technical resource potential for wind energy ranges from a low of 70 EJ/y (excluding off-shore) to a high of 1,000 EJ/y (including on- and off-shore), or from 19,400 to 278,000 TWh/y. (Excluded here are those assessments that applied limited development constraints; if those assessment are included, the absolute range of technical potential would expand to 70 EJ/y to 3,050 EJ/y). This range equates to between one and 14 times 2007 global electricity demand. Results vary based on whether off-shore wind energy is included, the wind speed data that are used, the areas assumed available for wind energy development, the rated output of wind turbines installed per unit of land area, and the assumed performance of wind power plants, which itself is related to hub height and turbine technology. Estimates of technical potential are dependent on technical assumptions as well as subjective judgements of development constraints.

There are three main reasons to believe that many of the studies reported in Table 7.1 may understate the global technical resource potential for wind energy. First, several of the studies are dated, and considerable advances have occurred in both wind energy technology and resource assessment methods. In part as a result, the six most-recent studies listed in Table 7.1 calculate larger technical resource potentials than the earlier studies (i.e., WBGU, 2004; Hoogwijk *et al.*, 2004; Archer and Jacobson, 2005; Hoogwijk and Graus, 2008; Krewitt *et al.*, 2009; Lu *et al.*, 2009). Second, a number of the studies included in Table 7.1 exclude the technical potential of off-shore wind energy. Though research has consistently found the technical potential for off-shore wind energy to be smaller than for on-shore wind energy and to be highly dependent on assumed technology developments, the potential for off-shore wind energy is nonetheless sizable, at 15-130 EJ/y (4,000-37,000 TWh/y).[3] Finally, even some of the more-recent studies reported in Table 7.1

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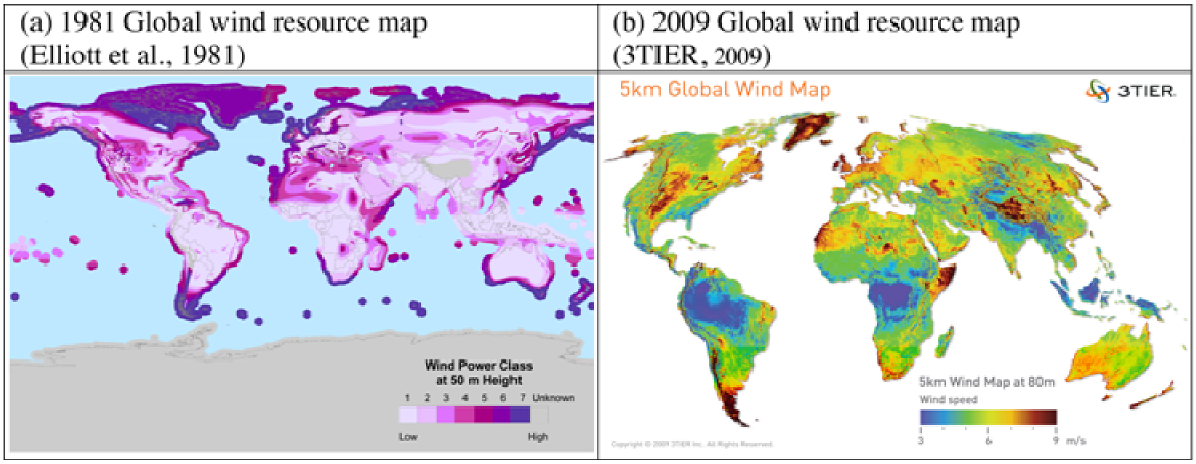
[3] The size of the off-shore wind energy resource is, at least theoretically, enormous, and constraints are primarily economic rather than technical. In particular, water depth, accessibility, and grid interconnection may limit development to relatively near-shore locations in the medium term, though technology improvements are expected, over time, to enable deeper-water and more-remote installations. Relatively few studies have investigated the global off-shore technical wind energy resource potential, and neither Archer and Jacobson (2005) nor WBGU (2004) report off-shore potential separately from the total potential reported in Table 7.1. In one study of global potential, Leutz *et al.* (2001) estimate an off-shore wind energy potential of 130 EJ/y (37,000 TWh/y) at depths less than 50m. Building from Fellows (2000) and Hoogwijk and Graus (2008), Krewitt *et al.* (2009) estimate a global off-shore wind energy potential of 57 EJ/y by 2050 (16,000 TWh/y) [Fellows (2000) provides an estimate of 15 EJ/y, or more than 4,000 TWh/y, whereas Hoogwijk and Graus (2008) estimate 23 EJ/y, or 6,100

likely understate the global technical potential for wind energy due to methodological limitations.[4] Enabled in part by an increase in computing power, more sophisticated and finer-geographic-resolution atmospheric modelling approaches are beginning to be applied (and increasingly validated with higher-quality measurement data) on a country or regional basis, as described in more depth in Section 7.2.2. Experience shows that these techniques have often identified greater actual wind energy resource potential than the earlier global assessments had estimated (see Section 7.2.2). As visual demonstration of these advancements, Figure 7.1(a,b) presents two global wind resource maps, one created in 1981 (Elliot *et al.*, 1981) and another in 2009 (3Tier, 2009).[5]



(a) 1981 Global wind resource map (Elliott et al., 1981)

(b) 2009 Global wind resource map (3TIER, 2009)

Figure 7.1(a,b). Example global wind resource maps from 1981 and 2009.

Despite the limitations of the available literature, it can be concluded that the IPCC (2007) estimate of 180 EJ/y likely understates by at least a factor of two the technical potential for wind energy, and that the global wind resource is unlikely to be a limiting factor on global wind energy development. Instead, economic constraints associated with the cost of wind energy, the institutional constraints and costs associated with transmission grid access and operational integration, and issues associated with social acceptance and environmental impacts are likely to restrict growth well before any absolute global technical resource limits are encountered.

TWh/y]. In another study, Siegfriedsen *et al.* (2003) calculate the technical potential of off-shore wind energy outside of Europe as 17 EJ/y (4,600 TWh/y). Lu *et al.* (2009) estimate an off-shore wind energy resource potential of 540 EJ/y (150,000 TWh/y), of which 150 EJ/y (42,000 TWh/y) is available at depths of less than 20m, though this study does not consider as many development constraints as the other estimates listed here. A number of regional studies have been completed as well, including (but not limited to) those that have estimated the size of the off-shore wind energy resource in the EU (Matthies and Garrad, 1995; Delft University *et al.*, 2001), the U.S. (Kempton *et al.*, 2007; Jiang *et al.*, 2008; Heimiller *et al.*, 2010), and China (CMA, 2006).

[4] The global assessments described in this section often use relatively simple analytical techniques with coarse spatial resolutions, rely on interpolations of wind speed data from a limited number (and quality) of surface stations, and apply limited validation from wind speed measurements in prime wind resource areas.

[5] Although there are a variety of reasons to believe that global wind resource assessments have, to date, understated the actual size of the technical potential for wind energy, there is at least one methodological issue that would suggest the opposite. In particular, the assessments summarized here use point-source estimates of the wind resource, and assess the global potential for wind energy by summing local wind resource potential. Large-scale atmospheric dynamics, thermodynamic limits, and array effects, however, may bound the aggregate amount of energy that can be extracted by wind power plants on a regional or global basis. Relatively little is known about the nature of these constraints, though early research suggests effect sizes that are unlikely to significantly constrain the use of wind energy in the electricity sector (see Section 7.6.2.3).

7.2.2 Regional technical resource potential

7.2.2.1 Global assessment results, by region

The global assessments presented in Section 7.2.1 come to varying conclusions about the relative technical potential for on-shore wind energy among different regions, and Table 7.2 summarizes results from a sub-set of the global assessments, by region. Differences among these studies are due to variations in wind speed data and key input parameters, including the minimum wind speed assumed to be exploitable, land-use constraints, density of wind energy development, and assumed wind power plant performance (Hoogwijk *et al.*, 2004); differing regional categories also complicate comparisons. Nonetheless, the resource in North America and Eastern Europe/CIS are found to be particularly sizable, while some areas of Asia and OECD Europe appear to have more limited on-shore potential. Visual inspection of Figure 7.1 also demonstrates limited resource potential in certain areas of Latin America and Africa, though other portions of those continents have significant potential. Caution is required in interpreting these results, however, as other studies find significantly different regional allocations of global technical potential (e.g., Fellows, 2000), and more detailed country and regional assessments have come to differing conclusions on, for example, the wind energy resource in East Asia and other regions (Hoogwijk and Graus, 2008)**.**

Table 7.2. Regional allocation of global technical on-shore wind energy resource potential* [TSU: table width needs to be adjusted].

Grubb and Meyer (1993)		**WEC (1994)**		**Krewitt *et al.* (2009) ****		**Lu *et al.* (2009)**	
Region	%	Region	%	Region	%	Region	%
Western Europe	9%	Western Europe	7%	OECD Europe	5%	OECD Europe	4%
North America	26%	North America	26%	OECD North America	42%	North America	22%
Latin America	10%	L. America & Carib.	11%	Latin America	10%	Latin America	9%
E. Europe & FSU	20%	E. Europe & CIS	22%	Transition Economies	17%	Non-OECD Europe & FSU	26%
Africa	20%	Sub-Saharan Africa	7%	Africa and Middle East	9%	Africa and Middle East	17%
Australia	6%	M. East & N. Africa	8%	OECD Pacific	14%	Oceania	13%
Rest of Asia	9%	Pacific	14%	Rest of Asia	4%	Rest of Asia	9%
		Rest of Asia	4%				

* Some regions have been combined to improve comparability among the four studies.
** Hoogwijk and Graus (2008) and Hoogwijk et al. (2004) show similar results.

Hoogwijk *et al.* (2004) also compare *on-shore* technical potential against regional electricity consumption in 1996. In most of the 17 regions evaluated, technical on-shore wind energy potential exceeded electricity consumption in 1996. The multiple was over five in 10 regions: East Africa, Oceania, Canada, North Africa, South America, Former Soviet Union (FSU), Central America, West Africa, United States, and the Middle East. Areas in which on-shore wind energy resource potential was estimated to be less than a 2x multiple of 1996 electricity consumption were South Asia (1.9), Western Europe (1.6), East Asia (1.1), South Africa (1), Eastern Europe (1), South East Asia (0.1), and Japan (0.1), though again, caution is warranted in interpreting these results. More recent resource assessments and data on regional electricity consumption would alter these figures.

The estimates reported in Table 7.2 ignore *off-shore* wind energy potential. Krewitt *et al.* (2009), however, estimate that of the 57 EJ/y (16,000 TWh/y) of technical off-shore resource potential by 2050, the largest opportunities exist in OECD Europe (22% of global potential), Rest of Asia (21%), Latin America (18%), and the Transition Economies (16%), with lower but still significant potential in North America (12%), OECD Pacific (6%), and Africa and the Middle East (4%).

Overall, these studies find that ample potential exists in most regions of the world to enable significant wind energy development. However, the wind resource is not evenly distributed across the globe, and wind energy will therefore not contribute equally in meeting the energy needs and GHG reduction demands of every region or country.

7.2.2.2 Regional assessment results

The global wind resource assessments described above have historically relied primarily on relatively coarse and imprecise estimates of the wind resource, sometimes relying heavily on measurement stations with relatively poor exposure to the wind (Elliott, 2002; Elliot *et al.*, 2004). The regional results from these global assessments, as presented in Section 7.2.2.1, should therefore be viewed with caution, especially in areas where wind measurement data are of limited quantity and quality. In contrast, specific country and regional assessments have benefited from: wind speed data collected with wind resource estimation in mind; sophisticated numerical wind resource prediction techniques; improved model validation; and a dramatic growth in computing power. These advancements have allowed the most-recent country and regional resource assessments to capture smaller-scale terrain features and temporal variations in predicted wind speeds, and at a variety of possible turbine heights.

These techniques were initially applied in the EU[6] and the U.S.[7], but there are now publicly available high-resolution wind resource assessments covering a large number of regions and countries. The United Nations Environment Program's Solar and Wind Energy Resource Assessment (SWERA), for example, provides wind resource information for a large number of its partner countries around the world[8]; the European Bank for Reconstruction and Development has developed RE assessments in its countries of operation (Black and Veatch, 2003); the World Bank's Asia Sustainable and Alternative Energy Program has prepared wind resource atlas' for the Pacific Islands and Southeast Asia[9]; and wind resource assessments for portions of the Mediterranean region are available through Observatoire Méditerranéen de l'Energie.[10] A number of other publicly available country-level assessments have been produced by the U.S. National Renewable Energy Laboratory[11], Denmark's Risø DTU[12], and others[13]. Text Box 7.2 presents details on the status of wind resource assessment in China and Russia.

These more-detailed assessments have generally found the actual size of the wind resource to be greater than estimated in previous global or regional assessments. This is due primarily to improved data, spatial resolution, and analytic techniques, but is also the result of wind turbine technology developments, e.g., higher hub heights and improved machine efficiencies (see, e.g., Elliott, 2002; Elliot *et al.*, 2004). Nevertheless, even greater spatial and temporal resolution and enhanced validation of model results with observational data are needed, as is an expanded geographic coverage of these assessments (see, e.g., IEA, 2008; Schreck *et al.*, 2008; IEA, 2009a). These developments will allow further refinement of estimates of the technical potential for wind energy, and will likely highlight regions with high-quality potential that have not previously been identified.

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[6] For the latest publicly available European wind resource map, see http://www.windatlas.dk/Europe/Index.htm. Publicly available assessments for individual EU countries are summarized in EWEA (2009).

[7] A large number of publicly available U.S. wind resource maps have been produced at the state level, many of which have subsequently been validated by the National Renewable Energy Laboratory (see http://www.windpoweringamerica.gov/wind_maps.asp).

[8] See http://swera.unep.net/index.php?id=7

[9] http://web.worldbank.org/WBSITE/EXTERNAL/COUNTRIES/EASTASIAPACIFICEXT/EXTEAPASTAE/0,,contentMDK:21084082~menuPK:3031665~pagePK:64168445~piPK:64168309~theSitePK:2822888,00.html

[10] See http://www.omenergie.com/

[11] See http://www.nrel.gov/wind/international_wind_resources.html

[12] See http://www.windatlas.dk/World/About.html

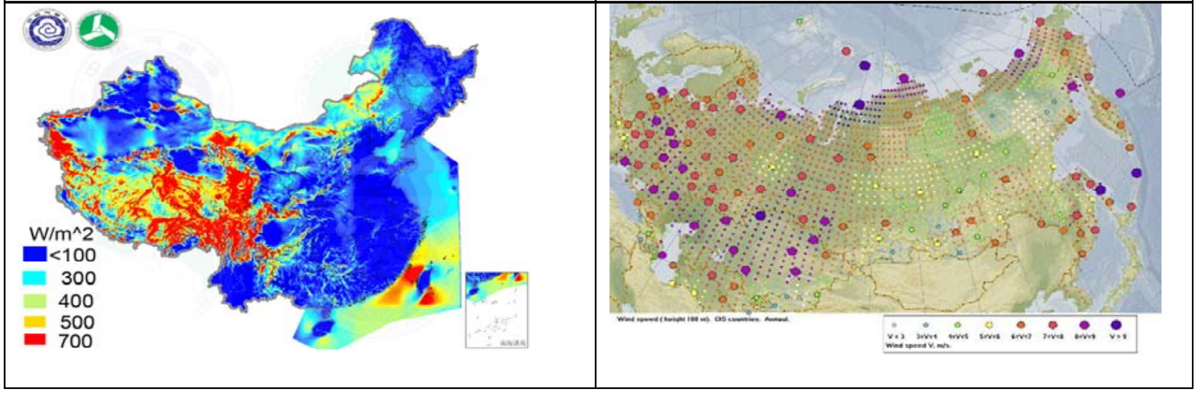
[13] A number of companies offer wind resource mapping assessments for a fee.

Box 7.2. Advancements in wind resource assessment in China and Russia

As demonstration of the growing use of sophisticated wind resource assessment tools outside of the EU and U.S., historical and ongoing efforts in China and Russia to better characterize their wind resources are described here. In both cases, the wind energy resource has been found to be sizable compared to present electricity consumption, and recent analyses offer enhanced understanding of the size and location of those resources.

China's Meteorological Administration (CMA) completed its first wind resource assessment in the 1970s. In the 1980s, a second wind resource investigation was performed based on data from roughly 900 meteorological stations, and a spatial distribution of the resource was delineated. The CMA estimated the availability of 253 GW (510 TWh/y at a 23% average capacity factor) of on-shore wind energy potential (Xue *et al.*, 2001). A third assessment was based on data from 2,384 meteorological stations, supplemented with data from other sources. Though still mainly based on measured wind speeds at 10m, most data covered a period of over 50 years, and this assessment led to an estimate 297 GW (600 TWh/y at a 23% average capacity factor) of on-shore wind energy potential (CMA 2006). More recently, improved mesoscale atmospheric models and access to higher-elevation meteorological station data have facilitated higher-resolution assessments. Figure 7.2(a) shows the results of a recent investigation, focused on on-shore wind resources and off-shore resources at 5-25m water depth. Based on this research, the CMA now estimates 2,380 GW of on-shore (4,800 TWh/y at a 23% average capacity factor) and 200 GW of off-shore (610 TWh/y at a 35% average capacity factor) wind energy potential (CMA, 2010). Other recent research has similarly estimated far-greater potential than past assessments (see, e.g., McElroy *et al.*, 2009).

Considerable progress has also been made in understanding the magnitude and distribution of the wind energy resource in Russia (as well as the other CIS countries, and the Baltic countries), based in part on data from approximately 3,600 surface meteorological stations and 150 upper-air stations. A recent assessment by Nikolaev *et al.* (2008) uses these data and meteorological and statistical modeling to estimate the distribution of the wind resource in the region (Figure 7.2(b)). Based on this work and after making assumptions on the characteristics and placement of wind turbines, Nikolaev *et al.* (2008) estimate that the technical potential for wind energy in Russia is more than 14,000 TWh/y, 15-times that of Russia's electricity consumption in 2006. The more promising regions of Russia for wind energy development are in the Western part of the country, the South Ural area, in Western Siberia, and on the coasts of the seas of the North and Pacific Oceans.



(a) China wind resource map (CMA, 2010)

(b) Russia, CIS, Baltic wind resource map (Nikolaev *et al.*, 2008)

Figure 7.2(a,b). Wind resource maps for China and Russia/CIS/Baltic.

7.2.3 Possible impact of climate change on resource potential

There is increasing recognition that global climate change may alter the geographic distribution and/or the inter- and intra-annual variability of the wind resource, or alter the prevalence of extreme weather events that may impact wind turbine design and operation. Research in this field is nascent, however, and Global and Regional Climate Models (GCMs and RCMs) do not fully reproduce contemporary wind climates (Goyette *et al.*, 2003) or historical trends (Pryor *et al.*, 2009). Additional uncertainty in wind resource projections under global climate change scenarios derive, in part, from substantial variations in simulated circulation and flow regimes when using different RCMs and GCMs (Pryor *et al.*, 2005, 2006; Bengtsson *et al.*, 2009; Pryor and Schoof, 2010). Nevertheless, based on research to date, it appears unlikely that multi-year annual mean wind speeds and energy densities will change by more than a maximum of ±25% over most of Europe and North America during the present century (Breslow and Sailor, 2002; Pryor *et al.*, 2005, 2006; Walter *et al.*, 2006; Bloom *et al.*, 2008; Sailor *et al.*, 2008; Pryor and Schoof, 2010). Prior research from the UK indicates high historical variability and weak evidence for slight increases in the wind resource based on output from one GCM run under one climate forcing scenario (Palutikof *et al.*, 1987, 1992). Brazil, meanwhile, has a large wind resource that was shown in one study to be relatively insensitive to (and perhaps even increase as a result of) global climate change (de Lucena *et al.*, 2009), and simulations for the west coast of South America showed increases in mean wind speeds of up to +15% (Garreaud and Falvey, 2009).

In addition to the possible impact of climate change on long-term average wind speeds, impacts on intra-annual, inter-annual, and inter-decadal variability in wind speeds are also of interest. Wind climates in northern Europe, for example, exhibit seasonality with the highest wind speeds during the winter (Rockel and Woth, 2007), and some analyses in the Northeast Atlantic (1874-2007) have found notable differences in temporal trends in winter and summer (Wang *et al.*, 2009). Internal climate modes have been found to be responsible for relatively high intra-annual, inter-annual, and inter-decadal variability in wind climates in the mid-latitudes (e.g., Petersen *et al.*, 1998; Pryor *et al.*, 2009). The ability of climate models to accurately reproduce these conditions in current and possible future climates is the subject of intense research (Stoner *et al.*, 2009). Equally, the degree to which historical variability and change in near-surface wind climates is attributable to global climate change or to other factors (Pryor *et al.*, 2009; Pryor and Ledolter, 2010), and whether that variability will change as the global climate continues to evolve, are also being investigated.

Finally, the prevalence of extreme winds and the probability of icing have implications for wind turbine design and operation (Wang *et al.*, 2009). Preliminary studies from northern and central Europe show some evidence of increased wind speed extremes (Pryor *et al.*, 2005; Haugen and Iversen, 2008; Leckebusch *et al.*, 2008), though changes in the occurrence of inherently rare events are difficult to quantify, and further research is warranted. Sea ice, and particularly drifting sea ice, potentially enhances turbine foundation loading for off-shore plants, and changes in sea ice and/or permafrost conditions may also influence access for wind power plant [TSU: operation and maintenance] (O&M) (Laakso *et al.*, 2003). One study conducted in northern Europe found substantial declines in the occurrence of both icing frequency and sea ice extent under reasonable climate change scenarios (Claussen *et al.*, 2007). Other meteorological drivers of turbine loading may also be influenced by climate change but are likely to be secondary in comparison to changes in resource magnitude, weather extremes, and icing issues (Pryor and Barthelmie, 2010).

Additional research on the possible impact of climate change on the size, geographic distribution, and variability of the wind resource is warranted, as is research on the possible impact of climate change on extreme weather events and therefore wind turbine operating environments. Overall, however, research to date suggests that these impacts are unlikely to be of a magnitude that will greatly impact the global potential of wind energy to reduce carbon emissions.

7.3 Technology and applications

7.3.1 Introduction

Modern grid-connected wind turbines have evolved from small, simple machines to large-scale, highly sophisticated devices. Scientific and engineering expertise, as well as computational tools and design standards, have supported these technology developments. As a result, wind turbine nameplate capacity ratings have increased dramatically since the late 1970s and early 1980s (from under 25 kW to 1.5 MW and larger), while the cost of wind energy production has declined by a factor of five (EWEA, 2009).

On-shore wind energy technology is already being manufactured and deployed on a commercial basis. Nonetheless, additional R&D advancements are anticipated, and are expected to further reduce the cost of wind energy. Off-shore wind energy technology is still developing, with greater opportunities for additional advancement. This section summarizes the historical development and technology status of large grid-connected on-shore and off-shore wind turbines (7.3.2), discusses international wind energy technology standards (7.3.3), and reviews grid connection issues (7.3.4); a later section (7.7) describes opportunities for further technical advancements.

7.3.2 Technology development and status

Generating electricity from the wind requires that the kinetic energy of moving air be converted to mechanical and then electrical energy, and the engineering challenge for the wind energy industry is to design efficient wind turbines to perform this conversion. The amount of energy in the wind that is available for extraction increases with the cube of wind speed. However, a turbine only captures a portion of that available energy, with the Lanchester-Betz limit providing a theoretical upper limit (59%) on the amount of energy that can be extracted.

Modern, large wind turbines employ rotors that start extracting energy from the wind at speeds of roughly 3-5 m/s (cut-in speed). The turbine increases power production until it reaches its rated power level, corresponding to a wind speed of about 12-15 m/s. At still-higher wind speeds, control systems limit power output to prevent overloading the wind turbine, either through stall control or through pitching the blades. Turbines stop producing energy at wind speeds of approximately 25-30 m/s (cut-out speed) to limit loads on the rotor and prevent damage to the turbine’s structural components. When the power in the wind exceeds the wind speed for which the mechanical and electrical system of the machine has been designed (the rated power of the turbine), excess energy is allowed to pass through the rotor uncaptured (see Figure 7.3).

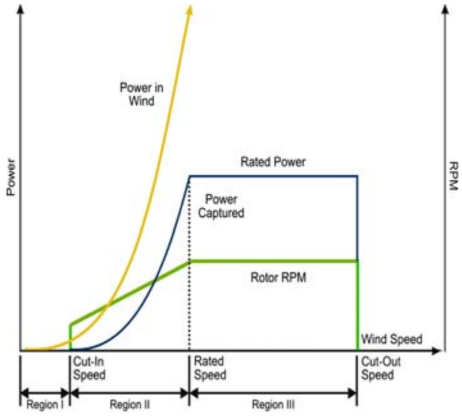


Figure 7.3. Conceptual power curve for a modern variable-speed wind turbine (US DOE, 2008).

In general, the speed of the wind increases with height above the ground, encouraging engineers to design taller and larger wind turbines while minimizing the cost of materials. Wind speeds also vary geographically and temporally, influencing the location of wind power plants, the economics of those plants, and the implications of increased wind energy on electric system operations.

7.3.2.1 On-shore wind energy technology

In the 1970s and 1980s, a variety of wind turbine configurations were investigated, including both horizontal- and vertical-axis designs (see Figure 7.4). Gradually, the horizontal axis design came to dominate, although configurations varied, in particular the number of blades and whether those blades were oriented upwind or downwind of the tower. After a period of further consolidation, turbine designs centred (with some notable exceptions) around the 3-blade, upwind rotor; locating the turbine blades upwind of the tower prevents the tower from blocking wind flow onto the blades and producing extra aerodynamic noise and loading. The three blades are attached to a rotor, from which power is transferred (sometimes through a gearbox, depending on design) to a generator. The gearbox and generator are contained within a housing called the nacelle. Figure 7.5 shows the components in a modern wind turbine with a gearbox; in wind turbines without a gearbox, the rotor is mounted directly on the generator shaft.

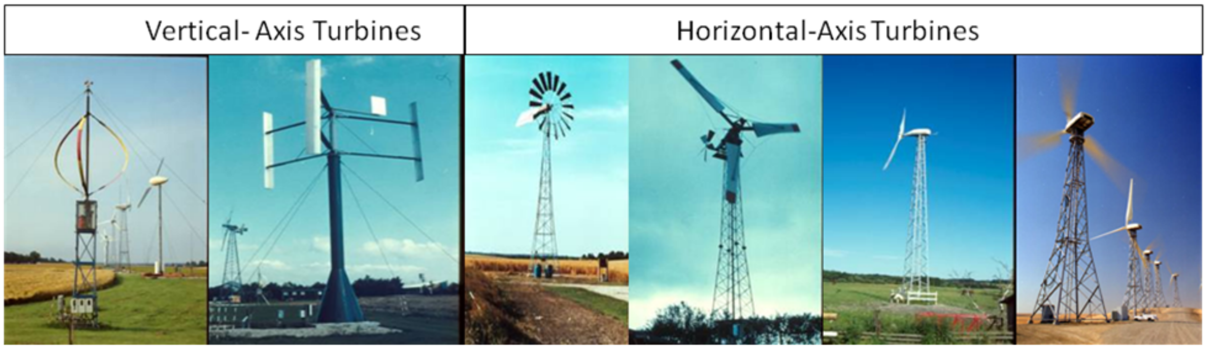


Figure 7.4. Early wind turbine designs, including vertical- and horizontal-axis turbines. Source: Risø DTU

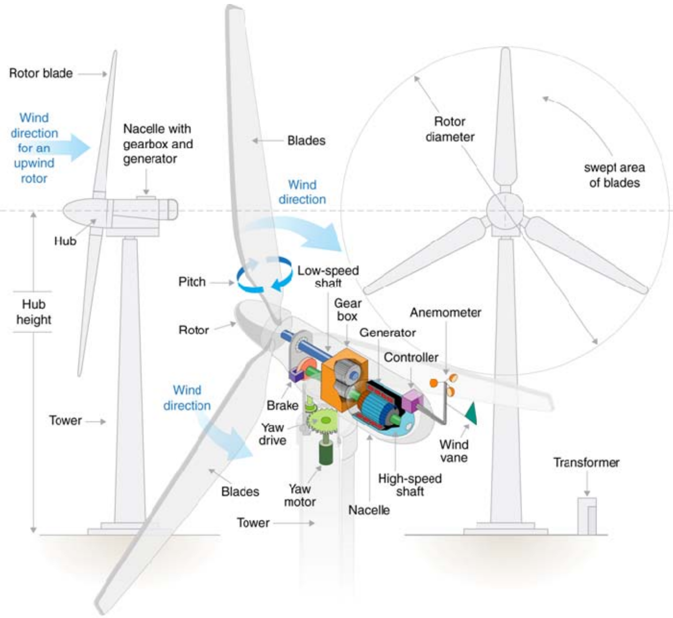


Figure 7.5. Basic components of a modern, horizontal-axis wind turbine with a gearbox. Source: NREL

In the 1980s, larger machines were rated at around 100 kW and primarily relied on aerodynamic blade stall to regulate power production from the fixed blades. These turbines generally operated at one or two rotational speeds. As turbine size increased over time, development went from stall control to full-span pitch control in which turbine output is controlled by pitching (i.e., rotating) the blades along their long axis. In addition, the advent of inexpensive power electronics allowed variable speed wind turbine operation. Initially, variable speeds were used to smooth out the torque fluctuations in the drive train caused by wind turbulence and to allow more efficient operation in variable and gusty winds. More recently, almost all electric system operators require the continued operation of large wind power plants during electrical faults, together with being able to provide reactive power: these requirements have accelerated the adoption of variable speed operation with power electronic conversion (see Section 7.5 for a fuller discussion of electric system integration issues). Today, wind turbines typically operate at variable speeds using full-span blade pitch control. Blades are commonly constructed with composite materials, and the towers are usually tubular steel structures that taper from the base to the nacelle at the top.

Over the past 30 years, average wind turbine size has grown significantly (Figure 7.6), with the largest fraction of land-based wind turbines installed globally in 2009 having a rated capacity of 1.5 MW to 2.5 MW; the average size of turbines installed in 2009 was 1.6 MW (BTM, 2010). As of 2010, such turbines typically stand on 50-100 meter towers, with rotors that are often 50-100 meters in diameter; larger machines with rotor diameters and tower heights of 130 meters are operating, and even larger machines are in use and under development. Modern turbines operate with rotational speeds of about 10 RPM, which compares to the faster and potentially more visually disruptive speeds exceeding 60 RPM common of the smaller turbines installed during the 1980s. The main reason for the continual increase in turbine size has been to minimize the levelized cost of wind energy by increasing electricity production (taller towers provide access to a higher-quality wind resource, and larger rotors allow a greater exploitation of those winds as well as more cost-effective exploitation of lower wind resource sites), reducing installed costs per unit of capacity (installation of a fewer number of larger turbines can, to a point, also reduce installed costs), and reducing O&M costs (larger turbines can reduce maintenance costs per unit of capacity). For land-based turbines, however, additional growth in turbine size may be limited due to the logistical constraints of transporting the very large blades, tower, and nacelle components by road, as well as the cost of and difficulty in obtaining large cranes to lift the components in place.

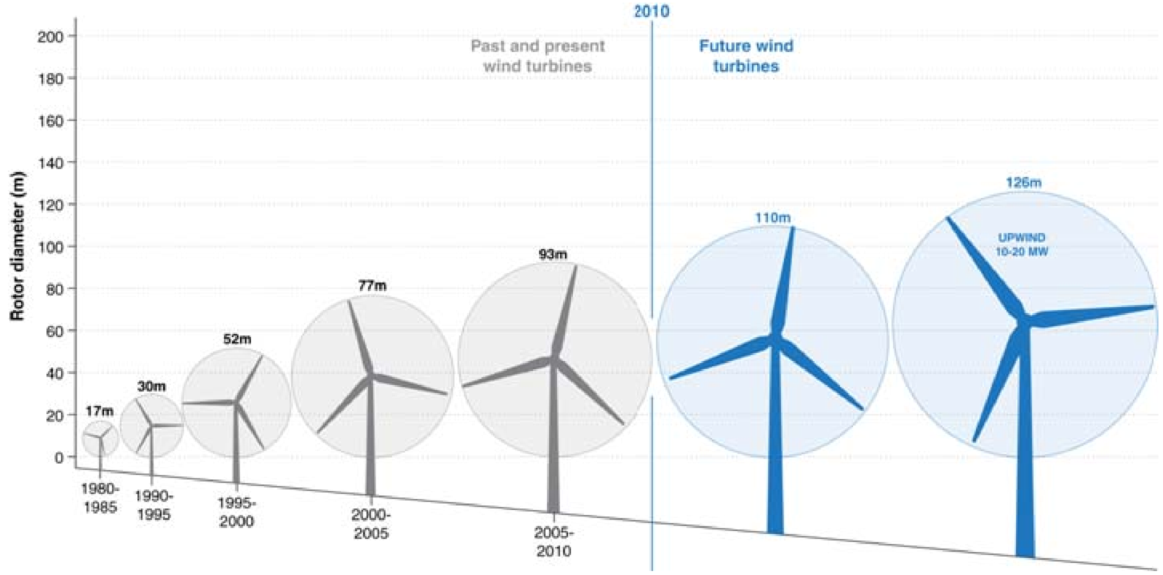


Figure 7.6. Growth in size of commercial wind turbines. Source: NREL

Modern on-shore wind turbines are typically grouped together into [TSU: word(s) missing?] wind power plants, sometimes called wind projects or wind farms. These wind power plants are often 5 MW to 300 MW in size, though smaller and larger plants do exist.

As a result of the above developments, on-shore wind energy technology is already viable for large-scale commercial deployment. Moreover, modern wind turbines have nearly reached the theoretical maximum of aerodynamic efficiency, with the coefficient of performance rising from 0.44 in the 1980s to about 0.50 by the mid 2000s.[14] The value of 0.50 is near the practical limit dictated by the drag of aerofoils and compares with a theoretical limit of 0.59 known as the Lanchester-Betz limit. The design requirement for wind turbines is normally 20 years, with 4,000 to 7,000 hours of operation each year depending on the characteristics of the local wind resource. By comparison, a domestic car that travels 20,000 km per year at an average speed of 30 km per hour operates 666 hours each year. O&M teams work to maintain high plant availability despite component failure rates that have, in some instances, been higher than expected. Though domestically manufactured wind turbines in China are reportedly under-performing (Li, 2010), data collected through 2008 show that modern wind turbines in mature markets can achieve an availability of 97% or more (Blanco, 2009; EWEA, 2009; IEA, 2009a).

These results are encouraging, and the technology has reached sufficient commercial maturity to allow large-scale manufacturing and deployment. Nonetheless, additional advancements to improve reliability, increase electricity production, and reduce costs are anticipated, and are discussed in Section 7.7. Additionally, most of the historical technology developments have occurred in developed countries. Increasingly, however, developing countries are investigating the potential installation of wind energy technology, and opportunities for technology transfer in wind turbine design, component manufacturing, and wind power plant siting exist. Moreover, extreme environmental conditions, such as icing or typhoons, may be more prominent in some of these markets, providing impetus for continuing research. Other aspects unique to less developed countries, such as minimal transportation infrastructure, could also influence wind turbine designs as these markets develop.

7.3.2.2 Off-shore wind energy technology

The first off-shore wind power plant was built in 1991 in Denmark, and consisted of eleven 450 kW wind turbines. By the end of 2009, many of the off-shore installations had taken place in the UK and Denmark, but significant development activity exists in other EU countries, in the U.S., in China, and elsewhere (e.g., Mostafaeipour, 2010). The off-shore wind energy sector remains relatively immature, however, and, by the end of 2009, about 2,100 MW of off-shore wind power capacity was installed globally, just 1.3% of total installed wind power capacity (GWEC, 2010b).

Interest in off-shore wind energy is the result of several factors: the higher-quality wind resources located at sea (e.g., higher average wind speeds, lower turbulence, and lower shear near hub height); the ability to use even-larger wind turbines due to avoidance of certain land-based transportation constraints and the potential to thereby gain further economies of scale; the ability to use more-flexible turbine designs given the uniqueness of the off-shore environment (e.g., lower turbulence, less wind shear near hub height, fewer constraints on noise); a potential reduction in the need for new, long-distance, land-based transmission infrastructure[15]; the ability to build larger power plants

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[14] Wind turbines achieve maximum aerodynamic efficiency when operating at wind speeds corresponding to power levels below the rated power level. Aerodynamic efficiency is reduced when operating at wind speeds above the rated power level (see Figure 7.3).

[15] Of course, transmission infrastructure would be needed to connect off-shore wind power plants with electricity demand centres, and the per-km cost of off-shore transmission typically exceeds that for on-shore lines. Whether off-shore transmission needs are more or less extensive than that needed to access on-shore wind energy varies by location.

than on-shore, gaining plant-level economies of scale; and the potential reduction of visual impacts and mitigation of siting controversies if wind power plants are located far-enough from shore (Carbon Trust, 2008b; Twidell and Gaudiosi, 2009; Snyder and Kaiser, 2009b). These factors, combined with a significant off-shore wind resource potential, have created considerable interest in off-shore wind energy technology in the EU and, increasingly, in other regions as well.

Wind turbine sizes of 2 MW to 5 MW were common for off-shore wind power plants built from 2007 through 2009, with even larger turbines under development. Off-shore wind power plants installed from 2007-09 were typically 20-120 MW in size, with a clear trend towards larger turbines and power plants over time. Water depths for most off-shore wind turbines installed through 2005 were less than 10 meters, but from 2006-09 water depths from 10 to more than 20 meters were common (EWEA, 2010a). As experience is gained, water depths are expected to increase further and more exposed locations with higher winds will be utilized.

To date, off-shore turbine technology has been very similar to on-shore designs, with some modifications and with special foundations (Musial, 2007; Carbon Trust, 2008b). The mono-pile foundation is the most common, though concrete gravity-based foundations have also been used with some frequency; a variety of other foundation designs are being considered and in some instances used, especially as water depths increase, as discussed in Section 7.7. In addition to differences in foundations, modification to off-shore turbines (relative to on-shore) include structural upgrades to the tower to address wave loading; air conditioned and pressurized nacelles and other controls to prevent the effects of corrosive sea air from degrading turbine equipment; and personnel access platforms to facilitate maintenance. Additional design changes for marine navigational safety (e.g., warning lights, fog signals) and to minimize expensive servicing (e.g., more extensive condition monitoring, on-board service cranes) are common. Wind turbine tip-speed is often greater than for on-shore turbines because concerns about noise are reduced for off-shore power plants and higher tip speeds can sometimes lead to lower torque and lighter drive train components for the same power output. In addition, tower heights are often lower due to reduced wind shear (i.e., wind speed does not increase with height to the same degree as on-shore).

Off-shore wind energy technology is still under development, and lower power plant availabilities and higher O&M costs have been common for the early installations (Carbon Trust, 2008b). Wind energy technology specifically tailored for off-shore applications will become more prevalent as the off-shore market expands, and it is expected that larger turbines in the 5-10 MW range may come to dominate this market segment (EU, 2008).

7.3.3 International wind energy technology standards

Wind turbines in the 1970s and 1980s were designed using simplified design models, which in some cases led to machine failures and in other cases resulted in design conservatism. The need to address both of these issues, combined with advancements in computer processing power, motivated designers to improve their calculations during the 1990s (Quarton, 1998; Rasmussen *et al.*, 2003). Improved design and testing methods have been codified in International Electrotechnical Commission (IEC) standards, and the rules and procedures for Conformity Testing and Certification of Wind Turbines (IEC, 2008a) relies upon these standards. These certification procedures provide for third-party conformity evaluation of a wind turbine type, a major component type, or one or more wind turbines at a specific location. Certification agencies rely on accredited design and testing bodies to provide traceable documentation of the execution of rules and specifications outlined in the standards in order to certify turbines, components, or entire wind power plants. The certification system assures that a wind turbine design or wind turbines installed in a given location meet common guidelines relating to safety, reliability, performance, and testing. Figure 7.7(a) illustrates the design and testing procedures required to obtain a wind turbine type certification. Project certification, shown in Figure 7.7(b), requires a type certificate for the turbine and includes procedures for evaluating site conditions and turbine design parameters associated with that specific site, as well as other site-specific conditions including soil properties, installation, and plant commissioning.

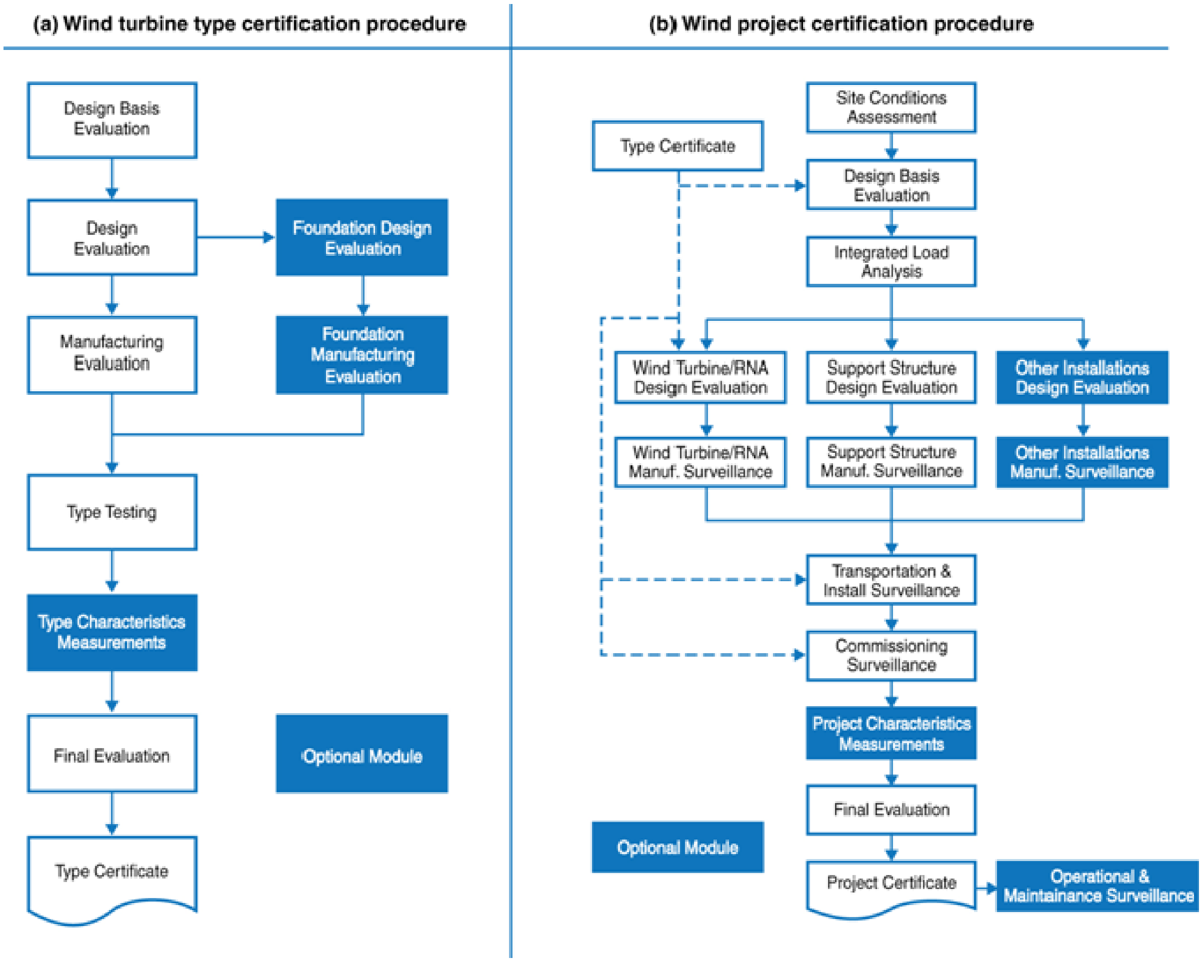

Figure 7.7(a,b). Modules for (a) type certification and (b) project certification (IEC, 2008a).

Insurance companies, financing institutions, and power plant owners normally require some form of certification for plants to proceed. These standards provide a common basis for certification to reduce uncertainty and increase the quality of wind turbine products available in the market. In emerging markets, the lack of highly qualified testing laboratories and certification bodies limits the opportunities for manufacturers to obtain certification according to IEC standards and may lead to lower-quality products. As markets mature and design margins are compressed to reduce costs, reliance on internationally recognized standards will likely become even more widespread to assure consistent performance, safety, and reliability of wind turbines.

7.3.4 Power conversion and related grid connection issues

From an electric system reliability perspective, an important part of the wind turbine is the electrical conversion system. For large grid-connected turbines, electrical conversion systems come in three broad forms. Fixed-speed induction generators were popular in earlier years for both stall regulated and pitch controlled turbines; in these arrangements, wind turbines were net consumers of reactive power that had to be supplied by the electric system. For new turbines, these designs have now been largely replaced with variable speed machines. Two arrangements are common, doubly-fed induction generators (DFIG) and synchronous generators with a full power electronic convertor, both of which are almost always coupled to pitch controlled rotors. These turbines can provide real and reactive-power control and some fault ride-through capability, which are increasingly being required for electric system reliability (further discussion of these requirements and the institutional elements of wind energy integration are addressed in Section 7.5, with a more general discussion of RE integration covered in Chapter 8). These variable speed designs essentially decouple the rotating masses of the turbine from the electric system, thereby offering a number of power quality advantages over earlier turbine designs (Ackermann, 2005; EWEA, 2009). These designs, however, differ from the synchronous generators found in most conventional power plants in that they result in no intrinsic inertial response capability. The lack of inertial response is an important consideration for electric system planners because less overall inertia makes the maintenance of stable system operation more challenging (Gautam *et al.*, 2009). Wind turbine manufacturers have recognized this lack of intrinsic inertial response as a possible long term impediment to wind energy and are actively pursuing a variety of solutions; for example, additional turbine controls can be added to provide inertial response (Mullane and O'Malley, 2005; Morren *et al.*, 2006).

7.4 Global and regional status of market and industry development

This section summarizes the global (7.4.1) and regional (7.4.2) status of wind energy development, discusses trends in the wind energy industry (7.4.3), and highlights the importance of policy actions for the wind energy market (7.4.4). As documented in this section, the wind energy market has expanded substantially in the 2000s, demonstrating the commercial and economic viability of the technology and industry, and the importance placed on wind energy development by a number of countries through policy support measures. Wind energy expansion has been concentrated in a limited number of regions, however, and the wind power capacity installed by the end of 2009 was capable of meeting roughly 1.8% of global electricity demand. Further expansion of wind energy, especially in regions of the world with little wind energy development to date and in off-shore locations, is likely to require additional policy measures.

7.4.1 Global status and trends

Wind energy has quickly established itself as part of the mainstream electricity industry. From a cumulative capacity of 14 GW by the end of 1999, the global installed capacity increased twelve-fold in ten years to reach almost 160 GW by the end of 2009, an average annual increase in cumulative capacity of 28% (see Figure 7.8). Global annual wind power capacity additions equalled more than 38 GW in 2009, up from 26 GW in 2008 and 20 GW in 2007, and this despite the global financial crisis that led to fears of a slow-down in market growth (GWEC, 2010a).

The majority of the capacity has been installed on-shore, with off-shore installations constituting a small proportion of the total market. About 2.1 GW of off-shore wind turbines were installed by the end of 2009; 0.6 GW were installed in 2009, including the first off-shore wind power plant outside of Europe, in China (GWEC, 2010a). Off-shore wind energy is expected to develop in a more-significant way in the years ahead as the technology becomes more mature and as on-shore wind energy sites become constrained by local resource availability and/or siting challenges in some regions (BTM, 2010; GWEC, 2010a).

In terms of economic value, the total cost of new wind power generating equipment installed in 2009 was US$57 billion (2005$, GWEC, 2010a). Direct employment in the wind energy sector in 2009 has been estimated at roughly 190,000 in the EU and 85,000 in the United States. Worldwide, direct employment has been estimated at approximately 500,000 (GWEC, 2010a).

Despite these trends, wind energy remains a relatively small fraction of worldwide electricity supply. The total wind power capacity installed by the end of 2009 would, in an average year, meet roughly 1.8% of worldwide electricity demand, up from 1.5% by the end of 2008, 1.2% by the end of 2007, and 0.9% by the end of 2006 (Wiser and Bolinger, 2010).

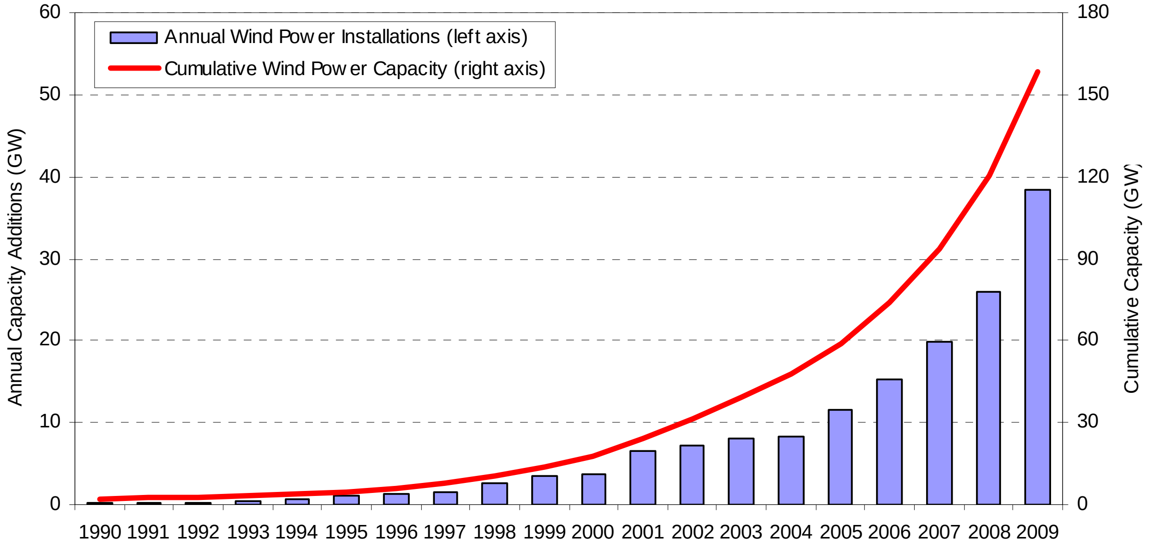

Figure 7.8. Global annual wind power capacity additions and cumulative capacity (GWEC, 2010a; Wiser and Bolinger, 2010).

7.4.2 Regional and national status and trends

The countries with the highest total installed wind power capacity by the end of 2009 were the United States (35 GW), China (26 GW), Germany (26 GW), Spain (19 GW), and India (11 GW). After its initial start in the United States in the 1980s, wind energy growth centred on countries in the EU and India during the 1990s and the early 2000s. In the late 2000s, however, the U.S. and then China became the locations for the greatest annual capacity additions (Figure 7.9).

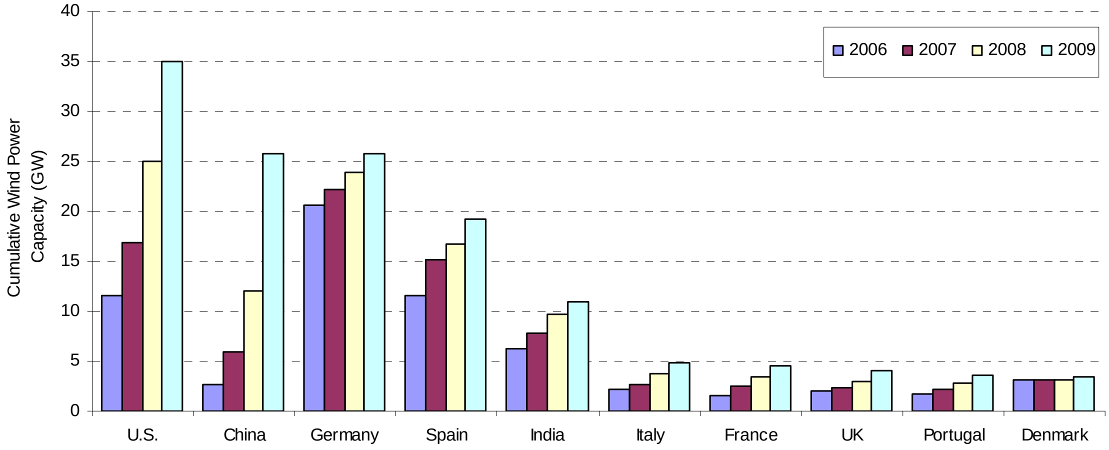

Figure 7.9. Top-10 countries in cumulative wind power capacity (GWEC, 2010a).

Regionally, Europe continues to lead the market with 76 GW of cumulative installed wind power capacity by the end of 2009, representing 48% of the global total (Asia represented 25%, while North America represented 24%). Notwithstanding the continuing growth in Europe, the trend over time has been for the wind energy industry to become less reliant on a few key markets, and other regions of the world have increasingly become the dominant markets for wind energy growth. The annual growth in the European wind energy market in 2009, for example, accounted for just 28% of the total new wind power additions in that year, down from over 60% in the early 2000s (GWEC, 2010a). More than 70% of the annual wind power capacity additions in 2009 occurred outside of Europe, with particularly significant growth in Asia (40%) and North America (29%) (Figure 7.10). Even in Europe, though Germany and Spain have been the strongest markets during the 2000s, there is a trend towards less reliance on these two countries.

Despite the increased globalization of wind power capacity additions, the market remains concentrated regionally. Latin America, Africa and the Middle East, and the Pacific regions have installed relatively little wind power capacity. And, even in the regions of significant growth, most of that growth has occurred in a limited number of countries. In 2009, for example, 90% of wind power capacity additions occurred in the 10 largest markets, and 62% was concentrated in just two countries: China (14 GW, 36%) and the United States (10 GW, 26%).

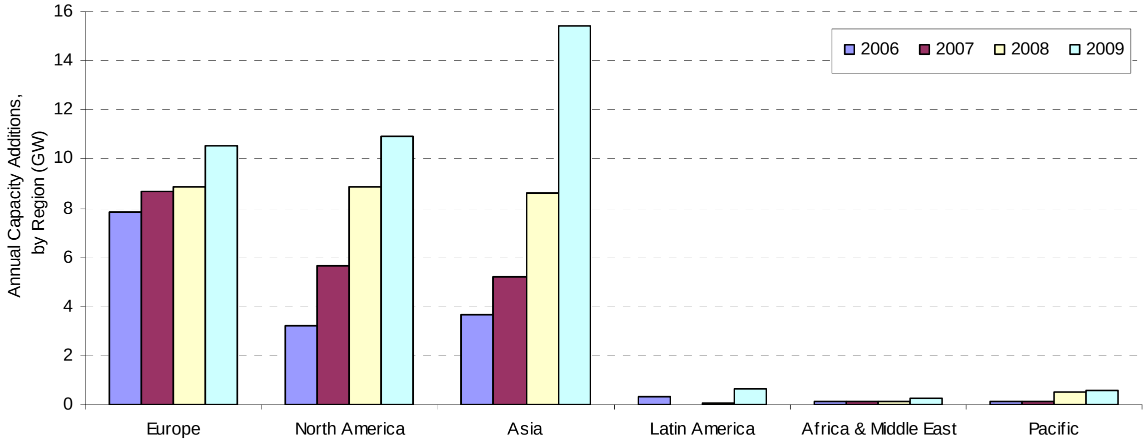

Figure 7.10. Annual wind power capacity additions by region (GWEC, 2010a).

In both Europe and the United States, wind energy represents a major new source of electric capacity additions. From 2000 through 2009, wind energy was the second-largest new resource added in the U.S. (10% of all gross capacity additions) and EU (33% of all gross capacity additions) in terms of nameplate capacity, behind natural gas, but ahead of coal. In 2009, 39% of all capacity additions in the U.S. and 39% of all additions in the EU came from wind energy (Figure 7.11). In China, 5% of the net capacity additions from 2000-2009 and 16% of the net additions in 2009 came from wind energy. On a global basis, from 2000 through 2009, wind energy represented roughly 11% of total net capacity additions; in 2009 alone, that figure was likely more than 20%.[16]

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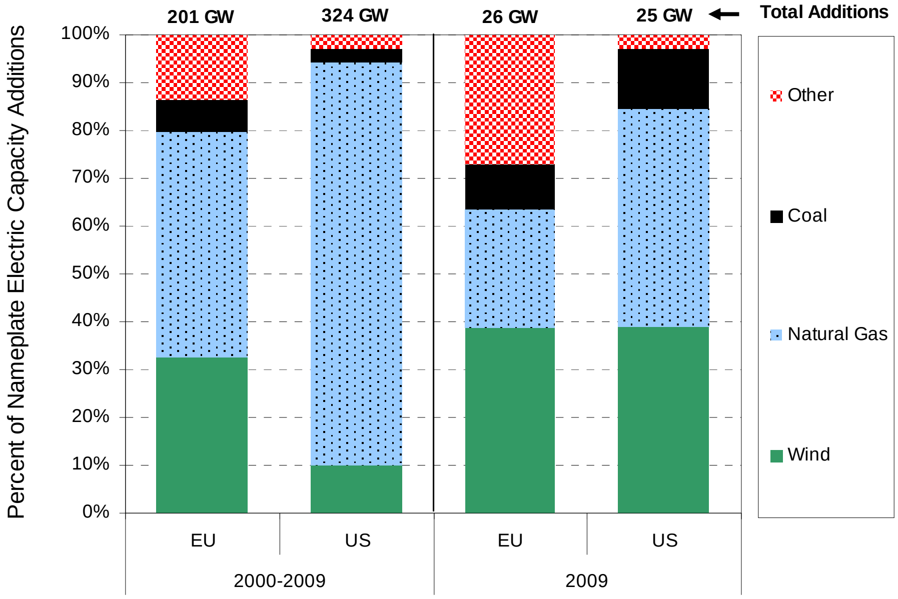
[16] Worldwide capacity additions from 2000 through 2007 come from historical data from the U.S. Energy Information Administration. Capacity additions for 2008 and 2009 are estimated based on historical capacity growth from 2000-2007.



Note: The "other" category includes other forms of renewable energy, nuclear energy, and fuel oil.

Figure 7.11. Relative contribution of electricity supply types to gross capacity additions in the EU and U.S. (EWEA, 2010b; Wiser and Bolinger, 2010).

As a result of this expansion, though wind energy remains a modest contributor to global electricity supply, a number of countries are beginning to achieve relatively high levels of wind electricity penetration in their respective electric systems. Figure 7.12 presents data on end-of-2009 (and end-of-2006/07/08) installed wind power capacity, translated into projected annual electricity supply, and divided by electricity consumption. On this basis, and focusing only on the 20 countries with the greatest cumulative wind power capacity, end-of-2009 wind power capacity is projected to be capable of supplying electricity equal to roughly 20% of Denmark's electricity demand, 14% of Portugal's, 14% of Spain's, 11% of Ireland's, and 8% of Germany's (Wiser and Bolinger, 2010).[17]

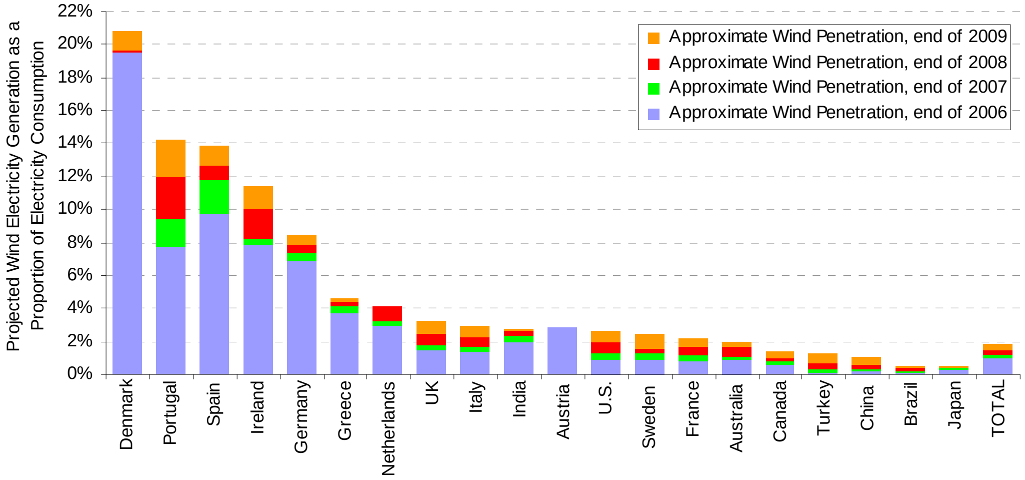


Figure 7.12. Approximate wind electricity penetration in the twenty countries with the greatest installed wind power capacity (Wiser and Bolinger, 2010).

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[17] Because of grid interconnections among electricity grids, these percentages do not necessarily equate to the amount of wind electricity consumed within each country.

7.4.3 Industry development

The growing maturity of the wind energy sector is illustrated not only by wind power capacity additions, but also by trends in the wind energy industry. In particular, companies from outside the traditional wind energy industry have become increasingly involved in the sector. For example, there has been a shift in the type of companies developing, owning, and operating wind power plants, from relatively small independent power plant developers towards large power generation companies (including electric utilities) and large independent power plant developers, often financed by investment banks. On the manufacturing side, the increase in the size of the wind energy market, along with manufacturing localization requirements in some countries, has brought in new players. The involvement of these new players has, in turn, encouraged a greater globalisation of the industry. Manufacturer product strategies are shifting to address larger scale power plants, higher capacity turbines, and lower wind speeds. More generally, the significant contribution of wind energy to new electric generation capacity investment in several regions of the world has attracted a broad range of players across the industry value chain, from local site-focused engineering firms to global vertically integrated utilities. The industry’s value chain has also become increasingly competitive as a multitude of firms seek the most profitable balance between vertical integration and specialization (BTM, 2010; GWEC, 2010a).

Despite these trends, the global wind turbine market remains somewhat regionally segmented, with just six countries hosting the majority of wind turbine manufacturing (China, Denmark, India, Germany, Spain, and the U.S.). With markets developing differently, market share for turbine supply has been marked by the emergence of national industrial champions, entry of highly focused technology innovators, and the arrival of new start-ups licensing proven technology from other regions (Lewis and Wiser, 2007). Regardless, the industry continues to globalize: Europe’s turbine and component manufacturers have begun to penetrate North America and Asia, and the growing presence of Asian manufacturers in Europe and North America is expected to become more pronounced in the years ahead. Chinese wind turbine manufacturers, in particular, are dominating their home market, are among the world’s top manufacturers, and will increasingly seek export opportunities in the years ahead. Wind turbine sales and supply chain strategies are therefore expected to continue to take on a more international dimension as volumes increase.

Amidst the growth in wind power capacity also come challenges. From 2005 through 2008, supply chain difficulties caused by growing demand strained the industry, and prices for wind turbines and turbine components increased to compensate for this imbalance; commodity price increases and other factors also played a role in pushing wind turbine prices higher (see Section 7.8). Overcoming supply chain difficulties is not simply a matter of ramping up the production of wind turbine components to meet the increased levels of demand. After all, large-scale investment decisions are more easily made based on a sound long-term outlook for the industry. In most markets, however, both the projections and actual demand for wind energy depend on a number of factors, some of which are outside of the control of the industry, such as political frameworks and policy measures.

7.4.4 Impact of policies

The deployment of wind energy must overcome a number of barriers that vary in type and magnitude depending on the wind energy application and region. The most significant barriers to wind energy development are summarized here. Perhaps most importantly, in many regions of the world, wind energy remains more expensive than fossil-fuel generation options, at least if environmental impacts are not internalized and monetized (NRC, 2010b). Additionally, a number of other barriers exist that are at least somewhat unique to wind energy. The most critical of these barriers include: (1) concerns about the impact of wind energy’s variability on electricity reliability; (2) challenges to building the new transmission infrastructure both on- and off-shore (and within country and cross-border) needed to enable access to the most-attractive wind resource areas; (3) cumbersome and slow planning, siting, and permitting procedures that impede wind energy development; (4) the relative immaturity and therefore high cost of off-shore wind energy technology; and (5) lack of institutional and technical knowledge in regions that have not experienced substantial wind energy development to this point.

As a result of these issues, growth in the wind energy sector is affected by and responsive to political frameworks and a wide range of government policies. During the past two decades, a significant number of developed countries and, more recently, a growing number of developing nations have laid out RE policy frameworks that have played a major role in the expansion of the wind energy market. These efforts have been motivated by the environmental, fuel diversity, and economic development impacts of wind energy deployment. An early significant effort to deploy wind energy at commercial scale occurred in California, with a feed-in tariff and aggressive tax incentives spurring growth in the 1980s (Bird *et al.*, 2005). In the 1990s, wind energy deployment moved to Europe, with feed-in tariff policies initially established in Denmark and Germany, and later expanding to Spain and then a number of other countries (Meyer, 2007); renewables portfolio standards have been implemented in other European countries and, more recently, European renewable energy policies have been motivated in part by the EU's binding 20%-by-2020 target for renewable energy. In the 2000s, growth in the U.S. (Bird *et al.*, 2005; Wiser and Bolinger, 2009), China (Li *et al.*, 2007; Li, 2010), and India (Goyal, 2010) was based on varied policy frameworks, including renewables portfolio standards, tax incentives, feed-in tariffs, and government-overseen bidding. Still other policies have been used in a number of countries to directly encourage the localization of wind turbine and component manufacturing (Lewis and Wiser, 2007).

Though economic support policies differ, and a healthy debate exists over the relative merits of different approaches, a key finding is that both policy transparency and predictability are important (see Chapter 11). Moreover, though it is not uncommon to focus on economic policies for wind energy, as noted above and as discussed elsewhere in this chapter and in Chapter 11, experience shows that wind energy markets are also dependent on a variety of other factors. These include local resource availability, site planning and approval procedures, operational integration concerns, transmission grid expansion, wind energy technology improvements, and the availability of institutional and technical knowledge in markets unfamiliar with wind energy (IEA, 2009a). For the wind energy industry, these issues have been critical in defining both the size of the market opportunity in each country and the rules for participation in those opportunities; many countries with sizable wind resources have not deployed significant amounts of wind energy as a result of these factors. Successful frameworks for the deployment of wind energy have generally included the following elements: support systems that offer adequate profitability and that ensure investor confidence; appropriate administrative procedures for wind energy planning, siting, and permitting; a degree of public acceptance of wind power plants to ease implementation; access to the existing transmission system and strategic transmission planning and new investment for wind energy; and proactive efforts to manage wind energy's inherent output variability and uncertainty. In addition, research and development by government and industry has been essential to enabling incremental improvements in on-shore wind energy technology and to driving the improvements needed in off-shore wind energy technology. Finally, for those markets that are new to wind energy deployment, both knowledge (e.g., wind resource mapping expertise) and technology (e.g., to develop local wind turbine manufacturers and to ease grid integration) transfer can help facilitate early installations.

7.5 Near-term grid integration issues

7.5.1 Introduction

As wind electricity penetration levels have increased so too have concerns about the integration of that energy into electric systems (e.g., Fox *et al.*, 2007). The nature and magnitude of the integration challenge will be system specific and will vary with the degree of wind electricity penetration. Nonetheless, the existing literature generally suggests that, at low to medium levels of wind electricity penetration (under 20% of total electricity demand), the integration of wind energy is technically and economically manageable, though institutional constraints will need to be overcome. Moreover, increased operating experience with wind energy along with improved technology and additional research should facilitate the integration of even greater quantities of wind energy without degrading electric system reliability.

The integration issues covered in this section include how to address wind power variability and uncertainty, how to provide adequate transmission capacity to connect wind power plants to electricity demand centres, and the development of connection standards and grid codes. The focus is on those issues faced at low to medium levels of wind electricity penetration (under 20%). Even higher levels of penetration may depend on the availability of additional flexibility options, such as mass-market demand response, large-scale deployment of electric vehicles and their associated contributions to system flexibility through controlled battery charging, increased deployment of other storage technologies, and improvements in the interconnections between electric systems; the deployment of a diversity of RE technologies may also help facilitate overall electric system integration. These options relate to broader developments within the energy sector that are not specific to wind energy, however, and are therefore addressed in Chapter 8.

This section begins by describing the specific characteristics of wind energy that present integration challenges (7.5.2). The section then discusses how these characteristics impact issues associated with the planning (7.5.3) and operation (7.5.4) of electric systems to accommodate wind energy, including experience in systems with high wind electricity penetration. The final section (7.5.5) summarizes the results of various integration studies that have sought to better quantify the technical and economic integration issues associated with increased wind electricity supply.

7.5.2 Wind energy characteristics

Integrating wind energy into electric systems relies on the same basic planning and operating tools that are used to ensure the reliable operation of electric systems without wind energy. Several important characteristics of wind energy are different from those of conventional generation, however, and these characteristics must be considered in electric system planning and operation.

First, the quality of the wind resource and therefore the cost of wind energy are location dependent. Because regions with the highest-quality wind energy resources may not be situated near high demand areas, additional transmission infrastructure is often needed to bring wind energy from the best wind resource sites to electricity demand centres (see Section 7.5.5).

Second, wind energy is weather dependent and therefore variable. The power output of a wind power plant varies from zero to its rated capacity depending on prevailing weather conditions; Figure 7.13 illustrates this variability by showing the output of an individual wind turbine, a small collection of wind power plants, and a large collection of wind power plants in Germany over ten consecutive days. The most relevant characteristic of wind power variability for electric system *operation* is the rate of change in wind power output over different time periods; Figure 7.13 demonstrates that the aggregate output of multiple wind power plants changes much more dramatically over longer periods (multiple hours) than over very short periods (minutes). The most relevant characteristic of wind power variability for the purpose of electric sector *planning*, on the other hand, is the correlation of wind power output with the periods of time when electric system reliability is at greatest risk, typically periods of high electricity demand. This correlation affects the capacity credit assigned by system planners to wind power, as discussed further in Section 7.5.3.4.

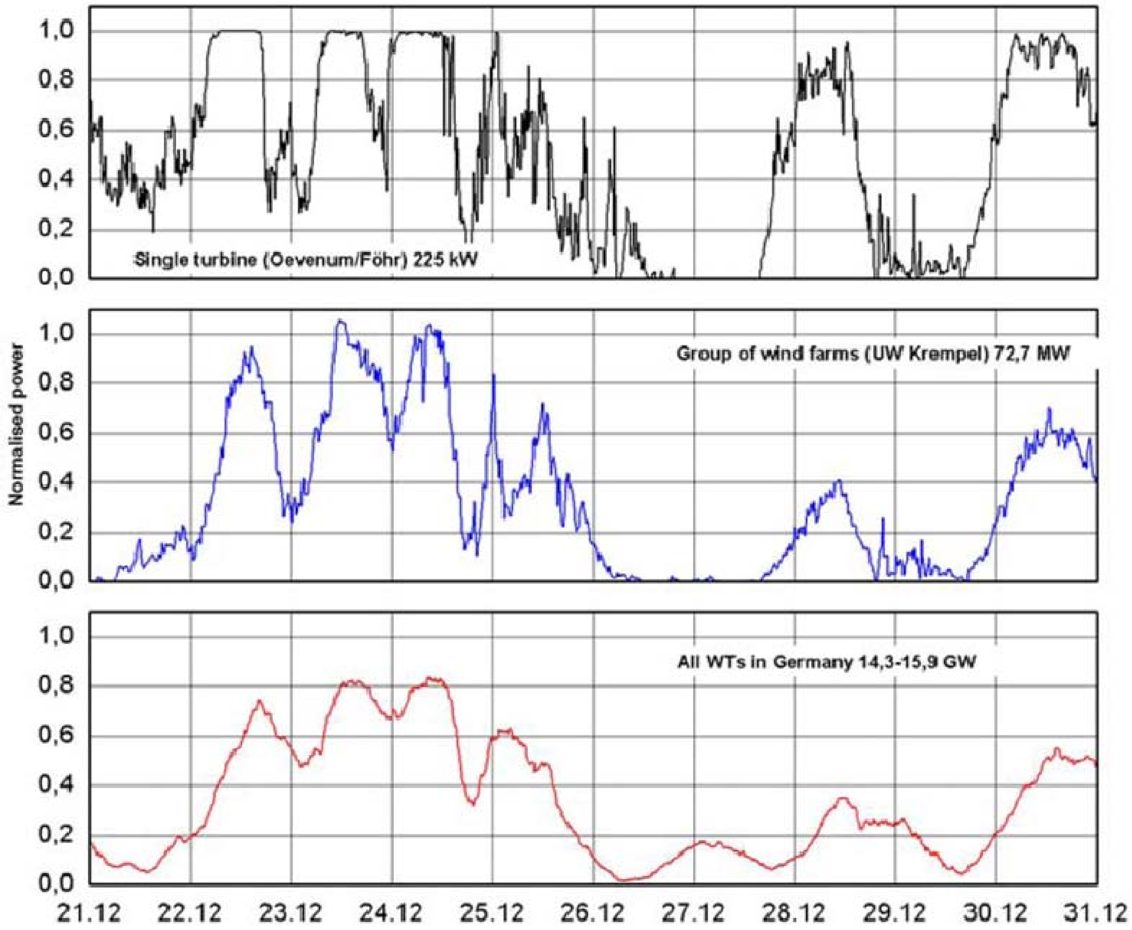

Figure 7.13. Example time series of wind power output normalised to wind power capacity for a single wind turbine, a group of wind power plants, and all wind power plants in Germany over a 10-day period in 2004 (Holttinen et al., 2009)

Third, in comparison with conventional power plants, wind power output has lower levels of predictability. Forecasts of wind power output use various approaches and have multiple goals, and significant improvements in forecast accuracy have been achieved in recent years (e.g., Costa *et al.*, 2008). Despite those improvements, however, forecasts are less accurate over longer forecast horizons (multiple hours to days) than over shorter periods (e.g., Madsen *et al.*, 2005 [TSU: reference missing]), which has implications for the ability of electric systems to manage wind power variability and uncertainty (Usaola, 2009; Weber, 2010).

The aggregate variability and uncertainty of wind power output depends, in part, on the degree of correlation in the output of geographically dispersed wind power plants. This correlation, in turn, depends on the geographic deployment of wind power plants and the regional characteristics of weather patterns, and especially wind speeds. Generally, the output of wind power plants that are further apart are less correlated, and variability over shorter time periods (minutes) is less correlated than variability over longer time periods (multiple hours) (e.g., Wan *et al.*, 2003; Sinden, 2007; Holttinen *et al.*, 2009; Katzenstein *et al.*, 2010). The output smoothing benefits of geographic diversity are illustrated in Figure 7.13: if the output of multiple wind turbines and power plants was perfectly correlated, then the aggregate variability would be equivalent to the scaled variability of a single wind turbine. Since correlation decreases with distance, however, the aggregate scaled variability shown for groups of wind power plants over a region is less than the scaled output of a single wind turbine. This output smoothing effect has implications for the variability of aggregate wind power output that electric systems must accommodate, and also influences forecast accuracy because accuracy improves with the number and diversity of wind power plants considered (e.g., Focken *et al*., 2002).

7.5.3 Planning electric systems with wind energy

Ensuring the reliable operation of electric systems in real-time requires detailed system planning over the time horizons required to build new generation or transmission infrastructure. Planners must evaluate the adequacy of transmission to allow interconnection of new generation and the adequacy of generation to maintain a balance between supply and demand under a variety of operation conditions. Four planning issues deserve attention when considering increased reliance on wind energy: the need for accurate electric system models of wind turbines and power plants, the creation of interconnection standards (i.e., power quality and grid codes) that account for the characteristics of wind energy, the transmission infrastructure needs of wind energy, and the maintenance of overall resource adequacy with increased wind electricity penetration.

7.5.3.1 Electric system models

Computer-based simulation models are used extensively to evaluate the ability of the electric system to accommodate new generation, changes in demand, and changes in operational practices. An important role of electric system models is to demonstrate the ability of an electric system to recover from severe events or contingencies. Generic models of conventional synchronous generators have been developed and validated over a period of multiple decades. These models are used inside industry standard software tools (e.g., PSSE, DigSilent, etc.) to study how the electric system and all its components will behave during system events or contingencies. Similar generic models of wind turbines and wind power plants are in the process of being developed and validated. Because wind turbines are non-standard when compared to conventional synchronous generators, this modelling exercise requires significant effort. As a result, though considerable progress has been made, this progress is not complete and increased deployment of wind energy will require improved and validated models to allow planners to better assess the capability of electric systems to accommodate additional wind power plants (Coughlan *et al*., 2007; NERC, 2009).

7.5.3.2 Power quality and grid codes

As wind power capacity has increased, so too has the need for wind power plants to become more active participants in maintaining (rather than passively depending on) the operability and power quality of the electric system. Focusing here primarily on the technical aspects of grid interconnection, the electrical performance of wind turbines in interaction with the grid is often verified in accordance with IEC 61400-21, in which methods to assess the impact of one or more wind turbines on power quality are specified (IEC, 2008b). Additionally, an increasing number of electric system operators have implemented minimum interconnection requirements (sometimes called “grid codes”) that wind turbines and/or wind power plants (and other power plants) must meet when connecting to the grid to prevent equipment or facilities from adversely affecting the electric system during normal operation and contingencies. Electric system models and operating experience are used to develop these requirements, which can then typically be met through modifications to wind turbine design or through the addition of auxiliary equipment such as power conditioning devices. In some cases, the unique characteristics of specific generation types are addressed in grid codes, resulting in wind-specific grid codes (e.g., Singh and Singh, 2009).

Grid codes often require “fault ride-through” capability, or the ability of a wind power plant to remain connected and operational during brief but severe changes in electric system voltage (Singh and Singh, 2009). The imposition of fault ride-through requirements on wind power plants responded to the increasing penetration of wind energy and the significant size of individual wind power plants. Electric systems can typically maintain reliable operation when small individual power plants shut-down or disconnect from the system for protection purposes in response to fault conditions. When a large amount of wind power capacity disconnects in response to a fault, however, that disconnection can exacerbate the fault conditions. Electric system planners have therefore increasingly specified that wind power plants should continue to remain operational during faults and meet minimum fault ride-through standards similar to other large conventional power plants. System wide approaches have also been adopted: in Spain, for example, wind power output may be curtailed in order to avoid potential reliability issues in the event of a fault; the need to employ this curtailment, however, is expected to decrease as fault ride-through capability is added to new and existing wind power plants (Rivier Abbad, 2010). Reactive power control to help manage voltage is also often required by grid codes, enabling wind turbines to improve voltage stability margins particularly in weak parts of the electric system (Vittal *et al.*, 2010). Requirements for wind turbine inertial response to improve system stability after disturbances are less common, but are increasingly being considered (Hydro-Quebec TransEnergie, 2006; Doherty *et al.*, 2010). Finally, active power control (including ramp-rate limits) and frequency control are sometimes required (Singh and Singh, 2009).

7.5.3.3 Transmission infrastructure

As noted earlier, the addition of large quantities of wind energy will require upgrades to the transmission system, in part because the strongest wind resources (whether on- or off-shore) are often located at a distance from load centres. Accurate transmission adequacy evaluations must account for the locational dependence of the wind resource, the relative smoothing benefits of aggregating wind power plants over large areas, and the transmission capacity required to manage the variability of wind energy (Burke and O'Malley, 2010). One of the primary challenges with transmission expansion to accommodate increased wind energy development is the long time it takes to plan, site, permit, and construct new transmission infrastructure relative to the relatively shorter period of time it takes to add new wind power plants. The institutional challenges of transmission expansion, including cost allocation and siting, can be substantial (e.g., Vajjhala and Fischbeck, 2007; Benjamin, 2007; Swider *et al.*, 2008). Enabling high penetrations of wind electricity may therefore require proactive rather than reactive transmission planning (Schumacher *et al.*, 2009). Estimates of the cost of the new transmission required to achieve low to medium levels of wind electricity penetration in a variety of locations around the world are summarized in Section 7.5.5.

7.5.3.4 Resource adequacy

Resource adequacy evaluations are used to assess the capability of generating resources to reliably meet electricity demand. Planners evaluate the long-term reliability of the electric system by estimating the probability that the system will be able to meet expected demand in the future, as measured by the load carrying capability of the system. Each electricity supply resource contributes some fraction of its name-plate capacity to the overall capability of the system, as indicated by the capacity credit assigned to the resource; the capacity credit is greater when power output is well-correlated with periods of time when there is a high risk of generation shortage. The capacity credit of a generator is therefore a “system” characteristic in that it is determined not only by the generator’s characteristics but also by the characteristics of the system to which that generator is connected.

The contribution of wind energy towards long-term reliability can be evaluated using standard approaches, and wind power plants are typically found to have a capacity credit of 5-40% of name-plate capacity (Holttinen *et al.*, 2009). The correlation between wind power output and electrical demand is an important determinant of the capacity credit of an individual wind power plant. In many cases, wind power output is uncorrelated or is weakly negatively correlated with periods of high electricity demand, reducing the capacity credit of wind power plants; this is not always the case, however, and wind power output in the UK has been found to be weakly positively correlated with periods of high demand (Sinden, 2007). These correlations are case specific as they depend on the diurnal, seasonal, and yearly characteristics of both wind power output and electricity demand. A second important characteristic of the capacity credit for wind energy is that its value decreases as wind electricity penetration levels rise because increased deployment of wind energy shifts the periods of greatest electric system risk to times with lower average levels of wind power output (Hasche *et al.*, 2010). Aggregating wind power plants over larger areas reduces the correlation between wind power outputs, as described earlier, and can therefore slow the decline in capacity credit as wind electricity penetration increases, though adequate transmission capacity is required to aggregate wind power plants over larger areas (Tradewind, 2009; EnerNex Corp, 2010).[18]

The relatively low average capacity credit of wind power plants (compared to conventional fossil units, for example) suggests that systems with large amounts of wind energy will also tend to have significantly more total nameplate generation capacity to meet the same peak load than will an electric system without large amounts of wind energy. Some of this generation capacity will operate infrequently, however, and the mix of conventional generation in an electric system with large amounts of wind energy will therefore increasingly shift towards “peaking” resources and away from “baseload” resources (e.g., Lamont, 2008; Milborrow, 2009; Boccard, 2010).

7.5.4 Operating electric systems with wind energy

The unique characteristics of wind energy, and especially power output variability and uncertainty, also hold important implications for electric system operations. Here we summarize those implications in general (Section 7.5.4.1), and then briefly discuss three specific case studies of the integration of wind energy into real electricity systems (Section 7.5.4.2).

7.5.4.1 Integration, flexibility, and variability

Because wind electricity is generated with a near-zero marginal operating cost, it is typically used to meet demand when it is available, thereby displacing the use of conventional generators that have higher marginal costs. This results in electric system operators and markets primarily dispatching conventional generators to meet demand minus any available wind energy (i.e., “net demand”[19]).

As wind electricity penetration grows, the variability of wind energy results in an overall increase in the magnitude of changes in net demand, and also a decrease in the minimum net demand. Figure 7.14 shows that, at relatively low levels of wind electricity penetration (7.5% of total electricity demand from wind energy), the magnitude of changes in net demand, as shown in the 15-minute ramp duration curve, is similar to the magnitude of changes in total demand (Figure 7.14(c)). At higher levels of wind electricity penetration (40% of total electricity demand from wind energy), however, the changes in net demand are greater than changes in total demand (Figure 7.14(d)). The figure also shows that, at high levels of wind electricity penetration, the magnitude of net demand

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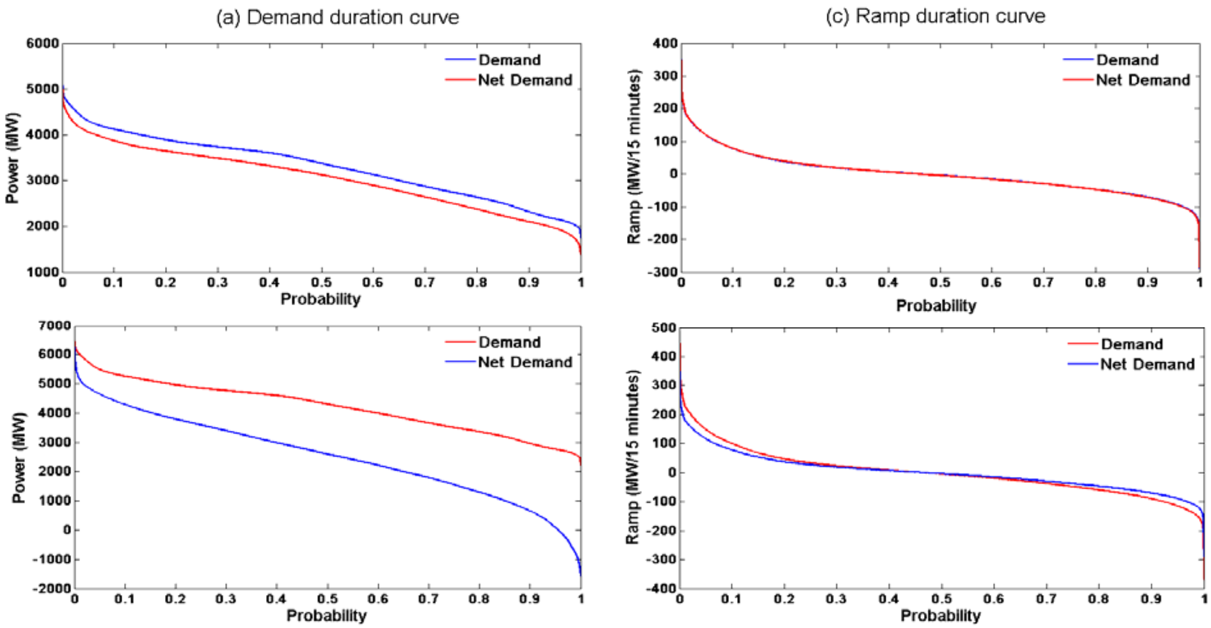
[18] Generation resource adequacy evaluations are also beginning to include the capability of the system to provide adequate flexibility and operating reserves to accommodate more wind energy (NERC, 2009). The increased demand from wind energy for operating reserves and flexibility is addressed in Section 7.5.4.

[19] Net demand is defined as total electrical demand minus wind electricity supply.

across all hours of the year is lower than total demand, and that in some hours the net demand is near or even below zero (Figure 7.14(b)).



(b) Demand duration curve (projected) (d) Ramp duration curve (projected)

Figure 7.14. Demand duration and 15-minute ramp duration curves for Ireland in (a,c) 2008 (7.5% wind electricity penetration), and (b,d) projected for high wind electricity penetration levels (40%).[20] Source: Data from www.eirgrid.com

As a result of these trends and the underlying variability and uncertainty in wind power output, wholesale electricity prices will tend to decline when wind power output is high, with a greater frequency of low or even negative prices (e.g., Jonsson *et al.*, 2010 [TSU: reference missing]). Increased wind electricity penetrations will therefore tend to reduce average wholesale prices in the short-term, though in the long-run the average effect of wind energy on wholesale prices is not as clear as pricing signals begin to influence decisions about the type of new generation that is built (Lamont, 2008; Sensfuß *et al.*, 2008; Sáenz de Miera *et al.*, 2008; MacCormack *et al.*, 2010).

These price impacts are a reflection of the fact that increased wind energy deployment will require conventional generating units to operate in a more flexible manner than required without wind energy. At low to medium levels of wind electricity penetration, the increase in *minute-to-minute* variability is expected to [TSU: be] relatively small and therefore inexpensive to manage in large electric systems (Smith *et al.*, 2007). The more significant operational challenges relate to the variability and commensurate increased need for flexibility to manage changes in wind power output over *1 to 6 hours* (Doherty and O'Malley, 2005). Incorporating state-of-the-art forecasting of wind energy over multiple time horizons into electric system operations can reduce the need for flexibility and operating reserves, and has been found to be especially important with high levels of wind electricity penetration (e.g., Doherty *et al.*, 2004; Tuohy *et al.*, 2009; GE Energy, 2010). Even with high-quality forecasts and geographically dispersed wind power plants, however, additional start-ups and shut-downs, part-load operation, and ramping will be required from conventional units to maintain the supply/demand balance (e.g., Göransson and Johnsson, 2009; Troy *et al.*, 2010).

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[20] Projected demand and ramp duration curves are based on scaling 2008 data (demand is scaled by 1.27 and wind power is scaled on average by 7). Ramp duration curves show the cumulative probability distributions of 15-minute changes in demand and net demand.

This additional flexibility is not free, as it increases wear and tear on boilers and other equipment, increases maintenance costs, and reduces power plant life (Denny and O'Malley, 2009). Various kinds of economic incentives can be used to ensure that the operational flexibility of conventional generators is made available to system operators. Some electricity systems, for example, have day-ahead, intra-day, and/or hour-ahead markets for electricity, as well as markets for reserves, balancing energy, and other ancillary services. These markets can provide pricing signals for increased (or decreased) flexibility when needed as a result of rapid changes in or poorly predicted wind power output, and can therefore reduce the cost of integrating wind energy (Smith *et al.*, 2007). Markets with shorter scheduling periods have also been found to be more responsive to variability and uncertainty in net load, and thereby facilitate wind energy integration (Kirby and Milligan, 2008), as have coordinated system operations across larger areas (Milligan and Kirby, 2008). Where wholesale electricity markets do not exist, other planning methods or incentives would be needed to ensure that existing conventional plants are flexible enough to accommodate increased deployment of wind energy. Planning systems and incentives may also need to be adopted to ensure that new conventional plants are sufficiently flexible to accommodate expected wind energy deployment. Moreover, in addition to flexible fossil units, hydropower stations, electrical storage, and various forms of demand response can also be used to facilitate the integration of wind energy. Wind power plants, meanwhile, can provide some flexibility by curtailing output or by limiting or even (partially) controlling ramp rates. Though curtailing wind power output is a simple and often times readily available source of flexibility, it is expensive to curtail plants that have low operating costs before reducing the output from conventional plants that have high fuel costs; as a result, wind power curtailment is not likely to be used extensively for this purpose, at least at low levels of wind electricity penetration.

7.5.4.2 Practical experience with operating electric systems with wind energy

Actual operating experience in different parts of the world demonstrates that wind energy can be reliably integrated into electric systems (Söder *et al.*, 2007). In some countries, as discussed earlier, wind energy already supplies in excess of 10% of annual electricity demand. The three examples reported here demonstrate the challenges associated with this operational integration, and the methods used to manage the additional variability and uncertainty associated with wind energy. Naturally, these impacts and management methods vary across regions for reasons of geography, electric system design, and regulatory structure.

Denmark has the largest wind electricity penetration of any country in the world, with wind energy supply equating to approximately 20% of total annual electricity demand. Total wind power capacity installed by the end of 2009 equalled 3.4 GW on a system with a peak demand of 6.5 GW. Much of the wind power capacity (2.7 GW) is located in Western Denmark, resulting in instantaneous wind power output exceeding total demand in some instances (see Figure 7.15). The Danish example demonstrates the value of access to markets for flexible resources and strong transmission connections to neighbouring countries. The Danish system operates without serious reliability issues in part because Denmark is well interconnected to two different synchronous electric systems. In conjunction with wind power output forecasting, this allows wind electricity to be exported to other markets and helps the Danish operator manage wind power variability. The interconnection with the Nordic system, in particular, provides access to flexible hydropower resources. Balancing the Danish system is much more difficult during periods when one of the interconnections is down, however, and more flexibility is expected to be required if Denmark markedly increases its penetration of wind electricity (EA Energianalyse, 2007).

In contrast to the strong interconnections of the Danish system with other electric systems, the island of Ireland has a single synchronous system; it is of similar size system to the Danish system but interconnection capacity is limited to a single 500 MW link. The wind power capacity installed by the end of 2009 was capable of supplying roughly 11% of Ireland's annual electricity demand, and the Irish system operators have successfully managed that level of wind electricity penetration. The large daily variation in electricity demand in Ireland, combined with the isolated nature of the Irish system, has resulted in a very flexible electric system that is particularly well suited to integrating wind energy. As a result, despite the lack of significant interconnection capacity, the Irish system has successfully operated with instantaneous levels of wind electricity penetration of over 40% (see Figure 15). Nonetheless, it is recognized that as wind electricity penetration levels increase further, new challenges will arise. Of particular concern is the possible lack of inertial response of wind turbines without additional turbine controls (Lalor *et al.*, 2005), the need for greater flexibility to maintain supply-demand balance, and the need to build substantial amounts of additional high-voltage transmission (AIGS, 2008). Moreover, in common with the Danish experience, much of the wind energy is and will be connected to the distribution system, requiring attention to reactive power control issues (Vittal *et al.*, 2010). Figure 7.15 illustrates the high levels of wind electricity penetration that exist in Ireland and West Denmark.

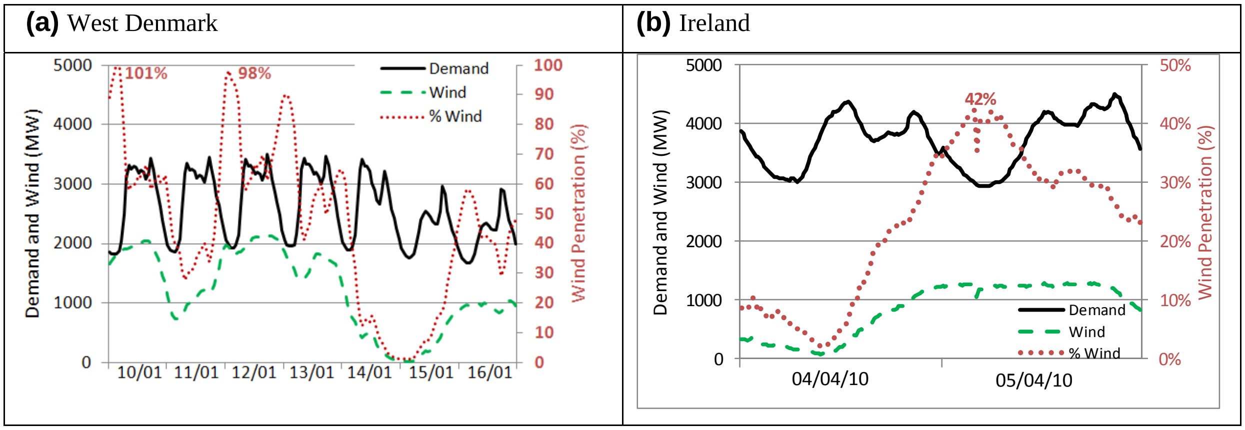
(a) West Denmark **(b)** Ireland

Figure 7.15. Wind energy, electricity demand, and instantaneous penetration levels in (a) West Denmark for a week in January 2005, and (b) the island of Ireland for two days in April 2010. Source: Data from (a) www.energinet.dk; (b) www.eirgrid.com and SONI.

The Electric Reliability Council of Texas (ERCOT) operates a synchronous system with a peak demand of 63 GW and 8.5 GW of wind power capacity, and with a wind electricity penetration level of 6% of annual electricity demand by the end of 2009. ERCOT's experience demonstrates the importance of incorporating wind energy forecasts into system operations, and the need to schedule adequate reserves to accommodate system uncertainty. During February 26, 2008 a combination of factors led ERCOT to implement its emergency curtailment plan. On that day, ERCOT experienced a decline in wind power output of 1,500 MW over a three hour period, roughly 30% of the installed nameplate wind power capacity (Ela and Kirby, 2008; ERCOT, 2008). The event was exacerbated by the fact that scheduling entities – which submit updated resource schedules to ERCOT one hour prior to the operating hour – consistently reported an expectation of more wind power output than actually occurred. A state-of-the-art forecast was available, but was not yet integrated into ERCOT system operations, and that forecast predicted the wind energy event much more accurately. As a result of this experience, ERCOT accelerated its schedule for incorporating the advanced wind energy forecasting system into its operations.

7.5.5 Results from integration studies

In addition to actual operating experience, a number of high-quality studies of the increased transmission and generation resources required to accommodate wind energy have been completed, covering many different regions of the world. These studies employ a wide variety of methodologies and have diverse objectives, but typically seek to quantify the costs and benefits of integrating wind energy into electric systems. The costs considered by these studies often include the need for additional transmission, the requirement to maintain sufficient resource adequacy, and the operating reserves required to accommodate the increased variability and uncertainty caused by wind energy. Benefits might include reduced fossil fuel usage and the CO_2 emissions savings from displaced conventional plants.

The results of these studies, as described in more detail below, demonstrate that the cost of integrating up to 20% wind electricity into electric systems is, in most cases, modest but not insignificant. Specifically, at low to medium levels of wind electricity penetration, the available literature suggests that the additional costs of managing electric system variability and uncertainty, ensuring resource adequacy, and adding new transmission to accommodate wind energy will generally not exceed 30% of the generation cost of wind energy.[21] That said, concerns about (and the costs of) wind energy integration will grow with wind energy deployment and, even at medium penetration levels, integration issues must be actively managed.

Addressing all integration impacts requires several different simulation models that operate over different time scales, and most studies therefore focus on a subset of the potential issues. The results of wind energy integration studies are also dependent on pre-existing differences in electric system designs and regulatory environments: important differences include generation capacity mix and the flexibility of that generation, the variability of demand, and the strength and breadth of the transmission system. Finally, study results differ because a standard methodology has not been developed for these studies, though significant progress has been made in developing agreement on many high-level study design principles (Holttinen *et al.*, 2009).

One of the most significant challenges in executing these studies is simulating wind power output data at high-time-resolutions for a chosen future wind electricity penetration level and for a sufficient duration for the results of the analysis to be statistically reliable. The data are then used in electric system simulations to mimic system planning and operations, thereby quantifying the costs, emissions savings, and transmission needs of high wind electricity penetrations. The first-generation integration studies used models that were not designed to fully reflect the variability and uncertainty of wind energy, resulting in studies that addressed only parts of the larger system. More recent studies have used models that can incorporate the uncertainty of wind power output from the day-ahead time scale to some hours ahead of delivery (e.g., Meibom *et al.*, 2009; Tuohy *et al.*, 2009). In additional, integration studies are increasingly simulating high wind electricity penetration scenarios over entire synchronized systems (not just individual, smaller balancing areas) (e.g., Tradewind, 2009; EnerNex Corp, 2010; GE Energy, 2010).

Regardless of the challenges to executing such studies, a number of significant wind energy integration studies in Europe and the U.S. have concluded that accommodating wind electricity penetrations of up to (and in a limited number of cases, exceeding) 20% is technically feasible, but not without challenges (Gross *et al.*, 2007; Smith *et al.*, 2007; Holttinen *et al.*, 2009; Milligan *et al.*, 2009). The estimated increase in short-term reserve requirements in eight studies summarized by Holttinen *et al.* (2009) has a range of 1-15% of installed wind power capacity at 10% wind electricity penetration, and 4-18% of installed wind power capacity at 20% wind electricity penetration. Those studies that predict a need for higher levels of reserves generally assume that day-ahead uncertainty and/or multi-hour variability of wind power output is handled with short-term reserves. In contrast, markets that are optimized for wind energy will generally be designed so

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[21] Section 8 estimates that the levelized cost of on-shore wind energy in 2009 ranged from US$50-150/MWh. As reported below, the high-end of the cost range for managing wind energy's variability and uncertainty ($5/MWh), ensuring resource adequacy (US$10/MWh), and adding new transmission (US$15/MWh) sums to $30/MWh, or roughly 30% of the mid-point of the 2009 levelized cost of on-shore wind energy (US$100/MWh).

that additional opportunities to balance supply and demand exist, reducing the reliance on more-expensive short-term reserves (e.g., Weber, 2010). Notwithstanding these differences in results and methods, however, the studies reviewed by Holttinen *et al.* (2009) find that, in general, wind electricity penetrations of up to 20% can be accommodated with increased system operating costs of roughly US$1.4–5.6/MWh of wind energy generated. Similar results are found by Gross *et al.* (2007), Smith *et al.* (2007), and Milligan *et al.* (2009). State-of-the-art wind power forecasts are often found to be a key factor in minimizing the impact of wind energy on market operations.

The benefits of adding a wind power plant to an electric system are often compared to the benefits of a baseload, or fully utilized, plant that generates an equivalent amount of energy on an annual basis. Using this framework, Gross *et al.* (2007) and Boccard (2010) estimate that the difference between the contribution to resource adequacy of a wind power plant and an energy-equivalent baseload plant can result in a US$5-10/MWh resource adequacy cost for wind energy at electricity penetration levels up to 20%. As discussed earlier, the correlation of wind power output to electricity demand, the geographic distribution of wind power plant siting, and the level of wind electricity penetration will all impact the capacity value of wind energy, and therefore this relative cost of resource adequacy.

Finally, several broad assessments of the need for and cost of transmission for wind energy have similarly found modest, but not insignificant, costs. The transmission cost for 300 GW of wind power capacity in the United States was estimated to add about $150-$300/kW to the installed cost of wind power plants (US DOE, 2008). More-detailed assessments of the transmission needed to accommodate increased wind energy deployment in the U.S. have found a wider range of results, with estimated costs sometimes reaching (or even exceeding) $400/kW (JCSP, 2009; Mills *et al.*, 2009; EnerNex Corp, 2010). Large-scale transmission for wind energy has also been considered in Europe (Czisch and Giebel, 2000) and China (Lew *et al.*, 1998). Results from country specific transmission assessments in Europe have resulted in varied estimates of the cost of transmission; Auer *et al.* (2004) and EWEA (2005) identified transmission costs for a number of European studies, with cost estimates that are somewhat lower than those found in the U.S. Holttinen *et al.* (2009) review wind energy transmission costs from several European national case studies, and find costs as high as $350/kW. At the high end of the range from the available literature ($400/kW), these costs would add roughly $15/MWh to the levelized cost of wind energy. Transmission expansion for wind energy can be justified by the reduction in congestion costs that would occur for the same level of wind energy deployment without transmission expansion. A European-wide study, for example, identified several transmission upgrades between nations and between high quality off-shore wind resource areas that would reduce transmission congestion and ease wind energy integration for a 2030 scenario (Tradewind, 2009). The avoided congestion costs associated with transmission expansion are similarly found to justify transmission investments in two U.S.-based detailed integration studies of high wind electricity penetrations (Milligan *et al.,* 2009).

7.6 Environmental and social impacts

Wind energy has significant potential to reduce (and already is reducing) GHG emissions, together with the emissions of other air pollutants, by displacing fossil fuel-based electricity generation. Because of the commercial readiness (Section 7.3) and cost (Section 7.8) of the technology, wind energy can be immediately deployed on a large scale (Section 7.9). As with other industrial activities, however, wind energy also has the potential to produce some detrimental impacts on the environment and on human beings, and many local and national governments have established planning, permitting, and siting requirements to minimize those impacts. These potential concerns need to be taken into account to ensure a balanced view of the advantages and disadvantages of wind energy. This section summarizes the best available knowledge on the most relevant environmental net benefits of wind energy (7.6.1), while also addressing ecological (7.6.2) and human impacts (7.6.3), public attitudes and acceptance (7.6.4), and processes for minimizing social and environmental concerns (7.6.5).

7.6.1 Environmental net benefits of wind energy

The environmental benefits of wind energy come primarily from a reduction of emissions from fossil fuel-based electricity generation. However, the manufacturing, transport, and installation of wind turbines induces some indirect negative effects, and the variability of wind power output also impacts the operations and emissions of conventional plants; such effects need to be subtracted from the gross benefits to begin to estimate the net benefits of wind energy. As shown below, these latter effects are modest compared to the net GHG reduction benefits of wind energy.

7.6.1.1 Direct impacts

The major environmental benefits of wind energy (as well as other forms of RE) result from displacing electricity generation from fossil-fuel based power plants, as the operation of wind turbines does not directly emit greenhouse gases or other air pollutants. In addition, by lowering the need for other forms of electricity supply, wind energy can reduce the need for cooling water for steam generators, the waste ash produced by coal generation, and the adverse impacts of coal mining and natural gas drilling.

Estimating the environmental benefits of wind energy is somewhat complicated by the operational characteristics of the electric system and the investment decisions that are made in new power plants to economically meet electricity load (Deutsche Energie-Agentur, 2005; NRC, 2007). In the short-run, increased wind energy will typically displace the operations of existing fossil plants that are otherwise on the margin. In the longer-term, however, new generating plants may be needed, and the presence of wind energy will influence what types of power plants are built in the future; specifically, increased wind energy will tend to favour peaking plants over baseload units (Kahn, 1979; Lamont, 2008). Because the impact of these factors are both complicated and system specific, the benefits of wind energy will also be system specific and are difficult to forecast with precision.

Despite these complications, it is clear that the direct impact of wind energy is to reduce air pollutants and GHG emissions. Depending on the characteristics of the electric system into which wind energy is integrated and the amount of wind energy supply, the reduction of air pollution and GHG emissions may be substantial. Globally, it has been estimated that the roughly 160 GW of wind power capacity already installed by the end of 2009 could generate 340 TWh/y of electricity and save more than 200 MMT CO_2/y (GWEC, 2010b).

7.6.1.2 Indirect lifecycle impacts

One indirect impact of wind energy arises from the release of GHGs and air pollutants during the manufacturing, transport, and installation of wind turbines, and their subsequent decommissioning. Life-cycle assessment (LCA) procedures based on ISO 14040 and ISO 14044 standards (ISO, 2006) have been used to analyze these impacts. Though these studies may include a range of impact categories, LCA studies for wind energy have often been used to determine the life-cycle GHG emissions per unit of wind-electricity generated (allowing for full fuel-cycle comparisons with other forms of electricity production) and the energy payback time of wind power plants (i.e., the time it takes a wind turbine to generate an amount of electricity equivalent to that used in its manufacture and installation). The results of a number of these recent LCA studies are summarized in Table 7.3.

Table 7.3. Wind energy carbon intensity and energy payback from various LCA studies

Article	Wind Turbine Size	Location	Capacity Factor	Energy Payback (years)	Carbon Intensity (gCO_2/kWh)
Schleisner (2000)	0.5 MW	on-shore	43.5%	0.26	9.7
Krohn (1997)	0.6 MW	on-shore	n/a	0.25	n/a
Voorspools (2000)	0.6 MW	on-shore*	n/a	n/a	27
Jungbluth *et al.* (2005)	0.8 MW	on-shore	20%	n/a	11
Pehnt (2006)	1.5 MW	on-shore	n/a	n/a	10.2
Elsam Engineering (2004)	2.0 MW	on-shore	n/a	0.65	7.6
Martínez *et al.* (2009)	2.0 MW	on-shore	23%	0.40	n/a
Vestas (2006)	3.0 MW	on-shore	30%	0.55	4.6
Tremeac and Meunier (2009)	4.5 MW	n/a	30%	0.58	15.8
Schleisner (2000)	0.5 MW	off-shore	40%	0.39	16.5
Voorspools (2000)	0.6 MW	off-shore*	n/a	n/a	9.2
Elsam Engineering (2004)	2.0 MW	off-shore	n/a	0.75	7.6
Jungbluth *et al.* (2005)	2.0 MW	off-shore	30%	n/a	13
Pehnt (2006)	2.5 MW	off-shore	n/a	n/a	8.9
Vestas (2006)	3.0 MW	off-shore	54%	0.57	5.2
Vattenfall (2003)	Not stated	n/a	n/a	n/a	14

* In Voorspools (2000), on-shore is described as “inland” and off-shore is described as “coastal”

The reported carbon intensity (in gCO_2/kWh) and energy payback (in years) of wind energy are low, but vary somewhat among published LCA studies, reflecting both methodological differences and differing assumptions about the life cycle of wind turbines. The carbon intensity of wind energy estimated by the studies included in Table 7.3 ranges from 4.6 to 27 gCO_2/kWh. Where studies have identified the significance of different stages of the life cycle of a wind power plant, it is clear that emissions from the manufacturing stage dominate overall life-cycle GHG emissions (e.g., Jungbluth *et al.*, 2005). Energy payback times for the studies presented in Table 7.3 suggest that the embodied energy of modern wind turbines is repaid in 3 to 9 months of operation.

7.6.1.3 Indirect variability impacts

Another concern that is sometimes raised is that the temporal variability and limited predictability of wind energy will limit the GHG emissions benefits of wind energy by increasing the short-term balancing reserves required for an electric system operator to maintain reliability (relative to the balancing reserve requirement without wind energy). Short-term reserves are generally provided by generating plants that are online and synchronized with the grid, and plants providing these reserves may be part-loaded to maintain flexibility to respond to short-term fluctuations. Part-loading fossil fuel-based generators decreases the efficiency of the plants and therefore creates a fuel efficiency and GHG emissions penalty relative to a fully-loaded plant. Analyses of the emissions benefits of wind energy do not always account for this effect.

The UK Energy Research Centre performed an extensive literature review of the costs and impacts of variable electricity supply; over 200 reports and articles were reviewed (Gross *et al.*, 2007). The review included a number of analyses of the fuel savings and GHG emissions benefits[22] of wind energy that accounted for the increase in necessary balancing reserves and the reduction in part-load efficiency of conventional plants. The efficiency penalty due to the variability of wind power output in four studies that explicitly addressed the issue ranged from near 0% to as much as 7%, for up to 20% wind electricity penetration (Gross *et al.*, 2006). In short, for moderate levels of wind electricity penetration, “there is no evidence available to date to suggest that in aggregate efficiency reductions due to load following amount to more than a few percentage points" (Gross and Heptonstall, 2008).[23]

7.6.1.4 Net environmental benefits

The precise balance of positive and negative environmental and health effects of wind energy is system specific, but can in general be documented by the difference in estimated external costs for wind energy and other electricity supply options, as shown in Chapter 10. Monetized figures for climate change damages, human health impacts, material damages, and agricultural losses show significant benefits from wind energy (e,g., Krewitt and Schlomann, 2006). Krewitt and Schlomann (2006) also qualitatively assess the direction of possible impacts associated with other damage categories (ecosystem effects, large accidents, security of supply, and geopolitical effects), finding that the net benefits of RE sources tend to be underestimated by not including these impacts in the monetized results. The environmental damages associated with conventional generation and benefits associated with wind energy have been summarized many times in the broader externalities literature (e.g., EC, 2003; Owen, 2004; Sundqvist, 2004; NRC, 2009).

7.6.2 Ecological impacts

There are, nonetheless, ecological impacts that need to be taken into account when assessing wind energy. Potential ecological impacts of concern for on-shore wind power plants include the population-level consequences of bird and bat collision fatalities and more-indirect habitat and ecosystem modifications. For off-shore wind energy, the aforementioned impacts as well as implications for benthic resources, fisheries, and marine life more generally must be considered. Finally, the possible consequences of wind energy on the local climate have received attention. The focus here is on impacts associated with wind power plants themselves, but associated infrastructures also have impacts to consider (e.g., transmission lines, transportation to site, etc.). Moreover, wind energy is not unique among energy sources in have ecological consequences; more-systematic assessments are needed to evaluate the *relative* impacts of different forms of energy supply, especially within the context of the varying contributions of these energy sources towards global climate change (see Chapter 9).

7.6.2.1 Bird and bat collision fatalities

Bird and bat fatalities through collisions with wind turbines are among the most publicized environmental concerns associated with wind power plants. Populations of many species of birds and bats are in decline, leading to concerns about the effects of wind energy on vulnerable species.

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[22] Because CO_2 emissions are generally proportional to fuel consumption for a single fossil-fuel plant, the CO_2 emissions penalty is similar to the fuel efficiency penalty.

[23] Katzenstein and Apt (2009) conclude that the efficiency penalty could be as high as 20%, but inaccurately assume that every wind power plant requires spinning reserves equivalent to the nameplate capacity of the wind plant. Accounting for the smoothing benefits of geographic diversity (see section 7.5) and the ability to commit and de-commit conventional thermal plants lowers the estimated efficiency penalty substantially (Mills *et al.*, 2009).

Though much remains unknown about the nature and population-level implications of these impacts, avian fatality rates are power plant- and species-specific, and can vary with region, site characteristics, season, weather, turbine size and design, and other factors. Focusing on all bird species combined, the U.S. National Research Council surveyed the available (limited) literature through early 2007 and found bird mortality estimates that range from 0.95 to 11.67 per MW per year (NRC, 2007); other results, including those from Europe, provide a reasonably similar range of estimates (e.g., (De Lucas *et al.*, 2004; Drewitt and Langston, 2006; Everaert and Stienen, 2007; Kuvlesky *et al.*, 2007). Though most of the bird fatalities reported in the literature are of songbirds (Passeriformes), which are the most abundant bird group in terrestrial ecosystems (e.g., Erickson *et al.*, 2005; NRC, 2007), raptor fatalities are considered to be of greater concern as their populations tend to be relatively small. Compared to songbird fatalities, raptor fatalities have been found to be relatively low; nonetheless, these impacts are site specific, and there are cases in which raptor fatalities (and the potential for population-level effects) have raised concerns (e.g., Barrios and Rodriquez, 2004; Kuvlesky Jr. *et al.*, 2007; NRC, 2007; Smallwood and Thelander, 2008). As off-shore wind energy has increased, concerns have also been raised about seabirds. The limited research to date does not suggest that off-shore wind power plants pose a disproportionately large risk to birds, relative to on-shore wind energy (e.g., Dong Energy *et al.*, 2006); Desholm and Kahlert (2005), for example, find that seabirds tend to detect and avoid large off-shore wind power plants.

Bat fatalities have not been researched as extensively as bird fatalities at wind power plants, and data allowing reliable assessments of bat fatalities are somewhat limited (Dürr and Bach, 2004; Kunz *et al.*, 2007b; NRC, 2007). Several wind power plants have reported sizable numbers of bat fatalities, but other studies have shown low fatality rates. Surveying the available literature through early 2007, the U.S. National Research Council reported observed bat fatalities ranging from 0.8 to 41.1 bats per MW per year (NRC, 2007); a later review of 21 studies by Arnett *et al.* (2008) found fatality rates of 0.2 to 53.3 bats per MW per year. The specific role of different influences such as site characteristics, weather conditions, and turbine size, placement, and operation remain somewhat uncertain due to the lack of extensive and comparable studies (e.g., Kunz *et al.*, 2007b; Arnett *et al.*, 2008). Because bats are long-lived and have low reproduction rates, because of the patterns of bat mortality at wind power plants (e.g., research has shown that bats may be attracted to wind turbine rotors), and because of uncertainty about the current size of bat populations, the impact of wind power plants on bat populations is of particular contemporary concern (e.g., Barclay *et al.*, 2007; Horn *et al.*, 2008).

Significant uncertainty remains on the causal mechanisms underlying fatality rates and the effectiveness of mitigation measures, leading to limited ability to predict bird and bat fatality rates. Nonetheless, *possible* approaches to reducing fatalities that have been reported include siting power plants in areas with lower bird and bat population densities, placing turbines in areas with low prey density, avoiding lattice support towers, and using different numbers and sizes of turbines. Recent research also suggests that curtailing the operation of wind turbines during low wind situations may result in considerable reductions in bat fatalities (Arnett *et al.*, 2009; Baerwald *et al.*, 2009).

The magnitude and population-level consequences of bird and bat collision fatalities can also be viewed in the context of other fatalities caused by human activities. The number of bird fatalities at wind power plants is orders of magnitude lower than other anthropogenic causes of bird deaths (e.g., vehicles, buildings and windows, transmission lines, communications towers, house cats, pollution and other contaminants) (Erickson *et al.*, 2005; NRC, 2007). Moreover, it has been suggested that wind power plants are not currently causing meaningful declines in bird population levels (NRC, 2007), and that other energy supply options also impact birds and bats through collisions, habitat modifications, and contributions to global climate change (Lilley and Firestone, 2008; Sovacool, 2009). These assessments are based on aggregate comparisons, however, and the cumulative population-level impacts of wind energy development on some species where biologically significant impacts are possible remain uncertain (especially vis-à-vis bats). Improved methods to assess these population-level impacts and their possible mitigation are needed (Kunz *et al.*, 2007a), especially as wind energy increases and in comparison to the impacts associated with other electricity supply options.

7.6.2.2 Habit and ecosystem modifications

The habitat and ecosystem modification impacts of wind power plants on flora and fauna include, but are not limited to, avoidance of or displacement from an area, habitat destruction, and reduced reproduction (e.g., Drewitt and Langston, 2006; NRC, 2007; Stewart *et al.*, 2007). The relative biological significance of these impacts, compared to bird and bat collision fatalities, remains unclear. Moreover, the nature of these impacts will depend in part on the ecosystem into which wind power plants are integrated. Wind power plants are often installed in agricultural landscapes or on brown-field sites. In such cases, very different habitat and ecosystem impacts might be expected compared to wind power plants that are sited on previously undisturbed forested ridges or native grasslands. The development of wind power plants in largely undisturbed forests may, for example, lead to additional habitat destruction and fragmentation for intact forest-dependent species due to forest clearing for access roads, turbine foundations, and power lines (e.g., Kuvlesky Jr. *et al.*, 2007; NRC, 2007). Because habitat modification impacts are highly site and species specific, they are ideally addressed (with mitigation measures) in the wind power plant siting process; concerns for these impacts have also led to broader planning ordinances in some countries prohibiting the construction of wind power plants in ecologically sensitive areas.

The impacts of wind power plants on marine life have moved into focus as wind energy developments start to go off-shore and, as part of the licensing procedures for off-shore wind power plants, numerous studies on the possible impacts of wind power plants on marine life and ecosystems have been conducted. As Michel *et al.* (2007) point out, there are ‘several excellent reviews... on the potential impacts of offshore wind parks on marine resources; most are based on environmental impact assessments and monitoring programs of existing offshore wind parks in Europe…’. The localized impacts of off-shore wind energy development on marine life depend greatly on site-specific conditions, and can be both negative and positive (e.g., Dong Energy *et al.*, 2006; Köller *et al.*, 2006; Michel *et al.*, 2007; Wilhelmsson and Malm, 2008; Punt *et al.*, 2009; Wilson and Elliott, 2009). Potential negative impacts include underwater sounds, electromagnetic fields, physical disruption, and the establishment of invasive species. The physical structures may, however, create new breeding grounds or shelters and act as artificial reefs or fish aggregation devices (e.g., Wilhelmsson *et al.*, 2006). Additional research is warranted on these impacts, especially in comparison to other sources of energy supply, but the impacts do not appear to be disproportionately large. In advance of conclusive findings, however, concerns about the impacts of off-shore wind energy on marine life and migrating bird populations have led to national zoning efforts in some countries that exclude the most-sensitive areas from development.

7.6.2.3 Impact of wind power plants on the local climate

The possible impact of wind power plants on the local climate has also been the focus of some research. Wind power plants extract momentum from the air flow and thus reduce the wind speed behind the turbines, and also increase vertical mixing by introducing turbulence across a range of length scales (Petersen *et al.*, 1998). These two processes are described by the term “wind turbine wake” (Barthelmie *et al.*, 2004). Though intuitively turbine wakes must increase vertical mixing of the near-surface layer, and thus may increase atmosphere-surface exchange of heat, water vapour, and other parameters, the magnitude of the effect remains uncertain. One study using blade element momentum theory suggests that even very large scale wind energy deployment, sufficient to supply global energy needs, would remove less than 1/10,000th of the total energy within the lowest 1 km of the atmosphere (Sta. Maria and Jacobson, 2009). Other studies have sought to quantify more-local effects by treating large wind power plants as a block of enhanced surface roughness length or an elevated momentum sink in regional and global models. These studies have typically analyzed scenarios of substantial wind energy deployment, and have found changes in local surface temperature of up to or even exceeding 1°C, and in surface winds of several meters per second (Keith *et al.*, 2004; Kirk-Davidoff and Keith, 2008; Wang and Prinn, 2010); these local effects could have secondary impacts on rainfall, clouds, and other climate variables. Though the global average impact of these more-local changes is much less pronounced, the local changes could have implications for ecosystems and humans.

The assumptions and methods used by these studies may not, however, accurately represent the mechanisms by which wind turbines interact with the atmosphere. Studies often incorrectly assume that wind turbines act as invariant momentum sinks; that turbine densities are above what is the norm; and that wind energy development occurs at a more substantial and geographically concentrated scale than is likely. Observed data and models from large off-shore wind power plants, for example, indicate that they may be of sufficient scale to perceptibly interact with the entire (relatively shallow) atmospheric boundary layer (Frandsen *et al.*, 2006), but on-site measurements and remotely sensed near-surface wind speeds suggest that wake effects from large developments may no longer be discernible in near-surface wind speeds and turbulence intensity at approximately 20 km downwind (Christiansen and Hasager, 2005, 2006; Frandsen *et al.*, 2009). As a result, the impact of wind energy on local climates remains uncertain. More generally, it should also be recognized that wind turbines are not the only structures to potentially impact local climate variables, and that any impacts caused by increased wind energy development should be placed in the context of other anthropogenic climate influences (Sta. Maria and Jacobson, 2009).

7.6.3 Impacts on humans

In addition to ecological consequences, wind energy development impacts humans in various ways. The primary impacts addressed here include land and marine usage, visual impacts, proximal impacts such as noise, flicker, health, and safety, and property value impacts.

7.6.3.1 Land and marine usage

Wind turbines are sizable structures, and wind power plants can encompass a large area (5-10 MW per km^2 is often assumed), thereby using space that might otherwise be used for other purposes. The land footprint specifically disturbed by on-shore wind turbines and their supporting roads and infrastructure, however, typically ranges from 2% to 5% of the total area encompassed by a wind power plant, allowing agriculture, ranching, and certain other activities to continue within the area. Some forms of land use may be precluded from the area, such as housing developments, airport approaches, and some radar installations. Nature reserves and historical and/or sacred sites are also often particularly sensitive. Somewhat similar issues apply for off-shore wind power plants.

The impacts of wind power plants on aviation, shipping, communications, and radar must also be considered, and depend on the placement of wind turbines and power plants. By avoiding airplane landing corridors and shipping routes, interference of wind power plants with shipping and aviation can be kept to a minimum (Hohmeyer *et al.*, 2005). Integrated marine spatial planning and integrated coastal zone management approaches are also starting to include off-shore wind energy, thereby helping to assess the ecological impacts and economic and social benefits for coastal regions of alternative marine and coastal uses, and to minimize conflict among those uses (e.g., Murawski, 2007; Ehler and Douvere, 2009; Kannen and Burkhard, 2009).

Electromagnetic interference (EMI) associated with wind turbines can come in various forms (e.g., Krug and Lewke, 2009). In general, wind turbines can interfere with detection of signals through reflection and blockage of electromagnetic waves and creation of large reflected radar returns, including Doppler produced by the rotation of turbine blades. Many EMI effects can be avoided by appropriate siting, for example, not locating wind turbines in close proximity to transmitters or receivers (Summers, 2000; Hohmeyer *et al.*, 2005). Moreover, there are no fundamental physical constraints preventing mitigation of EMI (Brenner, 2008). In the case of military (or civilian) radar, reports have concluded that radar systems can sometimes be modified to ensure that aircraft safety and national defence are maintained (Butler and Johnson, 2003; Brenner 2008). In particular, radar system may have to be replaced, upgraded, or gap filling and signal fusion systems installed, at some cost. In addition, research is underway to investigate wind turbine design changes that may mitigate adverse impacts by making turbines less reflective to radar systems. EMI impacts can also extend to TV, GPS, and communications systems and, where they exist, these impacts can generally be managed by appropriate siting of wind power plants and through technical solutions.

7.6.3.2 Visual impacts

Visual impacts, and specifically how wind turbines and related infrastructures fit into the surrounding landscape, are often among the top concerns of communities considering wind power plants (NRC, 2007; Wolsink, 2007; Wustenhagen *et al.*, 2007; Firestone and Kempton, 2007; Firestone *et al.*, 2009; Jones and Eiser, 2009), of those living near existing wind power plants (Thayer and Hansen, 1988; Krohn and Damborg, 1999; Warren *et al.*, 2005), and of institutions responsible for overseeing wind energy development (Nadaï and Labussière, 2009). To capture the strongest and most consistent winds, wind turbines are often sited at high elevations and where there are few obstructions relative to the surrounding area. Moreover, wind turbines and power plants have grown in size, making the turbines and related transmission infrastructure more visible. Finally, as wind power plants increase in number and geographic spread, plants are being located in a wider diversity of landscapes (and, with off-shore wind energy, unique seascapes as well), including more highly valued areas.

Though concerns about visibility cannot be fully mitigated, many jurisdictions require an assessment of visual impacts as part of the siting process, including defining the geographic scope of impact and preparing photo and video montages depicting the area before and after wind energy development. Other recommendations that have emerged to minimize visual intrusion include: using similar size and shaped wind turbines, using light coloured paints, choosing a smaller number of larger turbines over a larger number of smaller ones, undergrounding interconnection cabling, and ensuring that blades rotate in the same direction (e.g., Hohmeyer *et al.*, 2005). More generally, a rethinking of traditional concepts of "landscape" to include wind turbines has sometimes been recommended (Pasqualetti *et al.*, 2002) including, for example, setting aside areas where development can occur and others where it is precluded, especially when such planning allows for public involvement (Nadaï and Labussière, 2009).

7.6.3.3 Noise, flicker, health, and safety

A variety of proximal “nuisance” effects are also sometimes raised with respect to wind energy development, the most prominent of which is noise. Noise from wind turbines can be a problem especially for those living within close range. Although environmental noise guidelines (US EPA, 1974, 1978; WHO, 1999, 2009) are sufficient to ensure that direct health effects are avoided (e.g., hearing loss) (McCunney and Meyer, 2007), some nearby residents experience annoyance from wind turbine sound (Pedersen and Waye, 2007, 2008; Pedersen *et al.*, 2010). This annoyance is correlated with acoustic factors (e.g., sound levels and characteristics) and also with non-acoustic factors (e.g., visibility of, or attitudes towards, the turbines) (Pedersen and Waye, 2007, 2008;

Pedersen *et al.*, 2010). Concerns about noise emissions may be especially great when hub-height wind speeds are high, but ground-level speeds are low (i.e., conditions of high wind shear). Under such conditions, the lack of wind-induced background noise at ground level coupled with higher sound levels from the turbines has been linked to increased audibility and in some cases annoyance (Van den Berg, 2004, 2005, 2008; Prospathopoulos and Voutsinas, 2005).

Significant efforts have been made to reduce the sound levels emitted by wind turbines. As a result, mechanical sounds from modern wind turbines (e.g., gearboxes and generators) have been significantly reduced. Aero-acoustic noise is now the dominant concern (Wagner *et al.*, 1996), and some of the specific aero-acoustic characteristics of wind turbines (e.g., Van den Berg, 2005) have been found to be particularly detectable (Fastl and Zwicker, 2007) and annoying (Bradley, 1994; Bengtsson *et al.*, 2004 [TSU: references missing]). Reducing aero-acoustic noise can be most easily accomplished by reducing blade speed, but different tip shapes and airfoil designs have also been explored (Migliore and Oerlemans, 2004; Lutz *et al.*, 2007). Regardless of these efforts, wind turbines create noise, and predictive models and environmental regulations to manage these impacts have improved. Specifically, in some jurisdictions, both the wind shear and maximum sound power levels under all operating conditions are taken into account when establishing regulations (Bastasch *et al.*, 2006). Absolute maximum sound levels during the day (e.g., 55 dBA) and night (e.g., 45 dBA) can also be coupled with maximum levels that are set relative to pre-existing background sound levels (Bastasch *et al.*, 2006). In other jurisdictions, simpler and cruder set-backs mandate a minimum distance between turbines and other structures (MOE, 2009).

In addition to sound impacts, rotating turbine blades can also cast moving shadows (i.e., shadow flicker), which may be annoying to residents living close to wind turbines. Turbines can be sited to minimize these concerns, or the operation of wind turbines can be stopped during acute periods (Hohmeyer *et al.*, 2005). In some countries, the use of such operation control systems is mandated by licensing authorities. Finally, wind turbines can shed parts of or whole blades as a result of an accident or icing (or more broadly, shed ice that has built up on the blades, or collapse entirely). Wind energy technology certification standards are aimed at reducing such accidents, and injuries are rare or non-existent (see Section 7.3.3).

7.6.3.4 Property values

The visibility of wind power plants may translate into negative impacts on residential property values at the local level. Further, if various proximal nuisance effects are prominent, such as turbine noise, shadow flicker, health, or safety concerns, additional impacts to local property values may occur. Although these concerns may be reasonable given effects found for other environmental disamenities (e.g., high voltage transmission lines, fossil fuel power plants, and landfills; see Simons, 2006), published research has not found strong evidence of an effect for wind power plants (e.g., Sims and Dent, 2007; Sims *et al.*, 2008; Hoen *et al.*, 2009). This might be explained by the setbacks normally employed between homes and wind turbines; studies on the impacts of transmission lines on property values, for example, sometimes find that effects can fade at distances of 100m (e.g., Des Rosiers, 2002). Alternatively, any effects may be too infrequent and/or small to distinguish statistically. More research is needed on the subject, but based on other disamenity research (e.g., Boyle and Kiel, 2001; Jackson, 2001; Simons and Saginor, 2006), if any impacts do exist, it is likely that those effects are most pronounced within short distances of wind turbines, in the period immediately following wind power plant announcement, but fade over distance and time after a wind power plant is constructed (Wolsink, 2007).

7.6.4 Public attitudes and acceptance

Despite the possible impacts described above, surveys have consistently found wind energy to be widely accepted by the general public (e.g., Warren *et al.*, 2005; Jones and Eiser, 2009; Klick and Smith, 2010; Swofford and Slattery, 2010). Translating this broad support into increased deployment (closing the "social gap" – see e.g., Bell *et al.,* 2005), however, often requires the support of local host communities and/or decision makers (Toke, 2006; Toke *et al.*, 2008). To that end, a number of concerns exist that might temper the enthusiasm of these stakeholders towards wind energy, such as land and marine use, and the visual, proximal, and property value impacts discussed above. In general, research has found that public concern towards wind energy development is greatest directly after the announcement of a wind power plant, but that acceptance increases after construction when actual impacts can be assessed (Wolsink, 1989; Warren *et al.*, 2005; Eltham *et al.*, 2008). Some studies have found that those most familiar with existing wind power plants, including those who live closest to them, are more accepting (or less concerned) than those less familiar and further away (Krohn and Damborg, 1999; Warren *et al.*, 2005), but other research has found the opposite to be true (van der Horst, 2007; Swofford and Slattery, 2010). Possible explanations for this apparent discrepancy include differences in attitudes towards *proposed* versus *existing* wind power plants (Swofford and Slattery, 2010), the pre-existing characteristics and values of the local community (van der Horst, 2007), and the degree of trust that the local community has towards the development process and its outcome (Thayer and Freeman, 1987; Jones and Eiser, 2009). Research has also found that pre-construction attitudes can linger after the turbines are erected: for example, those opposed to a wind power plant's development have been found to consider the eventual plant to be noisier and more visually intrusive that those who favoured the same plant in the pre-construction time period (Krohn and Damborg, 1999; Jones and Eiser, 2009). Finally, some research has found that concerns can be compounding. For instance, those who found turbines to be visually intrusive also found the noise from those turbines to be more annoying (Pedersen and Persson Waye, 2004).

7.6.5 Minimizing social and environmental concerns

Regardless of the type and degree of social and environmental concerns, addressing them directly is an essential part of any successful wind power planning and plant siting process. To that end, involving the local community in the planning and siting process has sometimes been shown to improve outcomes (Loring, 2007; Toke *et al.*, 2008; Nadaï and Labussière, 2009; Jones and Eiser, 2009). This might include, for example, allowing the community to weigh in on alternative wind power plant and turbine locations, and improving education by hosting visits to existing wind power plants. Public attitudes have been found to improve when the development process is perceived as being transparent (Wolsink, 2000; Loring, 2007; Gross, 2007). Further, experience suggests that ownership of local wind power plants can improve public attitudes towards wind energy development (Wolsink, 2007; Gross, 2007; Jones and Eiser, 2009).

Proper planning for both on- and off-shore wind energy can also help to minimize social and environmental impacts, and a number of siting guideline documents have been developed (e.g., Nielsen, 1996; NRC, 2007; AWEA, 2008). Appropriate planning and siting will generally avoid placing wind turbines too close to dwellings, streets, railroad lines, airports, and shipping routes, and will avoid areas of heavy bird and bat activity; a variety of pre-construction studies are often conducted to define these impacts and their mitigation. Habitat fragmentation can often be minimized by careful placement of wind turbines and wind power plants and by proactive governmental planning for wind energy deployment. Examples of such planning can be found in many jurisdictions across the world.

Although an all-encompassing numerical comparison of the full external costs and benefits of wind energy is impossible, as some impacts are very difficult to monetize, available evidence suggests that the positive environmental and social effects of wind energy generally outweigh any negative impacts that remain after careful planning and siting procedures are followed (see, e.g., Jacobson, 2009). In practice, however, complicated and time-consuming planning and siting processes are key obstacles to wind energy development in some countries and contexts (e.g., Bergek, 2010; Gibson and Howsam, 2010). In part, this is because even if the environmental and social impacts of wind energy are minimized through proper planning and siting procedures and community involvement, some impacts will remain. Efforts to better understand the nature and magnitude of these remaining impacts, together with efforts to minimize and mitigate those impacts, will therefore need to be pursued in concert with increasing wind energy deployment.

7.7 Prospects for technology improvement and innovation

Over the past three decades, innovation in the design of grid-connected wind turbines has led to significant cost reductions, while the capacity of individual turbines has grown markedly. The “square-cube law” is a rule of thumb that states that as a wind turbine increases in size, its theoretical energy output tends to increase by the square of the rotor diameter (i.e., the rotor-swept area), while the volume of material (and therefore its mass and cost) required to scale at the same rate increases as the cube of the rotor diameter, all else being equal. As a result, at some size, the cost of a larger turbine will grow faster than the resulting energy output and revenue, making further upscaling uneconomic. To date, engineers have successfully engineered around this relationship, preventing significant increases in the cost of wind energy as turbines have grown larger, by changing design rules with increasing turbine size and by removing material or using it more efficiently to trim weight and cost. Engineering around the “square-cube law” remains a fundamental objective of research efforts aimed at further reducing the delivered cost of energy from wind turbines, especially for off-shore installations.

This section describes research and development programs in wind energy (7.7.1), system-level design and optimization approaches that may yield further reductions in the levelized cost of wind energy (7.7.2), component-level opportunities for innovation in wind energy technology (7.7.3), and the need to improve the scientific underpinnings of wind energy technology (7.7.4). Significant opportunities remain for design optimization of on-shore and off-shore wind turbines, and sizable cost reductions remain possible in the years ahead, though improvements are likely to be more-incremental in nature than radical changes in fundamental design.[24]

7.7.1 Research and development programs

Public and private research and development (R&D) programmes have played a major role in the technical advances seen in wind energy over the last decades (Klaassen *et al.*, 2005; Lemming *et al.*, 2009). Government support for R&D, in collaboration with industry, has led to system and component-level technology advancements, as well as improvements in resource assessment, technical standards, grid integration, wind energy forecasting, and other areas. From 1974 to 2006, government R&D budgets for wind energy in IEA countries totalled $3.8 billion (2005$): this represents an estimated 10% share of RE R&D budgets, and just 1% of total energy R&D expenditures (IEA, 2008; EWEA, 2009). In 2008, OECD research funding for wind energy totalled $180 million (2005$), or 1.5% of all energy R&D funding; additional funding was provided by non-

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[24] This section focuses on scientific and engineering challenges directly associated with reducing the cost of wind energy, but additional research areas of importance include: research on the integration of wind energy into electricity systems and grid compatibility (e.g., forecasting, storage, power electronics); social science research on policy measures and social acceptance; and scientific research to understand the impacts of wind energy on the environment and on humans. These issues are addressed only peripherally in this section.

OECD countries. Government-sponsored R&D programs have often emphasized longer-term innovation, while industry-funded R&D has focusing on shorter-term production, operation, and installation issues. Though data are scarce on industry R&D funding, EWEA (2009), Carbon Trust (2008a), and Wiesenthal *et al.* (2009) [TSU: reference missing] find that the ratio of turbine manufacturer R&D expenditures to net revenue typically ranges from 2% to 3%, while Wiesenthal *et al.* (2009) finds that corporate wind energy R&D in the EU is three times as large as government R&D investments.

Wind energy research strategies have been developed through government and industry collaborations, historically centred on Europe and the United States, though growing public R&D efforts in other countries and regions bear note (e.g., Tan, 2010). In a study to explore the technical and economic feasibility of meeting 20% of electricity demand in the U.S. with wind energy, the U.S. Department of Energy found that key areas of further research included continued development of turbine technology, improved and expanded manufacturing processes, grid integration of wind energy, and siting and environmental concerns (US DOE, 2008). The European Wind Energy Technology Platform (TPWind), meanwhile, has developed a roadmap through 2020 that is expected to form the basis for future European wind energy R&D strategies, with the following areas of focus: new turbines and components; off-shore structures; grid integration; and wind resource assessment and spatial planning (EU, 2008; EC, 2009). One notable feature of both of these planning efforts is that neither envisions a sizable technology breakthrough for wind energy in the years ahead: instead, the path forward is seen as many evolutionary steps, executed through incremental technology advances, that may nonetheless result in significant improvements in the delivered cost of wind energy.

7.7.2 System-level design and optimization

Modern wind turbine design and operation requires advanced, integrated design approaches to optimize system cost and performance. Wind turbines are complex systems that span multiple disciplines. Optimization therefore requires a whole-system perspective that evaluates the wind turbine as an aerodynamic device, as a mechanical structure, as a control system, and finally as an electrical plant (EU, 2008). Studies have identified a number of areas where technology advancements could result in changes to the capital cost, annual energy production, reliability, O&M, and grid integration of wind energy. Examples of scaling studies that have explored the system-level impacts of advanced concepts include those conducted by the U.S. DOE under the Wind Partnership for Advanced Component Technologies (WindPACT) project (GEC, 2001; Griffin, 2001; Shafer *et al.*, 2001; Smith, 2001; Malcolm and Hansen, 2006). Ultimately, component-level advances must be evaluated based on system-level cost and performance impacts; to be viable, increased energy capture associated with larger rotors, for example, must increase expected electricity sales revenue to a greater extent than the additional materials and installation costs. Sophisticated design approaches are therefore required to systematically evaluate and optimize advanced wind turbine concepts.

One assessment of the possible impacts of technical advancements on wind energy production and capital costs is summarized in Table 7.4 (US DOE, 2008). Though not all of these improvements may be achieved, there is sufficient potential to warrant continued R&D. The most likely scenario, as shown in Table 7.4, is a sizeable increase in energy production with a modest drop in capital cost (compared to 2002 levels, which is the baseline for the estimates in Table 7.4).

Table 7.4. Areas of potential technology improvement from a 2002 baseline wind turbine (US DOE, 2008)*

Technical Area	Potential Advances	Increments from Baseline (Best/Expected/Least, Percent)	
		Annual Energy Production (%)	Turbine Capital Cost (%)
Advanced Tower Concepts	* Taller towers in difficult locations * New materials and/or processes * Advanced structures/foundations * Self-erecting, initial or for service	+11/+11/+11	+8/+12/+20
Advanced (Enlarged) Rotors	* Advanced materials * Improved structural-aero design * Active controls * Passive controls * Higher tip speed/lower acoustics	+35/+25/+10	-6/-3/+3
Reduced Energy Losses and Improved Availability	* Reduced blade soiling losses * Damage tolerant sensors * Robust control systems * Prognostic maintenance	+7/+5/0	0/0/0
Advanced Drive Trains (Gearboxes and Generators and Power Electronics)	* Fewer gear stages or direct drive * Medium/low-speed generators * Distributed gearbox topologies * Permanent-magnet generators * Medium-voltage equipment * Advanced gear tooth profiles * New circuit topologies * New semiconductor devices * New materials (GaAs, SiC)	+8/+4/0	-11/-6/+1
Manufacturing Learning	* Sustained, incremental design and process improvements * Large-scale manufacturing * Reduced design loads	0/0/0	-27/-13/-3
Totals		+61/+45/+21	-36/-10/+21

* The baseline for these estimates was a 2002 turbine system in the U.S. There have already been sizeable improvements in capacity factor since 2002, from just over 30% to almost 35%, while capital costs have increased due to large increases in commodity costs in conjunction with a drop in the value of the U.S. dollar. Therefore, working from a 2008 baseline, one might expect a more-modest increase in capacity factor, but the 10% capital cost reduction is still quite possible (if not conservative), particularly from the higher 2008 starting point. Finally, the table does not consider any changes in the overall wind turbine design concept (e.g., 2-bladed turbines).

7.7.3 Component-level innovation opportunities

The potential areas of innovation outlined in Table 7.4 are further described in Sections 7.7.3.1-7.7.3.5. These component-level innovations will impact both on-shore and off-shore wind energy, but some will be more important for off-shore wind energy technology due to the earlier state of and greater operational challenges facing that technology. Additional advancements that are more-specific to off-shore wind energy are described in Section 7.7.3.6.

7.7.3.1 Advanced tower concepts

Taller towers allow the rotor to access higher wind speeds in a given location, increasing annual energy capture. The cost of large cranes and transportation, however, acts as a limit to tower height.

As a result, research is being conducted into several novel tower designs that would eliminate the need for cranes for very high, heavy lifts. One concept is the telescoping or self-erecting tower, while other designs include lifting dollies or tower-climbing cranes that use tower-mounted tracks to lift the nacelle and rotor to the top of the tower. Still other developments aim to increase the height of the tower without unduly sacrificing material demands through the use of different materials, such as concrete and fibreglass, or different designs, such as space-frame construction or panel sections (see, e.g., GEC, 2001; Malcolm, 2004; Lanier, 2005).

7.7.3.2 Advanced rotors and blades

Due to technology advancements in recent years, blade mass has been scaling at roughly an exponent of 2.4 to rotor diameter, compared to the expected exponent of 3.0 based on the “square-cube” law (Griffin, 2001). The significance of this development is that wind turbine blades have become lighter for a given length over time.

If advanced R&D can provide even better blade design methods, coupled with better materials (such as carbon fibre composites) and advanced manufacturing methods, then it will be possible to continue to innovate around the square-cube law in blade design. A simple approach to reducing cost involves developing new blade airfoil shapes that are much thicker where strength is most required, near the blade root, allowing inherently better structural properties and reducing overall mass. These airfoil shapes potentially offer equivalent aerodynamic performance, but have yet to be proven in the field. Another approach to increasing blade length while limiting increased material demand is to reduce the fatigue loading on the blade. The benefit of this approach is that the approximate rule of thumb for fibreglass blades is that a 10% reduction in cyclic stress can more than double the fatigue lifetime. Blade fatigue loads can be reduced by controlling the blade’s aerodynamic response to turbulent wind by using mechanisms that vary the angle of attack of the blade airfoil relative to the wind inflow. This is primarily accomplished with full-span blade pitch control. An elegant concept, however, is to build passive means of reducing loads directly into the blade structure (Ashwill, 2009). By carefully tailoring the structural properties of the blade using the unique attributes of composite materials, the blade can be built in a way that couples the bending deformation of the blade resulting from the wind with twisting deformation that passively mimics the motion of blade pitch control. Another approach is to build the blade in a curved shape so that the aerodynamic load fluctuations apply a twisting movement to the blade, which will vary the angle of attack (Ashwill, 2009). Because wind inflow displays a complex variation of speed and character across the rotor disk, partial blade span actuation and sensing strategies to maximize load reduction are also promising (Buhl *et al.*, 2005; Lackner and van Kuik, 2009). Devices such as trailing edge flaps and micro-tabs, for example, are being investigated, but new sensors may need to be developed for this purpose, with a goal of creating “smart” blades with embedded sensors and actuators to control local aerodynamic effects (Andersen *et al.*, 2006; Berg *et al.*, 2009). To achieve these new designs, better understanding of wind turbine aeroelastic, aerodynamic, and aeroacoustic responses associated with complicated blade motion will be needed, as will control algorithms to incorporate these sensors and actuators in wind turbine operation schemes.

7.7.3.3 Reduced energy losses and improved availability

Advanced turbine control and condition monitoring are expected to provide a primary means to improve turbine reliability and availability, reduce O&M costs, and ultimately increase energy capture, both for individual turbines and wind power plants, and both on-shore and off-shore. Advanced controllers are envisioned that can better control the turbine during turbulent winds and thereby reduce fatigue loading and extend blade life (Bossanyi, 2003; Stol and Balas, 2003; Wright, 2004), monitor and adapt to wind conditions to increase energy capture and reduce the impact of blade soiling or erosion (Johnson *et al.*, 2004; Johnson and Fingersh, 2008; Frost *et al.*, 2009), and anticipate and protect against damaging wind gusts by using new sensors to detect wind speeds immediately ahead of the blade (Larsen *et al.*, 2004; Hand and Balas, 2007). Condition-monitoring systems of the future are expected to track and monitor ongoing conditions at critical locations in the turbine and report incipient failure possibilities and damage evolution, so that improved maintenance procedures can minimize outages and downtimes (Hameed *et al.*, 2010). The full development of advanced control and monitoring systems of this nature will require considerable operational experience, and optimization algorithms will likely be turbine-specific; the general approach, however, should be transferrable between turbine designs and configurations.

7.7.3.4 Advanced drive trains, generators, and power electronics

Several unique turbine designs are under development or in early commercial deployment to reduce drive train weight and cost while improving reliability (Poore and Lettenmaier, 2003; Bywaters *et al.*, 2004; EWEA, 2009). One option, already in commercial use, is a direct-drive generator (removing the need for a gearbox); more than 10% of the wind power capacity installed in 2009 used direct drive turbines (BTM, 2010). The trade-off is that the slowly rotating generator must have a high pole count and be large in diameter, imposing a weight penalty. The decreased cost and increased availability of rare-earth permanent magnets is expected to significantly affect the size and cost of future direct-drive generator designs, however, as permanent-magnet designs tend to be more compact and potentially lightweight, as well as reducing electrical losses in the windings.

A hybrid of the current geared and direct-drive approaches is the use of a single-stage drive using a low- or medium-speed generator. This allows the use of a generator that is significantly smaller and lighter than a comparable direct-drive design, and reduces (but does not eliminate) reliance on a gearbox. Another approach is the distributed drive train, where rotor torque is distributed to multiple smaller generators (rather than a single, larger one), reducing overall size and weight.

Power electronics that provide full power conversion from variable frequency AC electricity to constant frequency 50 or 60 Hz are also capable of providing ancillary grid services. The growth in turbine size is driving larger power electronic components as well as innovative higher-voltage circuit topologies. In the future, it is expected that wind turbines will use higher-voltage generators and converters than are used today (Erdman and Behnke, 2005), and therefore also make use of higher-voltage and higher-capacity circuits and transistors. New power conversion devices will need to be fully compliant with emerging grid codes to ensure that wind power plants do not degrade the reliability of the electric system.

7.7.3.5 Manufacturing learning

Manufacturing learning refers to the learning by doing achieved in serial production lines with repetitive manufacturing (see Section 7.8.4 for a broader discussion of learning in wind energy technology). Though turbine manufacturers already are beginning to operate at significant scale, as the industry expands further, additional cost savings can be expected. For example, especially as turbines have increased in size, concepts such manufacturing at wind power plant sites and segmented blades are being explored to reduce transportation costs. Further increases in manufacturing automation and optimized processes will also contribute to cost reductions in the manufacturing of wind turbines and components.

7.7.3.6 Off-shore research and development opportunities

The cost of off-shore wind energy exceeds that of on-shore wind energy due, in part, to higher operating costs as well as more-expensive installation and support structures. The potential component-level technology advancements described above will contribute to lower off-shore wind energy costs, and some of these advances may be driven by off-shore wind energy applications. In addition, however, there are several areas of possible advancement that are more-specific to off-shore wind energy, including O&M strategies, installation and assembly schemes, support structure design, and the development of larger turbines, possibly including new turbine concepts.

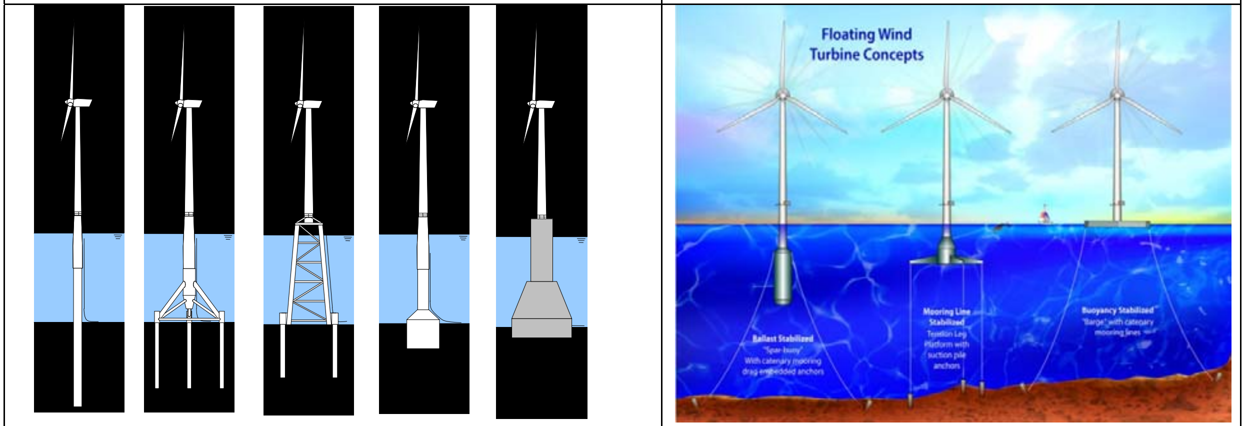
Off-shore wind turbines operate in harsh environments driven by both wind and wave conditions that can make access to turbines challenging or even impossible for extended periods. A variety of methods to provide greater access during a range of conditions, including inflatable boats or helicopters, are being evaluated (van Bussel and Bierbooms, 2003). Sophisticated O&M approaches that include remote assessments of turbine operability and the scheduling of preventative maintenance to maximize access during favourable conditions are also being investigated, and employed (Wiggelinkhuizen *et al.*, 2008). The development of more-reliable turbine components, even if more expensive on a first-cost basis, is also expected to play a major role in reducing the overall levelized cost of off-shore wind energy. Efforts are underway to more-thoroughly analyze gearbox dynamics, for example, to contribute to more reliable designs (Peeters *et al.*, 2006; Heege *et al.*, 2007). The component level innovations described earlier, such as advanced direct-drive generators and passive blade controls, may also improve overall technology reliability.

Off-shore wind turbine size is not restricted by road or other land-based infrastructure limits. As a result, though off-shore wind turbines are currently installed as individual components, concepts are being considered where fully-assembled turbines are transported on special-purpose vessels and mounted on previously installed support structures. In addition to creating the vessels needed for such installation practices, ports and staging areas would need to be designed to efficiently perform the assembly processes.

Additional off-shore wind energy R&D is required to improve support structure design. Foundation structure innovation offers the potential to access deeper waters, thereby increasing the potential wind resource available. Off-shore turbines have historically been installed in relatively shallow water, up to 30 m, on a mono-pile structure that is essentially an extension of the tower, but gravity-based structures have become more common. Other concepts that are more appropriate for deeper water depths include fixed-bottom space-frame structures, such as jackets and tripods, and floating platforms, such as spar-buoys, tension-leg platforms, semi-submersibles, or hybrids of these concepts. Offshore wind turbine support structures may undergo dynamic responses associated with wind and wave loads, requiring an integrated analysis of the rotor, tower, and support structure supplemented with improved estimates of soil stiffness and scour conditions specific to off-shore support structures (Nielsen *et al.*, 2009). Floating wind turbines further increase the complexity of turbine design due to the additional motion of the base but, if cost effective, can offer access to significant additional wind resource areas; encourage standard technology development that is independent of water depth and seabed condition; and lead to simplified installation and decommissioning practices (EWEA, 2009). In 2009, the first full-scale floating wind turbine pilot plant was deployed off the coast of Norway at a 220 m depth. Figure 7.16(a,b) depicts some of the foundation concepts (a) being employed or considered in the near term, while also (b) illustrating the concept of floating wind turbines, which are being considered for the longer term.

(a) Near-term off-shore foundation concepts

(b) Floating off-shore turbine concept



Source: UpWind.eu

Source: NREL

Figure 7.16(a,b). Off-shore wind turbine foundation designs

Future off-shore wind turbines may be larger, lighter, and more-flexible. Off-shore wind turbine size is not restricted in the same way as on-shore wind energy technology, and turbines of 10 MW or larger are under consideration. Future off-shore turbine designs can benefit from many of the possible component-level advances described previously. Nonetheless, the development of large turbines for off-shore applications remains a significant research challenge, requiring continued advancement in component design and system-level analysis. Concepts that reduce the weight of the blades, tower, and nacelle become more important as size increases, providing opportunities for greater advancement than may be incorporated in on-shore wind energy technology. In addition to larger turbines, design criteria for off-shore applications may be relaxed in cases where noise and visual impacts are of lesser concern. As a result, other advanced turbine concepts are under investigation, including 2-bladed, downwind turbines. Downwind turbine designs may allow less-costly yaw mechanisms, and the use of softer more flexible blades (Breton and Moe, 2009). Finally, innovative turbine concepts and significant upscaling of existing designs will require improved turbine modelling to better capture the operating environment in which off-shore turbines are installed, including the dynamic response of turbines to wind and wave loading (see Section 7.7.4).

7.7.4 The importance of underpinning science

Although wind energy technology is being deployed at a rapid scale today, there remains significant potential for continued innovation to further reduce cost and improve performance. International wind turbine design and safety standards dictate the level of analysis and testing required prior to commercializing new concepts. At the same time, technical innovation will push the design criteria and analysis tools to the limits of physical understanding. A significant effort is therefore needed to further advance the fundamental knowledge of the wind turbine operating environment in order to assure a new generation of reliable, safe, cost-effective wind turbines, and to further optimize wind power plant siting and design.

Wind turbines operate in a challenging environment, and are designed to withstand a wide range of conditions with minimal attention. Wind turbines are complex, nonlinear, dynamic systems forced by gravity, centrifugal, inertia, and gyroscopic loads as well as unsteady aerodynamic, hydrodynamic (for off-shore), and corrosion impacts. Modern wind turbines also operate in a layer of the atmosphere (from 50 m to 200 m) that is complex, and are impacted by phenomena that occur over scales ranging from microns to thousands of kilometres. Accurate, reliable wind measurements and computations across these scales are important (Schreck *et al.*, 2008). In addition, fundamental scientific research in a number of areas will improve the physical understanding of this operating environment, which in turn can lead to more-precise design requirements that can facilitate the development of the innovative concepts described in Section 7.7.3. Research in areas of aeroelastics, unsteady aerodynamics, aeroacoustics, advanced control systems, and atmospheric science has yielded improved design capabilities in the past (Schreck *et al.*, 2010), and can continue to improve mathematical models and experimental data that reduce the risk of unanticipated failures, increase the reliability of the technology, and encourage further design innovation.

Although the physics are strongly coupled, there are four primary spatio-temporal levels requiring additional research: (1) wind conditions that affect individual turbines, (2) wind power plant siting and array effects, (3) mesoscale atmospheric processes, and (4) global and local climate effects.

Wind conditions that affect individual wind turbines encompass detailed characterizations of wind flow fields and the interaction of those flows with wind turbines. Wind turbine aerodynamics are complicated by three-dimensional effects in rotating blade flow fields that are unsteady and create load oscillations linked to dynamic stall. Understanding these aerodynamic effects, however, is critical for making load predictions that are accurate enough for use in turbine designs. To this point, these effects have been identified and quantified based on wind tunnel and field experiments (Schreck *et al.*, 2000, 2001; Schreck and Robinson, 2003; Madsen *et al.*, 2010), and empirical models of these effects have been developed (Bierbooms, 1992; Du and Selig, 1998; Snel, 2003; Leishman, 2006). Currently, these aerodynamic models rely on Blade-Element Moment methods (Spera, 2009) augmented with analytically and empirically based models to calculate the aerodynamic forces along the span of the blade. The availability of effective Computational Fluid Dynamics codes and their potential to deliver improved predictive accuracy, however, is prompting broader application (Hansen *et al.*, 2006). Aeroelastic models, meanwhile, are used to translate aerodynamic forces into structural responses throughout the turbine system. As turbines grow in size and are optimized, the structural flexibility of the components will necessarily increase, causing more of the turbine’s vibration frequencies to play a prominent role. To account for these effects, future aeroelastic tools will have to better model large variations in the wind inflow across the rotor, higher-order vibration modes, nonlinear blade deflection, and aeroelastic damping and instability (Quarton, 1998; Rasmussen *et al.*, 2003; Riziotis *et al.*, 2004; Hansen, 2007). The application of novel load-mitigation control technologies to blades (e.g., deformable trailing edges) (Buhl *et al.*, 2005) will require analysis based on aeroelastic tools that are adapted for these architectures. Similarly, exploration of control systems that utilize wind-speed measurements in advance of the blade, such as Light Detection and Ranging (Harris *et al.*, 2006) or pressure probe measurements (Larsen *et al.* (2004), will also require improved aeroelastic tools. Off-shore wind energy will require that aeroelastic tools better model the coupled dynamic response of the wind turbine and the foundation/support platform, as subjected to combined wind and wave loads (Passon and Kühn, 2005; Jonkman, 2009). Finally, aeroacoustic noise (i.e., the noise of turbine blades) is an issue for wind turbines (Wagner *et al.*, 1996), and increasing sophisticated tools are under development to better understand and manage these effects (Wagner *et al.*, 1996; Moriarty and Migliore, 2003; Zhu *et al.*, 2005, 2007; Shen and Sörensen, 2007). As turbine aerodynamic, aeroelastic, and aeroacoustic modelling advances, the crucial role (e.g., Simms *et al.*, 2001) of research-grade turbine aerodynamics experiments (Hand *et al.*, 2001; Snel *et al.*, 2009) grows ever more evident, as does the need for future high-quality laboratory and field experiments. Even though wind turbines now extract energy from the wind at levels approaching the theoretical maximum, improved understanding of aerodynamic phenomena will allow more accurate calculation of loads and thus the development lighter, more reliable, and higher-performing turbines.

Wind power plant siting and array effects impact energy production and equipment reliability at the power plant level. Rotor wakes create aeroelastic responses on downwind turbines (Larsen *et al.*, 2008). Improved models of wind turbine wakes (Thomsen and Sørensen, 1999; Frandsen *et al.*, 2007) will therefore yield more reliable predictions of energy capture and better estimates of fatigue loading in large, multiple-row wind power plants, both on-shore and off-shore. This improved understanding may then lead to improved wind turbine and power plant designs intended to minimize energy capture degradations and manage wake-based load impacts.

Planetary boundary layer research is important for accurately determining wind flow and turbulence in the presence of various atmospheric stability effects and complex land surface characteristics. Research in mesoscale atmospheric processes aims at improved [TSU: improving] the fundamental understanding of mesoscale and local wind flows (Banta *et al.*, 2003; Kelley *et al.*, 2004). In addition to its contribution towards understanding turbine-level aerodynamic and array wake effects, a better understanding of mesoscale atmospheric processes will yield improved wind energy resource assessments and forecasting methods. Physical and statistical modelling to resolve spatial scales in the 100-m to 1000-m range, a notable gap in current capabilities (Wyngaard, 2004), could occupy a central role of this research.

Finally, additional research is warranted on the interaction between global and local climate effects, and wind energy. Specifically, work is needed to identify and understand historical trends in wind resource variability in order to increase the reliability of future wind energy performance predictions. As discussed earlier in this chapter, further work is also warranted on the possible impacts of climate change on wind energy resource conditions, and on the impact of wind energy development on local, regional, global climates.

Significant progress in many of the above areas requires interdisciplinary research. Also crucial is the need to use experiments and observations in a coordinated fashion to support and validate computation and theory. Models developed in this way will be essential for improving: (1) wind turbine design, (2) wind power plant performance estimates, (3) wind resource assessments, (4) short-term wind energy forecasting, and (5) estimates of the impact of large-scale wind energy deployment on the local climate, as well as the impact of potential climate change effects on wind resources.

7.8 Cost trends[25]

Though the cost of wind energy has declined significantly since the 1980s, in most regions of the world, policy measures are required to make wind energy economically attractive (e.g., NRC, 2010a). In areas with particularly good wind resources or particularly costly alternative forms of power supply, however, the cost of wind energy can be competitive with fossil generation (e.g., Berry, 2009; IEA, 2009a; IEA and OECD, 2010). Moreover, continued technology advancements in on- and off-shore wind energy are expected (Sections 7.7), supporting further cost reductions. Because the degree to which wind energy is utilized globally and regionally will depend largely on the economic performance of wind energy compared to alternative power sources, this section describes the factors that affect the cost of wind energy (7.8.1), highlights historical trends in the cost and performance of wind power plants (7.8.2), summarizes data and estimates the levelized cost of wind energy in 2009 (7.8.3), and forecasts the potential for further cost reductions (7.8.4). The relative economic competitiveness of wind energy, which includes other factors such as subsidies and environmental externalities, is not covered in this section. Similarly, the costs of integration and transmission are not covered here, but are instead discussed in Section 7.5.

7.8.1 Factors that affect the cost of wind energy

The cost of both on-shore and off-shore wind energy is affected by five fundamental factors: annual energy production, installation costs, operating and maintenance costs, financing costs, and the

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[25] All cost data are presented in real, 2005 U.S. dollars (US2005$)

assumed economic life of the plant. Available support policies can also influence the cost (and price) of wind energy, as well as the cost of other electricity supply options, but these factors are not addressed here.

The nature of the wind resource largely determines the annual energy production from a prospective wind power plant, and is among the most important economic factors. Precise micro-siting of wind power plants and even individual turbines is critical for maximizing energy production. The trend toward turbines with larger rotor diameters and taller towers has led to increases in annual energy production per unit of installed capacity, and has also allowed wind power plants in lower resource areas to become more economically competitive over time. Off-shore wind power plants will, generally, be exposed to better wind resources than will on-shore power plants.

Wind power plants are capital intensive and, over their lifetime, the initial capital investment ranges from 75-80% of total expenditure, with operating costs contributing the balance (Blanco, 2009; EWEA, 2009). The capital cost of wind power plant installation includes the cost of the turbines (turbines, transportation to site, and installation), grid connection (cables, sub-station, interconnection), civil works (foundations, roads, buildings), and other costs (engineering, licensing, permitting, environmental assessments, and monitoring equipment). Table 7.5 shows a rough breakdown of the capital cost components for modern wind power plants. Turbine costs comprise more than 70% of total installed costs for on-shore wind power plants. The remaining costs are highly site-specific. Off-shore wind power plants are dominated by these other costs, with the turbines often contributing less than 50% of the total. Site-dependent characteristics such as water depth and distance to shore significantly affect grid connection, civil works, and other costs. Off-shore turbine foundations and internal electric grids are also considerably more costly than those for on-shore power plants (see also, Junginger *et al.*, 2004).

Table 7.5. Installed cost distribution for on-shore and off-shore wind power plants (Blanco, 2009; EWEA, 2009)

Cost Component	On-shore	Off-shore*
Turbine	71% - 76%	37% - 49%
Grid connection	10% - 12%	21% - 23%
Civil works	7% - 9%	21% - 25%
Other capital costs	5% - 8%	9% - 15%

* Off-shore cost categories consolidated from original

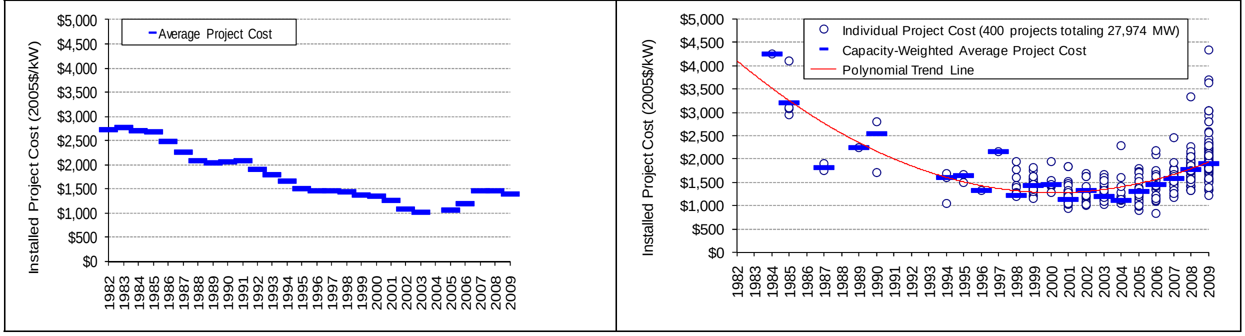
The O&M costs of wind power plants include fixed costs such as land leases, insurance, taxes, management, and forecasting services, as well as variable costs related to the maintenance and repair of turbines, including spare parts. O&M comprises approximately 20% of total wind power plant expenditure over a plant's lifetime (Blanco, 2009), with roughly 50% of total O&M costs associated directly with maintenance, repair, and spare parts (EWEA, 2009). Costs for off-shore wind energy are higher than for on-shore due to harsher weather conditions that impede access, as well as the higher transportation costs incurred to access off-shore turbines (Blanco, 2009).

Financing arrangements, including the cost of debt and equity and the proportional use of each, can also influence the cost of wind energy, as can the expected operating life of the wind power plant. For example, ownership and financing structures have evolved in the U.S. that minimize the cost of capital while taking advantage of available tax incentives (Bolinger *et al.*, 2009). Other research has found that the predictability of the policy measures supporting wind energy can have a sizable impact on financing costs, and therefore the ultimate cost of wind energy (Wiser and Pickle, 1998; Dunlop, 2006; Dinica, 2006; Agnolucci, 2007). Because off-shore wind power plants are still relatively new, with greater performance risk, higher financing costs are experienced than for on-shore plants (Dunlop, 2006; Blanco, 2009), and larger firms tend to dominate off-shore wind energy development and ownership (Markard and Petersen, 2009).

7.8.2 Historical trends

7.8.2.1 Installed capital costs

From the beginnings of commercial wind energy deployment to roughly 2004, the installed capital cost of on-shore wind power plants dropped, while turbine size grew significantly. With each generation of wind turbine technology during this period, design improvements and turbine scaling led to decreased installed costs. Historical installed capital cost data from Denmark and the United States demonstrate this trend (Figure 7.17(a,b)). From 2004 to 2009, however, capital costs increased. Wind power plant costs in Denmark in 2009 averaged approximately US$1,400/kW, while costs in the U.S. in 2009 averaged US$1,900/kW, both up substantially from earlier lows. Some of the reasons behind these increased costs are described in Section 7.8.3.



(a) Wind power plant costs in Denmark (Nielson et al., 2010)

(b) Wind power plant costs in the United States (Wiser and Bolinger, 2010)

Figure 7.17. Installed cost of on-shore wind power plants in (a) Denmark and (b) the United States

The installed costs of off-shore wind power plants are highly site-specific, but have historically been 50% to more than 100% more expensive than on-shore plants (IEA, 2008; BWEA and Garrad Hassan, 2009; EWEA, 2009). Off-shore costs have also been influenced by the same factors that caused rising on-shore costs from 2004 through 2009, as described in Section 7.8.3, leading to a doubling of the average installed cost of off-shore plants from 2004 through 2009 (BWEA and Garrad Hassan, 2009).

7.8.2.2 Operation and maintenance

Modern turbines that meet IEC standards are designed for a 20-year life, and plant lifetimes may exceed 20 years if O&M costs remain at an acceptable level. Few wind power plants were constructed 20 or more years ago, however, and there is therefore limited experience in plant operations over this entire time period. Moreover, those wind power plants that have reached or exceeded their 20-year lifetime tend to have turbines that are much smaller and less sophisticated than their modern counterparts. Early turbines were also designed using more conservative criteria, though they followed less stringent standards than today’s designs. As a result, these early plants only offer limited guidance for estimating O&M costs for more-recent turbine designs.

In general, O&M costs during the first couple of years of a wind power plant’s life are covered, in part, by manufacturer warranties that are included in the turbine purchase, resulting in lower ongoing costs than in subsequent years. Newer turbine models also tend to have lower initial O&M costs than older models, with maintenance costs increasing as turbines age (Blanco, 2009; EWEA, 2009; Wiser and Bolinger, 2009). Off-shore wind power plants have historically incurred higher O&M costs than on-shore plants (Junginger *et al.*, 2004; EWEA, 2009; Lemming *et al.*, 2009).

7.8.2.3 Energy production

The performance of wind power plants is primarily governed by local wind conditions, but is also impacted by wind turbine design optimization, performance, and availability, and by the effectiveness of O&M procedures. Improved resource assessment and siting methodologies developed in the 1970s and 1980s played a major role in improved wind power plant productivity. Advancements in wind energy technology, including taller towers and larger rotors, have also contributed to increased energy capture (EWEA, 2009).

Data on average fleet-wide capacity factors[26] over time for a large sample of on-shore wind power plants in the U.S. show a trend toward higher average capacity factors over time, as wind power plants built more recently have higher average capacity factors than those built earlier (Figure 7.18). Higher hub heights and larger rotor sizes are primarily responsible for these improvements, as the more-recent wind power plants built in this time period and included in Figure 7.18 were, on average, sited in increasingly lower wind resource regimes.

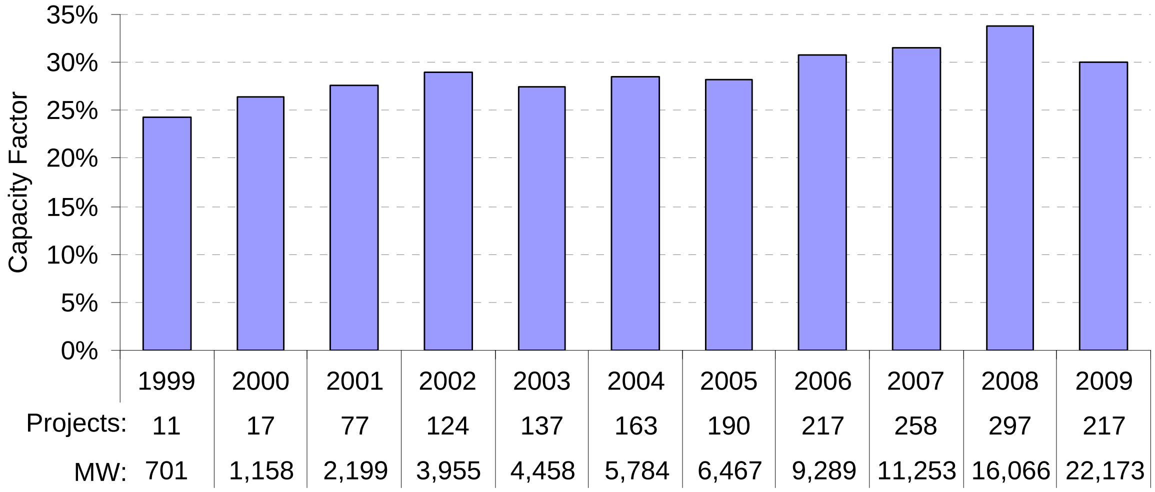


Figure 7.18. Fleet-wide average capacity factors for a large sample of wind power plants in the U.S. from 1999 - 2009 (Wiser and Bolinger, 2010)

Using a different metric for wind power plant performance, annual energy production per square meter of swept rotor area (kWh/m^2) for a given wind resource site, improvements of 2-3% per year over the last 15 years have been documented (IEA, 2008; EWEA, 2009).

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[26] A wind power plant's capacity factor is only a partial indicator of performance (EWEA, 2009). Most turbine manufacturers supply variations on a given generator capacity with multiple rotor diameters and hub heights. In general, for a given generator capacity, increasing the hub height, the rotor diameter, or the average wind speed will result in increased capacity factor. When comparing different wind turbines, however, it is possible to increase annual energy capture by using a larger generator, while at the same time decreasing the wind power plant's capacity factor.

7.8.3 Current conditions

7.8.3.1 Installed capital costs

The cost for on-shore wind power plants installed worldwide in 2009 averaged approximately US$1,750/kW, with the majority of plants falling in the range of US$1,400/kW to US$2,100/kW (Milborrow, 2010). Wind power plants installed in the United States in 2009 averaged US$1,900/kW (Wiser and Bolinger, 2010). Costs in some markets were lower: for example, average wind power plant costs in China in 2008-09 were around US$1,000-1,350/kW, driven in part by the dominance of several Chinese turbine manufacturers serving the market with lower-cost wind turbines (China Renewable Energy Association, 2009; Li and Ma, 2009; Li, 2010).

Wind power plant costs rose from 2004 to 2009 (Figure 7.17), an increase primarily caused by the rising price of wind turbines (Wiser and Bolinger, 2009). Those cost increases have been attributed to a number of factors, including: escalation (in real terms) in the cost of labour and materials inputs; increasing profit margins among turbine manufacturers and their component suppliers; the relative strength of the Euro currency; and the increased size of turbine rotors and hub heights (Bolinger *et al.*, 2010). Increased rotor diameters and hub heights have enhanced the energy capture of modern wind turbines, but those performance improvements have come with increased installed turbine costs, measured on a $/kW basis. The costs of raw materials, including steel, copper, cement, aluminium, and carbon fibre, also rose sharply from 2004 through mid-2008 as a result of strong global economic growth. In addition to higher raw materials costs, the strong demand for wind turbines over this period put upward pressure on labour costs, and enabled turbine manufacturers and their component suppliers to boost profit margins. Strong demand, in excess of available supply, also placed particular pressure on critical components such as gearboxes and bearings (Blanco 2009), which had traditionally been provided by only a small number of suppliers. Moreover, because many of the wind turbine manufacturers have historically been based in Europe, and many of the critical components like gearboxes and bearings have similarly been manufactured in Europe, the relative value of the Euro to other currencies such as the U.S. dollar also contributed to wind energy technology price increases in certain countries. Turbine manufacturers and component suppliers responded to the tight supply by expanding or adding new manufacturing facilities. Coupled with reductions in materials costs that began in late 2008 as a result of the global financial crisis, these trends began to moderate wind turbine costs at the beginning of 2009 (Wiser and Bolinger, 2009).

Due to the relatively small number of off-shore wind power installations, cost data are sparse. Nonetheless, the average cost of off-shore wind power plants is considerably higher than that for on-shore plants, and the factors that have increased the cost of on-shore plants have similarly affected the off-shore sector. The limited availability of turbine manufacturers supplying the off-shore market, and of vessels to install such plants, has exacerbated cost increases since 2004, as did the fierce competition among industry players for early-year (before 2005) off-shore demonstration plants (BWEA and Garrad Hassan, 2009). As a result, off-shore wind power plants over 50 MW in size, either built between 2006 and 2009 or planned for 2010, had installed costs that ranged from approximately US$2,000/kW to US$5,000/kW (IEA, 2008, 2009a; BWEA and Garrad Hassan, 2009; Snyder and Kaiser 2009a), with most estimates in a narrower range of US$3,200/kW to US$4,600/kW (Milborrow, 2010). These capital costs are roughly 100% higher than costs seen in the 2000-2004 timeframe (BWEA and Garrad Hassan, 2009).

7.8.3.2 Operation and maintenance

Though fixed O&M costs such as insurance, land payments, and routine maintenance are relatively easy to estimate, variable costs such as repairs and spare parts are more difficult to predict (Blanco, 2009). O&M costs can vary by wind power plant, turbine age, and the availability of a local servicing infrastructure, among other factors. Levelized O&M costs for on-shore wind energy are often estimated to range from US$12/MWh to US$23/MWh (Blanco, 2009): these figures are reasonably consistent with costs reported in IEA (2008), EWEA (2009), Wiser and Bolinger (2009), and Milborrow (2010).

Limited empirical data exist on O&M costs for off-shore wind energy, due in large measure to the limited number of operating plants and the limited duration of those plants' operation. Reported or estimated O&M costs for off-shore plants installed since 2002 range from US$20/MWh to US$40/MWh (EWEA, 2009; IEA, 2009a; Lemming *et al.*, 2009; Milborrow, 2010).

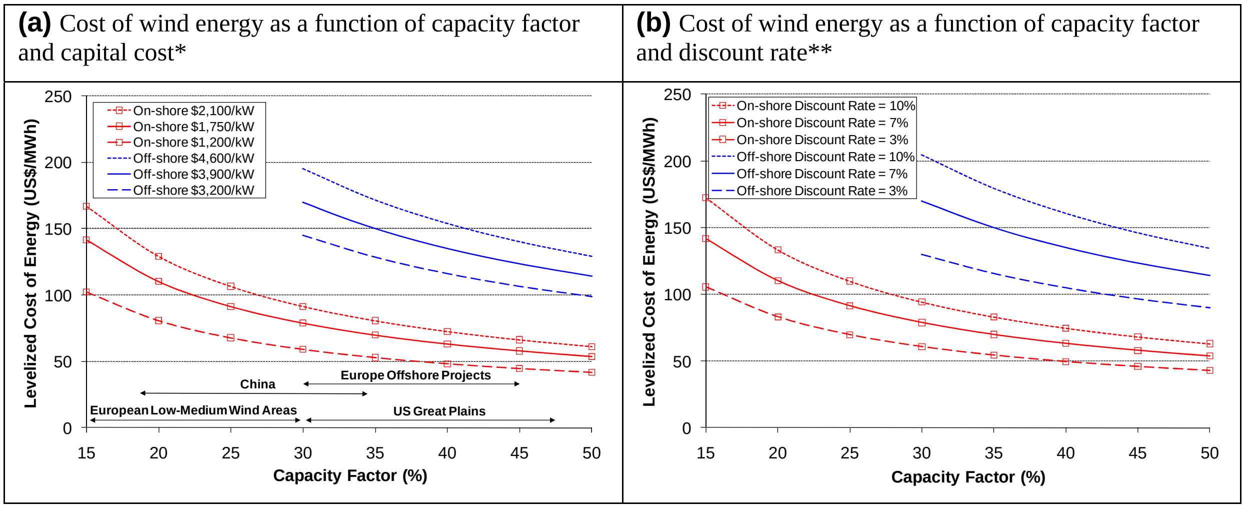
7.8.3.3 Energy production

On-shore wind power plant performance varies from site-to-site primarily as a function of the wind resource, with capacity factors ranging from below 20% to more than 50% depending on local resource conditions. Among countries, variations in average performance again reflect differing wind resource conditions: the average capacity factor for Germany's installed plants has been estimated at 20.5% (BTM, 2010); European country-level average capacity factors range from 20-30% (Boccard, 2009); average capacity factors in China are reported at roughly 23% (Li, 2010); average capacity factors in India are reported at around 20% (Goyal, 2010); and the average capacity factor for U.S. wind power plants is above 30% (Wiser and Bolinger, 2010). Off-shore wind power plants often experience a narrower range in capacity factors, with a typical range of 35% to 45% for the European plants installed to date (Lemming *et al.*, 2009).

Because of these variations among countries and individual plants, which are primarily driven by local wind resource conditions but are also affected by turbine design and operations, estimates of the levelized cost of wind energy must include a range of energy production estimates. Moreover, because the attractiveness of off-shore plants is enhanced by the potential for greater energy production than for on-shore plants, performance variations among on- and off-shore wind energy must also be considered.

7.8.3.4 Levelized cost of energy estimates

Using the methods summarized in Appendix II, the levelized cost of wind energy for power plants built in 2009 is presented in Figure 7.19(a, b). Estimated costs are presented over a range of energy production estimates to represent the cost variation associated with inherent differences in the wind resource. The x-axis for these charts roughly correlates to annual average wind speeds from 6 m/s to 10 m/s. On-shore capital costs are assumed to range from US$1,200/kW to US$2,100/kW (with a mid-level cost of US$1,750/kW); installed costs for off-shore wind energy range from US$3,200/kW to US$4,600/kW (mid-point of US$3,900/kW). Levelized O&M costs are assumed to average US$16/MWh and US$30/MWh over the life of the plant for on-shore and off-shore wind energy, respectively. A power plant design life of 20 years is assumed, and discount rates of 3% to 10% (mid-point estimate of 7%) are used to produce levelized cost estimates. Taxes and policy incentives are not included in these calculations.


(a) Cost of wind energy as a function of capacity factor and capital cost*

(b) Cost of wind energy as a function of capacity factor and discount rate**

* Discount rate assumed to equal 7%

** On-shore capital cost assumed at US$1,750/kW, and off-shore at US$3,900/KW

Figure 7.19. Estimated levelized cost of on-shore and off-shore wind energy, 2009

The levelized cost of on- and off-shore wind energy in 2009 varies substantially, depending on assumed capital costs, energy production, and discount rates. For on-shore wind energy, levelized costs in good to excellent wind resource regimes average US$50-100/MWh. Levelized costs can reach US$150/MWh in lower resource areas. The cost of wind energy in China and the U.S. tend toward the lower range of these estimates, due to lower average installed costs (China) and higher average capacity factors (U.S.); costs in much of Europe tend towards the higher end of the range due to relatively lower average capacity factors. Off-shore wind energy is generally more expensive than on-shore, with typical levelized costs that range from US$100/MWh to US$200/MWh; where the exploitable on-shore wind resource is limited, however, off-shore plants can sometimes compete with on-shore plants.

7.8.4 Potential for further reductions in the cost of wind energy

The wind energy industry has developed over a period of 30 years. Though the dramatic cost reductions seen in past decades will not continue indefinitely, the potential for further reductions remain given the many potential areas of technological advance described in Section 7.7. This potential spans both on- and off-shore wind energy technologies; given the relative immaturity of off-shore wind energy, however, greater cost reductions can be expected in that segment. Two approaches are commonly used to forecast the future cost of wind energy: (1) learning curve estimates that assume that future wind energy costs will follow a trajectory that is similar to an historical learning curve based on past costs; and (2) engineering-based estimates of the specific cost reduction possibilities associated with new or improved wind energy technologies or manufacturing capabilities.

7.8.4.1 Learning curve estimates

Learning curves have been used extensively to understand past cost trends and to forecast future cost reductions for a variety of energy technologies (e.g., McDonald and Schrattenholzer, 2001; Kahouli-Brahmi, 2009). Learning curves start with the premise that increases in the cumulative capacity of a given technology lead to a reduction in its costs. The principal parameter calculated by learning curve studies is the learning rate: for every doubling of cumulative installation or production, the learning rate specifies the associated percentage reduction in costs.

A number of studies have evaluated learning rates for on-shore wind energy. There is a wide range of calculated learning rates, from 4% to 32% (Table 7.6), suggesting that historical cost reductions have been significant, but that there is relatively little agreement on the magnitude of those reductions. This wide variation can be explained by differences in learning model specification (e.g., one factor or multi-factor learning curves), variable selection and assumed system boundaries (e.g., whether installed cost, turbine cost, or levelized energy costs are explained, and whether global or country-level cumulative installations are used), data quality, and the time period over which data are available. Because of these differences, the various learning rates for wind energy presented in Table 7.6 cannot easily be compared. Focusing only on those studies completed in 2004 and later, and that have prepared estimates of learning curves based on total wind power plant installed costs and global cumulative installations, the range of learning rates narrows to 10-17%.

Table 7.6. Summary of learning curve literature for wind energy

		Global or National		
Authors	**Learning By Doing Rate (%)**	**Independent Variable (cumulative installed capacity)**	**Dependent Variable**	**Data Years**
Neij (1997)	4%	Denmark	Denmark (turbine cost)	1982-1995
Mackay and Probert (1998)	14%	U.S.	U.S. (turbine cost)	1981-1996
Neij (1999)	8%	Denmark	Denmark (turbine cost)	1982-1997
Wene (2000)	32%	U.S. **	U.S. (production cost)	1985-1994
Wene (2000)	18%	EU **	EU (production cost)	1980-1995
Miketa and Schrattenholzer (2004)*	10%	Global	Global (installed cost)	1971-1997
Junginger *et al.* (2005)	19%	Global	UK (installed cost)	1992-2001
Junginger *et al.* (2005)	15%	Global	Spain (installed cost)	1990-2001
Klaassen *et al.* (2005) *	5%	Germany, Denmark, and UK	Germany, Denmark, and UK (installed cost)	1986-2000
Kobos *et al.* (2006) *	14%	Global	Global (installed cost)	1981-1997
Jamasb (2007) *	13%	Global	Global (installed cost)	1980-1998
Söderholm and Sundqvist (2007)	5%	Germany, Denmark, and UK	Germany, Denmark, and UK (installed cost)	1986-2000
Söderholm and Sundqvist (2007) *	4%	Germany, Denmark, and UK	Germany, Denmark, and UK (installed cost)	1986-2000
Neij (2008)	17%	Denmark	Denmark (production cost)	1980-2000
Kahouli-Brahmi (2009)	17%	Global	Global (installed cost)	1979-1997
Nemet (2009)	11%	Global	California (turbine cost)	1981-2004
Wiser and Bolinger (2009)	11%	Global	U.S. (installed cost)	1982-2008

* Two-factor learning curve that also includes R&D; all others are one-factor learning curves

** Independent variable is cumulative production of electricity

There are also a number of limitations to the use of such models to forecast future costs. First, learning curves typically (and simplistically) model how costs have decreased with increased installations in the past, and do not comprehensively explain the reasons behind the decrease. In reality, costs may decline in part due to traditional learning and in part due to other factors, such as

R&D expenditure and increases in turbine and power plant size. If learning curves are used to forecast future cost trends, one must not only assume that the factors that have driven costs in the past will be sustained into the future, but that those drivers operate based on cumulative installations. In reality, as technologies mature, diminishing returns in cost reduction can be expected (Arrow, 1962; Ferioli *et al.*, 2009). Second, the most appropriate cost measure for wind energy is arguably the levelized cost of energy, as wind energy production costs are affected by both installed costs and energy production (EWEA, 2009; Ferioli *et al.*, 2009). Unfortunately, only two of the published studies calculate the learning rate for wind energy using a levelized cost of energy metric (Wene, 2000; Neij, 2008); most studies have used the more-readily available metrics of total installed cost or turbine cost. Third, a number of the published studies have sought to explain cost trends based on cumulative wind power capacity installations or production in individual countries or regions of the world; because the wind energy industry is global in scope, however, it is likely that most learning is now occurring based on cumulative global installations. Finally, from 2004 through 2009, the installed cost of wind power plants increased substantially, countering the effects of learning, and questioning the sole reliance on cumulative installations as a predictor of future costs.

7.8.4.2 Engineering model estimates

Whereas learning curves examine aggregate historical data to forecast future trends, engineering-based models focus on the possible cost reductions associated with specific design changes and/or technical advancements. These models can lend support to learning curve predictions by defining the technology advances that can yield cost reductions and/or energy production increases.

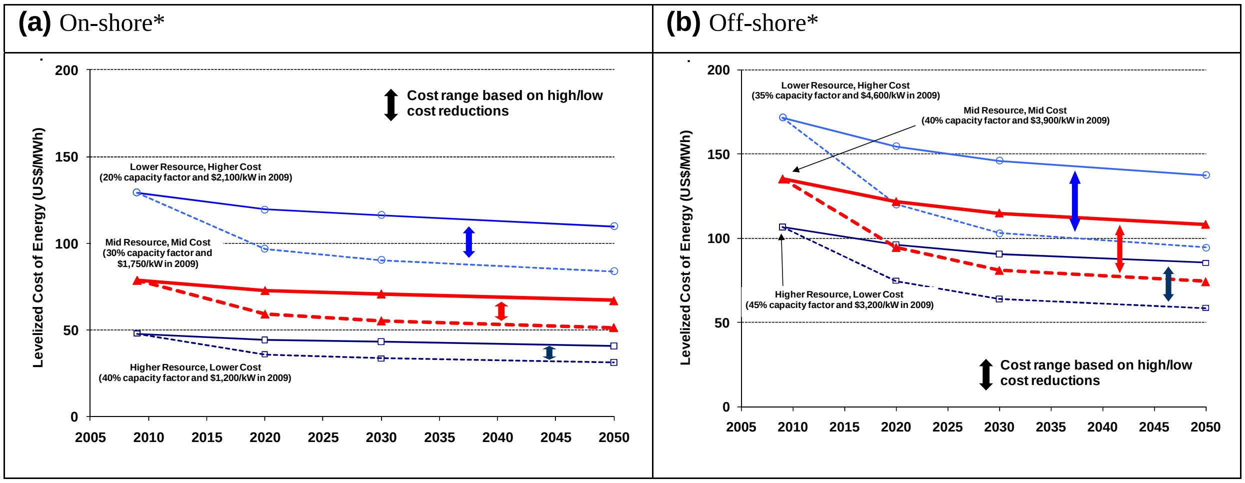
These models have been used to estimate the impact of potential technology improvements on wind power plant capital costs and energy production, as highlighted earlier in Section 7.3. Given these possible technology advancements (in combination with manufacturing learning), the U.S. DOE (2008) estimates that on-shore wind energy capital costs may decline by 10% by 2030, while energy production may increase by roughly 15%, relative to a 2008 starting point (see Table 7.4, and the note under that table). Combined, these two impacts correspond to a reduction in the levelized cost of energy from on-shore wind energy of 17% by 2030.

Given the relative immaturity of off-shore wind energy, there is arguably greater potential for technical advancements than in on-shore wind energy technology, particularly in foundation design, electrical system design, and O&M costs. Larger off-shore wind power plants are also expected to trigger more efficient installation procedures and dedicated vessels, enabling lower costs. Future energy cost reductions have been estimated by associating potential cost reductions with these technical improvements, resulting in cost reduction estimates ranging from 18-39% by 2020, and 17-66% by 2030 (Junginger *et al.*, 2004; Carbon Trust, 2008b; Lemming *et al.*, 2009).

7.8.4.3 Projected levelized cost of wind energy

A number of studies have estimated the cost trajectory for on-shore and off-shore wind energy based on learning curve estimates and/or engineering models (Junginger *et al.*, 2004; Carbon Trust 2008b; IEA, 2008; U.S. DOE, 2008; GWEC and GPI, 2008; Lemming *et al.*, 2009).

Using the estimates and assumptions for the expected percentage cost reduction in levelized cost of energy from these specific studies, a range of levelized cost trajectories have been developed for representative future on-shore and off-shore wind power plants (Figure 7.20(a,b)). In both of the graphics, a high, low, and mid-level starting point for the levelized cost of energy is calculated using various combinations of plant-level capacity factor and installed cost assumptions, representing a reasonable average range of 2009 values.[27] These levelized cost estimates for 2009 are the same as presented earlier in Figure 7.19. To forecast a range of future costs, high and low levelized cost reduction estimates were developed based on the literature cited above. That literature suggested a range of levelized cost reductions for on-shore wind of roughly 7.5-25% by 2020 and 15-35% by 2050, and for off-shore wind of roughly 10-30% by 2020 and 20-45% by 2050.[28]


(a) On-shore*

(b) Off-shore*

* Starting-point O&M costs are assumed to equal US$16/MWh (on-shore) and US$30/MWh (off-shore); a 7% discount rates is used throughout

Figure 7.20. Projected levelized cost of (a) on-shore and (b) off-shore wind energy, 2009-2050

Based on these assumptions, the levelized cost of on-shore wind energy could range from roughly US$30-110/MWh by 2050, depending on the wind resource, installed cost, and the speed of cost reduction. Off-shore wind energy is likely to experience somewhat deeper cost reductions, with a range of expected levelized costs of US$60-140/MWh by 2050.

Uncertainty exists over future wind energy costs, and the range of costs associated with varied wind resource strength introduces greater uncertainty. As installed wind power capacity increases, higher quality resource sites will tend to be utilized first, leaving higher-cost sites for later deployment. As a result, the average levelized cost of wind energy will depend on the amount of deployment. This “supply-curve” affect is not captured in the estimates presented in Figure 7.20: those projections present potential cost reductions associated with wind power plants located in specific wind resource regimes. The estimates presented here therefore provide an indication of the technology advancement potential for on- and off-shore wind energy, but should be used with caution.

7.9 Potential deployment

Wind energy offers significant potential for near- and long-term carbon emissions reduction. The wind power capacity installed by the end of 2009 was capable of meeting roughly 1.8% of worldwide electricity demand, and that contribution could grow to in excess of 20% by 2050. On a global basis, the wind resource is unlikely to constrain further development (Section 7.2). On-shore wind energy technology is already being deployed at a rapid pace (Sections 7.3 and 7.4), therefore offering an immediate option for reducing carbon emissions in the electricity sector. In good to excellent wind resource regimes, the cost of on-shore wind energy averages US$50-100/MWh

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[27] Figures outside of this range are certainly possible, however. Moreover, because of the cost drivers discussed earlier in this chapter, wind energy costs in 2009 were higher than in some previous years. Applying the percentage cost reductions from the available literature to the 2009 starting point is, therefore, arguably a conservative approach to estimating future cost reduction possibilities.

[28] The absolute range suggested by the studies reviewed is somewhat larger than that used here.

(Section 7.8), and no insurmountable technical barriers exist that preclude increased levels of wind energy penetration into electricity supply systems (Section 7.5). Continued technology advancements and cost reductions in on- and off-shore wind energy are expected (Sections 7.7 and 7.8), further improving the carbon emissions mitigation potential of wind energy over the long term.

This section begins by highlighting near-term forecasts for wind energy deployment (7.9.1). It then discusses the prospects for and barriers to wind energy deployment in the longer-term and the potential role of that deployment in meeting various GHG mitigation targets (7.9.2). Both subsections are largely based on energy-market forecasts and carbon and energy scenarios literature published in the 2007-2009 time period. The section ends with brief conclusions (7.9.3). Though the focus of this section is on larger on- and off-shore wind turbines for electricity production, alternative technologies for harnessing wind energy exist and have served and will continue to meet other energy service needs.

7.9.1 Near-term forecasts

The rapid increase in global wind power capacity from 2000-2009 is expected by many studies to continue in the near- to medium-term (Table 7.7). From the roughly 160 GW of wind power capacity installed by the end of 2009, the IEA [TSU: (2009b)] (IEA, 2009b) and U.S. Energy Information Administration (US EIA, 2010) *reference-case* forecasts predict growth to 295 GW and 277 GW by 2015, respectively. Wind energy industry organizations predict even faster deployment rates, noting that past IEA and EIA forecasts have understated actual wind energy growth by a sizable margin (BTM, 2010; GWEC, 2010a). However, even these more-aggressive forecasts estimate that wind energy will contribute less than 5% of global electricity supply by 2015. Asia, North America, and Europe are projected to lead in wind power capacity additions over this period.

Table 7.7. Near-term global wind energy forecasts

Study	**Wind Energy Forecast**		
	Installed Capacity	**Year**	**% of Global Electricity Supply**
IEA (2009b)*	295 GW	2015	2.8%
(US EIA, 2010)*	277 GW	2015	3.1%
GWEC (2010b)	409 GW	2014	not available
BTM (2010)	448 GW	2014	4.0%

* Reference case forecast

7.9.2 Long-term deployment in the context of carbon mitigation

A number of studies have tried to assess the longer-term potential of wind energy, especially in the context of carbon mitigation scenarios. As a variable, location-dependent resource with limited dispatchibility, modelling the economics of wind energy expansion presents unique challenges (e.g., Neuhoff *et al.*, 2008). The resulting differences among studies of the long-term deployment of wind energy may therefore reflect not just varying input assumptions and assumed policy and institutional contexts, but also differing modelling or scenario analysis approaches.

The IPCC's Fourth Assessment Report assumed that on- and off-shore wind energy could contribute 7% of global electricity supply by 2030, or 8 EJ/y (2,200 TWh/y) (IPCC, 2007). Not surprisingly, this figure is higher than some commonly cited business-as-usual, reference-case forecasts (after all, the IPCC estimate is not a business-as-usual case). The IEA's World Energy Outlook reference-case, for example, predicts 5.7 EJ/y (1,535 TWh/y) of wind energy by 2030, or 4.5% of global electricity supply (IEA, 2009b). The U.S. EIA forecasts 4.6 EJ/y (1,234 TWh/y) of wind energy in its 2030 reference case projection, or 3.9% of net electricity production from central producers (US EIA, 2010).

A summary of the literature on the possible contribution of RE supplies in meeting global energy needs under a range of CO_2 stabilization scenarios is provided in Chapter 10. Focusing specifically on wind energy, Figure 7.21 and Figure 7.22 present modelling results on the global supply of wind energy, in EJ/y and as a percent of global electricity supply, respectively; refer to Chapter 10 for a full description of the literature underlying these figures. Wind energy deployment results for 2020, 2030, and 2050 are presented for three CO_2 stabilization ranges, based on the IPCC's Fourth Assessment Report: 600-1000 ppm-CO_2 (baselines, or reference cases), 440-600 ppm (Categories III and IV), and 300-440 ppm (Categories I and II), all by 2100.

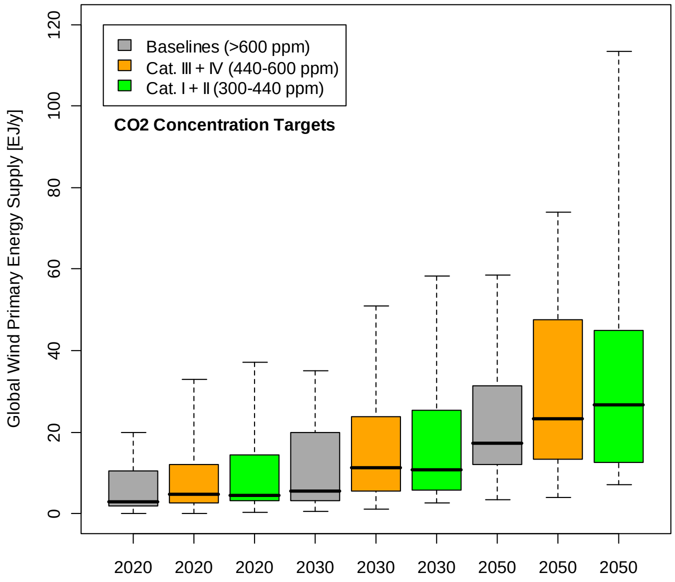

Figure 7.21. Global total primary energy supply of wind energy in carbon stabilization scenarios (median, 25th to 75th percentile range, and absolute range) [TSU: adapted from Krey and Clarke, 2010 (source will have to be included in reference list); see also Chapter 10.2]

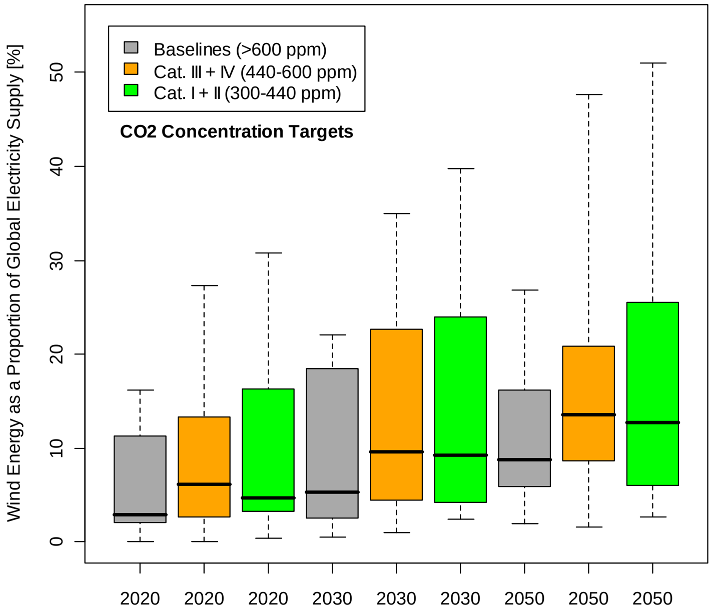

Figure 7.22. Wind electricity share in total global electricity supply (median, 25th to 75th percentile range, and absolute range) [TSU: adapted from Krey and Clarke, 2010 (source will have to be included in reference list); see also Chapter 10.2]

The reference, or baseline-case (600-1000 ppm-CO_2) projections of wind energy's role in global energy supply span a broad range, but with a median of roughly 3 EJ/y in 2020, 6 EJ/y in 2030, and 18 EJ/y in 2050 (Figure 7.21). Substantial growth of wind energy is therefore projected to occur even in the absence of GHG mitigation policies, with wind energy's median contribution to global electricity supply rising from 1.8% by the end of 2009 to 9% by 2050 (Figure 7.22). Moreover, the contribution of wind energy grows as GHG mitigation policies are assumed to become more stringent: by 2030, wind energy's median contribution equals roughly 10 EJ/y (~9% of global electricity supply) in the 440-600 and 300-440 ppm-CO_2 stabilization ranges, increasing to 22-26 EJ/y by 2050 (~13% of global electricity supply).[29]

The diversity of approaches and assumptions used to generate these scenarios is great, however, resulting in a wide range of findings. Reference case results for global wind energy supply in 2050 range from 3-58 EJ/y (median of 18 EJ/y), or 2-27% (median of 9%) of global electricity supply. In the most-stringent 300-440 ppm stabilization scenarios, wind energy supply in 2050 ranges from 7-113 EJ/y (median of 26 EJ/y), equivalent to 3-51% (median of 13%) of global electricity supply.

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[29] In addition to the global scenarios literature, a growing body of work has sought to understand the technical and economic limits of wind energy deployment in regional electricity systems. These studies have sometimes evaluated higher levels of deployment than contemplated by the global scenarios, and have often used more-sophisticated modelling tools. For a summary of a subset of these scenarios, see Martinot *et al.*, 2007; examples of studies of this type include Deutsche Energie-Agentur, 2005 (Germany); EC, 2006; Nikolaev *et al.*, 2008, 2009 (Russia); and US DOE, 2008 (United States). In general, these studies confirm the basic findings from the global scenarios literature: wind energy deployment to 10% of global electricity supply and then to 20% or more are plausible, assuming that cost and policy factors are favourable.

Despite this wide range, the IPCC (2007) estimate for potential wind energy supply of roughly 8 EJ/y by 2030 (which was largely based on literature available through 2005) appears somewhat conservative compared to the more-recent scenarios literature presented here. Other recent forecasts of the possible role of wind energy in meeting global energy demands confirm this assessment, as the IPCC (2007) estimate is roughly one-third to one-half that shown in GWEC and GPI (2008) and Lemming *et al.* (2009). The IPCC (2007) estimate is more consistent with but still somewhat lower than that offered by the IEA World Energy Outlook (2009 [TSU: 2009b]; 450 ppm case).

Though the literature summarized in Figures 7.21 and 7.22 shows an increase in wind energy with increasingly aggressive GHG targets, that impact is not as great as it is for biomass, geothermal, and solar energy, where increasingly stringent carbon stabilization ranges lead to more-dramatic increases in technology deployment (see Chapter 10). One explanation for this result is that wind energy is already comparatively mature and economically competitive; as a result, continued deployment is predicted even in the absence of aggressive efforts to reduce carbon emissions.

The scenarios literature also shows that wind energy could play a significant long-term role in reducing global carbon emissions: by 2050, the median contribution of wind energy in the two carbon stabilization scenarios is 22-26 EJ/y, increasing to 45-50 EJ/y at the 75th percentile, and to more than 100 EJ/y in the highest study. To achieve this contribution requires wind energy to deliver around 13% of global electricity supply in the median case, and 21-26% at the 75th percentile. Other scenarios generated by wind energy and RE organizations are consistent with this median to 75th percentile range; GWEC and GPI (2008) and Lemming *et al.* (2009), for example, estimate the possibility of 32-37 EJ/y of wind energy supply by 2050.

To achieve these levels of deployment, policies to reduce carbon emissions and/or increase RE supplies would likely be necessary, and those policies would need to be of adequate economic attractiveness *and* predictability to motivate substantial private investment (see Chapter 11). A variety of other possible challenges to aggressive wind energy growth also deserve discussion.

Resource Potential: First, even the highest estimates for long-term wind energy supply in Figure 7.21 are below the global technical wind resource potential estimates presented in Section 7.2, suggesting that – on a global basis, at least – technical resource potential is unlikely to be a limiting factor to aggressive levels of wind energy deployment. Moreover, ample potential exists in most regions of the world to enable significant wind energy development. In certain countries or regions, however, higher deployment levels will begin to constrain the most economical resource supply, and wind energy will therefore not contribute equally in meeting the needs of every country.

Regional Deployment: Second, wind energy would need to expand beyond its historical base in Europe and, increasingly, the U.S. and China. The IEA WEO reference-case forecast projects the majority of wind energy deployment by 2030 to come from OECD Europe (40%), with lesser quantities from OECD North America (26%) and portions of Asia (e.g., 15% in China and 5% in India) (IEA, 2009b). Under higher-penetration scenarios, however, a greater geographic distribution of wind energy deployment is likely to be needed. Scenarios from GWEC and GPI (2008), EREC and GPI (2008), and IEA (2008), for example, show North America, Europe, and China to be the areas of greatest wind energy deployment, but also identify a number of other regions that are projected to be significant contributors to wind energy growth in high-penetration scenarios (Table 7.8).[30] Enabling this level of wind energy development in regions new to wind energy would be a challenge, and would benefit from institutional and technical knowledge transfer from those regions that are already witnessing substantial wind energy activity (e.g., Lewis, 2007; IEA, 2009a).

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[30] Many of these other regions have lower expected electricity demands. As a result, some of the regions that are projected to make a small contribution to global wind electricity supply are still projected to obtain a sizable fraction of their own electricity supply from wind energy.

Table 7.8. Regional distribution of global wind electricity supply (percentage of total worldwide wind electricity supply)

Region	GWEC / GPI (2008)***** **2030** ***'Advanced' Scenario***	EREC and GPI (2008) **2050** ***'Energy Revolution' Scenario***	IEA ETP (2008) **2050** ***'BLUE' Scenario***
Global Supply of Wind Energy (EJ)	20 EJ	28 EJ	19 EJ
OECD North America	22%	20%	13%
Latin America	8%	9%	10%
OECD Europe	15%	13%	23%
Transition Economies	3%	9%	3%
OECD Pacific	9%	10%	7%
China	19%	20%	31%
India	10%	7%	4%
Developing Asia	9%	7%	3%
Africa and Middle East	5%	5%	6%

* For GWEC/GPI (2008), percentage of worldwide wind power capacity is presented.

Supply Chain Issues: Third, while efforts would be required to ensure an adequate supply of labour and materials, no insurmountable long-term constraints to materials supply, labour availability, or manufacturing capacity are envisioned if policy frameworks for wind energy are sufficiently economically attractive *and* predictable (e.g., US DOE, 2008). The wind energy industry has scaled rapidly over the last decades, resulting in greater globalization and competition throughout the value-chain (see Section 7.4). Annual additions and manufacturing volume reached 38 GW in 2009, and the significant further scaling needed to meet the increased manufacturing demands of higher-penetration scenarios (see Section 10.3) appears challenging, but feasible.

Technology and Economics: Fourth, due to resource and siting constraints in some countries and regions, greater reliance on off-shore wind energy, particularly in Europe, is likely to be required. Estimates of the proportion of total global wind energy supply likely to be delivered from off-shore wind energy in 2050 range from 18% to 30% (EREC and GPI, 2008; IEA, 2008; Lemming *et al.*, 2009), while the IEA forecasts a 20-28% share by 2030 (IEA, 2009b). Increases in off-shore wind energy of this magnitude would require technological advancements and cost reductions. Though R&D is expected to lead to incremental cost reductions for on-shore wind energy technology, enhanced R&D expenditures by government and industry may be especially important for off-shore wind energy technology given its less mature state (see Section 7.7).

Integration and Transmission: Fifth, technical and institutional solutions to transmission constraints and operational integration concerns will need to be implemented. Analysis results and experience suggest that many electric systems can operate with up to roughly 20% wind energy with relatively modest integration costs (see Section 7.5 and Chapter 8). Though comparatively few studies have explored wind electricity supply in excess of 20% in detail, there is little evidence to suggest that an insurmountable technical limit exists to wind energy's contribution to electricity supply.[31] Nevertheless, the concerns about (and the costs of) operational integration and

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[31] Some studies have looked at wind electricity penetrations in excess of 20% in certain regions, often using somewhat-less-detailed analysis procedures than formal wind energy integration studies, and often involving the use of structural change in generation portfolios, electrical or thermal storage, plug-in hybrid vehicles and the electrification of transportation, demand response, and/or other technologies to manage the variability of wind power output (e.g., Grubb, 1991; Watson *et al.*, 1994; Lund and Münster, 2003; Kempton and Tomic, 2005;

maintaining electric system reliability will grow with wind energy deployment, and efforts to ensure adequate system-wide flexibility, employ more-restrictive grid connection standards, develop and use improved wind forecasting systems, and encourage load flexibility and electrical storage are warranted. Moreover, given the locational dependence of the wind resource, substantial new transmission infrastructure both on- and off-shore would be required under even the more modest wind energy deployment scenarios presented earlier. Both cost and institutional barriers would need to be overcome to develop this needed transmission infrastructure (see Section 7.5 and Chapter 8).

Social and Environmental Concerns: Finally, given concerns about the social and environmental impacts of wind power plants summarized in Section 7.6, efforts to better understand the nature and magnitude of these impacts, together with efforts to minimize and mitigate those impacts, will need to be pursued in concert with increasing wind energy deployment. Prominent environmental concerns about wind energy include bird and bat collision fatalities and habitat and ecosystem modifications, while prominent social concerns include visibility and landscape impacts as well various nuisance effects and radar interference. Though community and scientific concerns need to be addressed, streamlined planning, siting, and permitting procedures for both on- and off-shore wind energy may be required to enable the wind power capacity additions envisioned under these scenarios.

7.9.3 Conclusions regarding deployment

The literature presented in this section suggests that wind electricity penetration levels that approach or exceed 10% of global electricity supply by 2030 are feasible, assuming that cost and policy factors are favourable towards wind energy deployment. The scenarios further suggest that even-more ambitious policies and/or technology improvements may allow wind energy to ultimately reach or exceed 20% of global electricity supply, and that these levels of supply would be economically attractive within the context of global carbon mitigation scenarios. There are, however, a variety of barriers that would need to be overcome if wind energy was to achieve these aggressive levels of penetration. In particular, the degree to which wind energy is utilized in the future will largely depend on: the economics of wind energy compared to alternative power sources; policies to directly or indirectly support wind energy deployment; local siting and permitting challenges; and real or perceived concerns about the ability to integrate wind energy into electric supply systems.

Denholm, 2006; DeCarolis and Keith, 2006; Lund, 2006; Black and Strbac, 2006; Cavallo, 2007; Greenblatt *et al.*, 2007; Hoogwijk *et al.*, 2007; Leighty, 2008; Lamont, 2008; Benitez *et al.*, 2008; Lund and Kempton, 2008; Kiviluoma and Meibom, 2009). These studies confirm that there are no insurmountable technical barriers to increased wind energy supply; instead, as deployment increases, transmission expansion and operational integration costs will increase, constraining growth on economic terms. These studies also find that new technical solutions that are not otherwise required at lower levels of wind energy deployment, such an expanded use of storage and responsive loads, will become increasingly valuable at higher levels of wind energy development.

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