Energy Technology Perspectives

Technology Roadmap

Wind energy

2013 edition

International
Energy Agency

INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate was – and is – two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy for its 28 member countries and beyond. The IEA carries out a comprehensive programme of energy co-operation among its member countries, each of which is obliged to hold oil stocks equivalent to 90 days of its net imports. The Agency's aims include the following objectives:

- Secure member countries' access to reliable and ample supplies of all forms of energy; in particular, through maintaining effective emergency response capabilities in case of oil supply disruptions.
- Promote sustainable energy policies that spur economic growth and environmental protection in a global context – particularly in terms of reducing greenhouse-gas emissions that contribute to climate change.
- Improve transparency of international markets through collection and analysis of energy data.
- Support global collaboration on energy technology to secure future energy supplies and mitigate their environmental impact, including through improved energy efficiency and development and deployment of low-carbon technologies.
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Foreword

Current trends in energy supply and use are unsustainable – economically, environmentally and socially. Without decisive action, energy-related greenhouse-gas (GHG) emissions could more than double by 2050, and increased oil demand will heighten concerns over the security of supplies. We can and must change the path we are now on; sustainable and low-carbon energy technologies will play a crucial role in the energy revolution required to make this change happen.

There is a growing awareness of the urgent need to turn political statements and analytical work into concrete action. To address these challenges, the International Energy Agency (IEA), at the request of the Group of Eight (G8), has identified the most important technologies needed to achieve a global energy-related CO_2 target in 2050 of 50% below current levels. It has thus been developing a series of technology roadmaps, based on the *Energy Technology Perspectives* modelling, which allows assessing the deployment path of each technology, taking into account the whole energy supply and demand context.

Wind is the most advanced of the "new" renewable energy technologies and was the subject of one of the first roadmaps produced by the IEA, in 2009. Since then, the development and deployment of wind power has been a rare good news story in the deployment of low-carbon technology deployment. A much greater number of countries in all regions of the world now have significant wind generating capacity. In a few countries, wind power already provides 15% to 30% of total electricity. The technology keeps rapidly improving, and costs of generation from land-based wind installations have continued to fall. Wind power is now being deployed in countries with good resources without special financial incentives.

Because of these improvements and other changes in the energy landscape, this updated roadmap targets an increased share (15% to 18%) of global electricity to be provided by wind power in 2050, compared to 12% in the original roadmap of 2009.

But more remains to be done to ensure that these objectives are met. There is a continuing need for improved technology. Increasing levels of low-cost wind still require predictable, supportive regulatory environments, and appropriate market designs. The challenges of integrating higher levels of variable wind power into the grid must be tackled. And for offshore wind – still at the early stages of the deployment journey – much remains to be done to develop appropriate large-scale systems and to reduce costs.

This updated roadmap recognises the very significant progress made since the last version was published. It provides an updated analysis of the barriers which remain to accelerated progress along with proposals to address them covering technology, legislative and regulatory issues. We hope that the analysis and recommendations will play a part in ensuring the continued success of wind energy.

This publication is produced under my authority as Executive Director of the IEA.

Maria van der Hoeven
Executive Director
International Energy Agency

Table of contents

List of tables

List of figures

List of boxes

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Key findings and actions

- Since 2008, wind power deployment has more than doubled, approaching 300 gigawatts (GW) of cumulative installed capacities, led by China (75 GW), the United States (60 GW) and Germany (31 GW). Wind power now provides 2.5% of global electricity demand – and up to 30% in Denmark, 20% in Portugal and 18% in Spain. Policy support has been instrumental in stimulating this tremendous growth.

- Progress over the past five years has boosted energy yields (especially in low-wind-resource sites) and reduced operation and maintenance (O&M) costs. Land-based wind power generation costs range from USD 60 per megawatt hour (USD/MWh) to USD 130/MWh at most sites. It can already be competitive where wind resources are strong and financing conditions are favourable, but still requires support in most countries. Offshore wind technology costs levelled off after a decade-long increase, but are still higher than land-based costs.

- This roadmap targets 15% to 18% share of global electricity from wind power by 2050, a notable increase from the 12% aimed for in 2009. The new target of 2 300 GW to 2 800 GW of installed wind capacity will avoid emissions of up to 4.8 gigatonnes (Gt) of carbon dioxide (CO_2) per year.

- Achieving these targets requires rapid scaling up of the current annual installed wind power capacity (including repowering), from 45 GW in 2012 to 65 GW by 2020, to 90 GW by 2030 and to 104 GW by 2050. The annual investment needed would be USD 146 billion to USD 170 billion.

- The geographical pattern of deployment is rapidly changing. While countries belonging to the Organisation for Economic Co-operation and Development (OECD) led early wind development, from 2010 non-OECD countries installed more wind turbines. After 2030, non-OECD countries will have more than 50% of global installed capacity.

- While there are no fundamental barriers to achieving – or exceeding – these goals, several obstacles could delay progress including costs, grid integration issues and permitting difficulties.

- This roadmap assumes the cost of energy from wind will decrease by as much as 25% for land-based and 45% for offshore by 2050 on the back of strong research and development (R&D) to improve design, materials, manufacturing technology and reliability, to optimise performance and to reduce uncertainties for plant output. To date, wind power has received only 2% of public energy R&D funding: greater investment is needed to achieve wind's full potential.

- As long as markets do not reflect climate change and other environmental externalities, accompanying the cost of wind energy to competitive levels will need transitional policy support mechanisms.

- To achieve high penetrations of variable wind power without diminishing system reliability, improvements are needed in grid infrastructure and in the flexibility of power systems as well as in the design of electricity markets.

- To engage public support for wind, improved techniques are required to assess, minimise and mitigate social and environmental impacts and risks. Also, more vigorous communication is needed on the value of wind energy and the role of transmission in meeting climate targets and in protecting water, air and soil quality.

Key actions in the next ten years

- Set long-term targets, supported by predictable mechanisms to drive investment and to apply appropriate carbon pricing.

- Address non-economic barriers. Advance planning of new plants by including wind power in long-term land and maritime spatial planning; develop streamlined procedures for permitting; address issues of land-use and sea-use constraints posed by various authorities (environment, building, traffic, defence and navigation).

- Strengthen research, development and demonstration (RD&D) efforts and financing. Increase current public funding by two- to five-fold to drive cost reductions of turbines and support structures, to increase performance and reliability (especially in offshore and other new market areas) and to scale up turbine technology for offshore.

- Adapt wind power plant design to specific local conditions (*e.g.* cold climates and low-wind sites), penetration rates, grid connection costs and the effects of variability on the entire system.

- Improve processes for planning and permitting transmission across large regions; modernise grid operating procedures (*e.g.* balancing area co-ordination and fast-interval dispatch and scheduling); increase power system flexibility using ancillary services from all (also wind) generation and demand response; and expand and improve electricity markets, and adapt their operation for variable generation.
- Increase public acceptance by raising awareness of the benefits of wind power (including emission reductions, security of supply and economic growth), and of the accompanying need for additional transmission.
- Enhance international collaboration in R&D and standardisation, large-scale testing harmonisation, and improving wind integration. Exchange best practices to help overcome deployment barriers.

Introduction

There is a pressing need to accelerate the development of advanced energy technologies in order to address the global challenges of clean energy, climate change and sustainable development. To achieve emission reductions envisioned, the IEA has undertaken an effort to develop a series of global technology roadmaps, under international guidance and in close consultation with industry. These technologies are evenly divided among demand-side and supply-side technologies and include several renewable energy roadmaps (www.iea.org/roadmaps/).

The overall aim is to advance global development and uptake of key technologies to limit global mean temperature increase to 2 degrees Celsius (°C) in the long term. The roadmaps will enable governments and industry and financial partners to identify steps needed and implement measures to accelerate required technology development and uptake.

The roadmaps take a long-term view, but highlight in particular the key actions that need to be taken by different stakeholders in the next five to ten years to reach their goals. This is because the actions undertaken within the next decade will be critical to achieve long-term emission reductions. Existing conventional plants together with those under construction lead to a lock-in of CO_2 emissions as they will be operating for decades. According to the IEA *Energy Technology Perspectives 2012 (ETP 2012)*, early retirement of 850 GW of existing coal capacity would be required to reach the goal of limiting climate change to 2°C. Therefore, it is crucial to build up low-carbon energy supply today.

Rationale for wind power in the overall energy context

ETP 2012 projects that – in the absence of new policies – CO_2 emissions from the energy sector will increase by 84% over 2009 levels by 2050 (IEA, 2012a). The *ETP 2012* model examines competition among a range of technology solutions that can contribute to preventing this increase: greater energy efficiency, renewable energy, nuclear power and the near-decarbonisation of fossil fuel-based power generation. Rather than projecting the maximum possible deployment of any given solution, the *ETP 2012* model calculates the least-cost mix to achieve the CO_2 emission reduction goal needed to limit climate change to 2°C (the *ETP 2012* 2°C Scenario [2DS]; Figure 1 and Box 1).

ETP 2012 shows wind providing 15% to 18% of the necessary CO_2 reductions in the electricity sector in 2050, up from the 12% projected in *Energy Technology Perspectives 2008* (IEA, 2008). This increase in wind compensates for slower progress in the intervening years in the area of carbon capture and storage (CCS) and higher costs for nuclear power. Yet, it also reflects faster cost reductions for some renewables, including wind.

Wind energy, like other power technologies based on renewable resources, is widely available throughout the world and can contribute to reduced energy import dependence. As it entails no fuel price risk or constraints, it also improves security of supply. Wind power enhances energy diversity and hedges against price volatility of fossil fuels, thus stabilising costs of electricity generation in the long term.

Wind power entails no direct greenhouse gas (GHG) emissions and does not emit other pollutants (such as oxides of sulphur and nitrogen); additionally, it consumes no water. As local air pollution and extensive use of fresh water for cooling of thermal power plants are becoming serious concerns in hot or dry regions, these benefits of wind become increasingly important.

Purpose of the roadmap update

The wind roadmap was one of the initial roadmaps developed by the IEA in 2008/09. This document is an update of that earlier document, outlining progress made in the last four years, as well as presenting updated goals and actions. This updated roadmap presents a new vision that takes into account this progress of wind technologies as well changing trends in the overall energy mix.

It presents a detailed assessment of the technology milestones that wind energy will need to reach the ambitious targets presented in the vision. The key objective is to seek measures to improve wind technology performance and reduce its costs in order to achieve the competitiveness needed for the large investments foreseen.

The roadmap also provides an extensive list of non-economic barriers that hamper deployment and identifies policy actions to overcome them. For instance, addressing issues such as permitting processes and public acceptance, transmission and system integration is critically important.

This roadmap thus identifies actions and time frames to achieve the higher wind deployment needed for targeted global emission reductions. In some markets, certain actions will already have been taken, or will be underway. Many countries, particularly in emerging regions, are only just beginning to develop wind energy. Accordingly, milestone dates should be considered as indicative of urgency, rather than as absolutes. Individual countries will have to choose what to prioritise in the rather comprehensive action lists, based on their mix of energy and industrial policies.

This roadmap is addressed to a variety of audiences, including policy-makers, industry, utilities, researchers and other stakeholders. It provides a consistent overall picture of wind power at global and continental levels. It further aims at triggering and informing the elaboration of action plans, target setting or updating, as well as roadmaps of wind power deployment at national level.

Roadmap process, content and structure

This roadmap was developed with inputs from diverse stakeholders representing the wind industry, the power sector, R&D institutions, the finance community, and government institutions. Following a workshop to identify technological and deployment issues, a draft was circulated to participants and a wide range of additional reviewers. It is consistent with the *Long Term R&D Needs Report* of the Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Energy Systems (Wind Implementing Agreement [IA], 2013).

This roadmap is organised into seven major sections. First, the current state of the wind industry and progress since 2008 is discussed, followed by a section that describes the targets for wind energy deployment between 2010 and 2050 based on *ETP 2012*. This discussion includes information on the regional distribution of wind generation projects and the associated investment needs, as well as the potential for cost reductions.

The next three sections describe approaches and specific tasks required to address the major challenges facing large-scale wind deployment in three major areas, namely wind technology development; transmission and grid integration; policy framework development, public engagement and international collaboration.

The final section sets out next steps and categorises the actions from the previous sections by stakeholders (policy makers, industry and power system actors) to help guide their efforts to successfully implement the roadmap activities and achieve the global wind deployment targets.

Wind energy progress since 2008

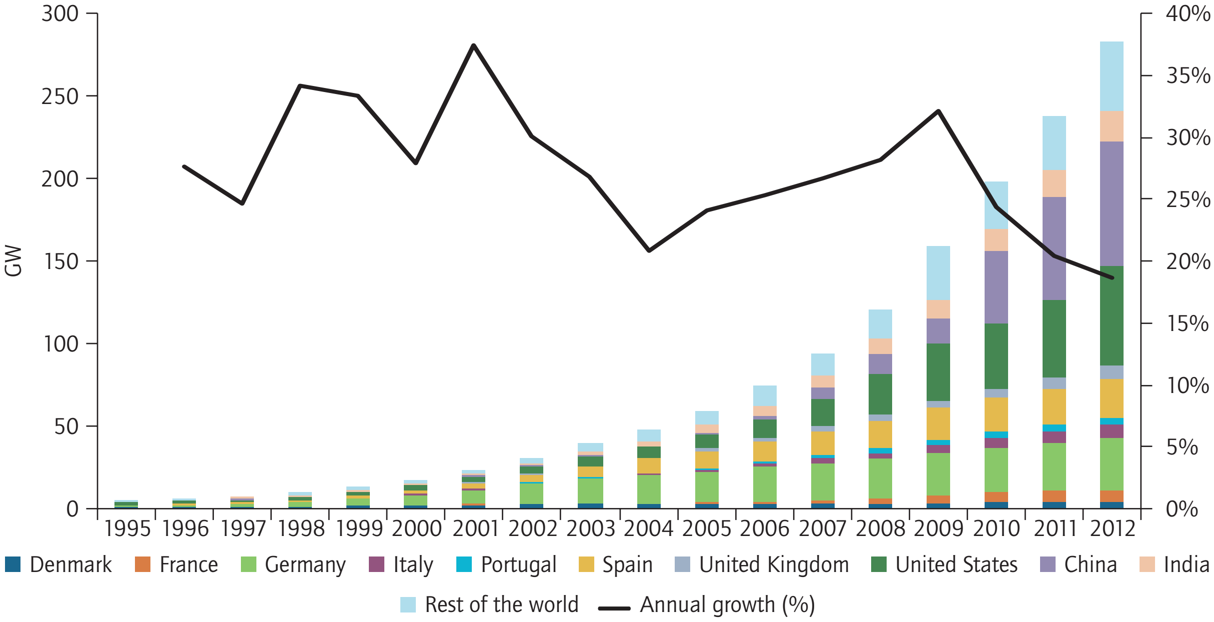
Wind energy is developing towards a mainstream, competitive and reliable power technology. Globally, progress continues to be strong, with more active countries and players, and increasing annual installed capacity and investments. Technology improvements have continuously reduced energy costs, especially on land. The industry has overcome supply bottlenecks and expanded supply chains.

Recent developments in wind markets

Since 2000, cumulative installed capacity has grown at an average rate of 24% per year (%/yr) (Figure 1). In 2012, about 45 GW of new wind power capacity were installed in more than 50 countries, bringing global onshore and offshore capacity to a total of 282 GW (GWEC, 2013; IEA, 2013). New investment in wind energy in 2012 was USD 76.56 billion (Liebreich, 2013). Among the largest clean energy projects financed in 2012 were four offshore wind sites (216 megawatts [MW] to 400 MW) in the German, United Kingdom and Belgian waters of the North Sea, with investments of EUR 0.8 billion to EUR 1.6 billion (USD 1.1 billion to USD 2.1 billion).

Thriving markets exist where deployment conditions are right. Progress made since 2008 shows a positive trend: in 2012, wind power generated about 2.6% of global electricity (Table 1) while capacity and production information for wind resources around the globe show steady expansion (Figure 2).

Figure 1: Global cumulative growth of wind power capacity



Source: unless otherwise indicated, all material in figures and tables derive from IEA data and analysis.

KEY POINT: cumulative wind power capacity grew at almost 25%/yr on average.

Table 1: Progress in wind power since 2008

	End of 2008	***End of 2012***
Total installed capacity	122 GW	282 GW
Annual installed capacity	28 GW	45 GW
Annual investment	USD 52 billion	USD 78 billion
Number of countries with GW installed	17	24
Number of countries with 500 MW yearly market	10	14
Wind generation during the year	254 TWh	527 TWh
Wind penetration levels	% of yearly electricity consumption	
Global	1.3	2.5
Europe	4.0	6.0
Of which:		
● Denmark	20.0	29.9
● Ireland	9.0	14.5
● Portugal	9.0	20.0
● Spain	9.0	17.8
United States	1.9	3.5
China	< 1.0	2.0

Note: TWh = terawatt hour.
Source: IEA, 2013; Wind IA, 2013.

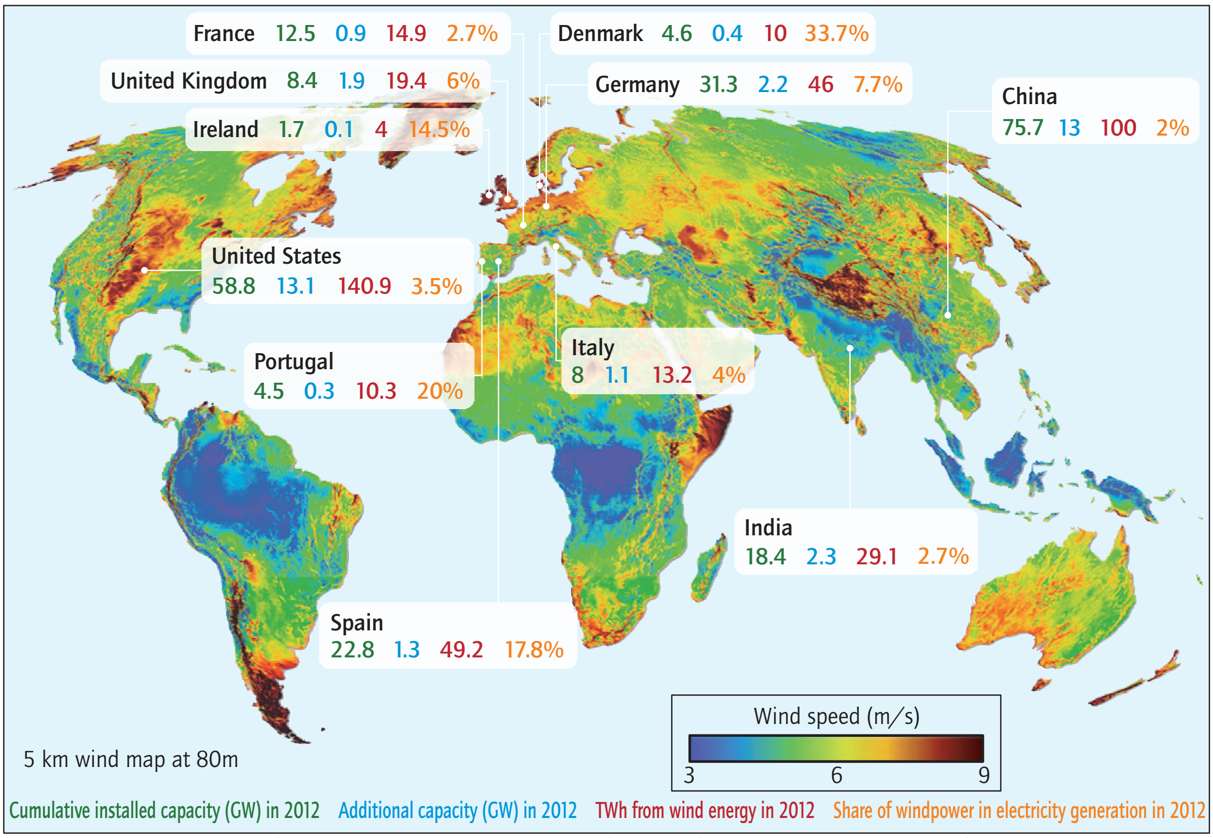
Large-scale offshore deployment has started, more slowly than initially hoped, mostly in Europe. By the end of 2012, 5.4 GW had been installed (up from 1.5 GW in 2008), mainly in the United Kingdom (3 GW) and Denmark (1 GW), with large offshore wind power plants installed in Belgium, China, Germany, the Netherlands and Sweden. Additional offshore turbines are operating in Norway, Japan, Portugal and Korea, while new projects are planned in France and the United States. In the United Kingdom, 46 GW of offshore projects are registered, of which around 10 GW have been progressing to consenting, construction or operation.

An increasing number of turbines are being installed in cold climates, where they are exposed to icy conditions and/or low temperatures outside the design limits of standard wind turbines (Wind IA, 2012). At the end of 2012, nearly 69 GW of installed capacity were estimated to be located in cold climate areas in Scandinavia, North America, Europe and Asia, of which 19 GW were in areas with temperatures below 20°C and the rest subject to icing risks. Between 45 GW and 50 GW of additional capacity are likely to be installed in cold climates before end 2017 (Navigant, 2013a).

Repowering, *i.e.* replacing "old" wind turbines with more modern and productive equipment, is on the rise. Repowering is shown to increase wind power while reducing its footprint. A 2 MW wind turbine with an 80 metre (m) diameter rotor now generates four to six times more electricity than a 500 kW 40 m diameter rotor built in 1995. Repowering began in Denmark and Germany, and has expanded to India, Italy, Portugal, Spain, the United Kingdom and the United States. In Germany, 325 turbines totalling 196 MW were replaced in 2012 with 210 turbines of 541 MW in total. On the pioneer site Altamont Pass in California, NextEra is replacing 780 old turbines with only 34 turbines of 2.3 MW. GlobalData expects repowering to grow dramatically over the coming five years, increasing annual power generation at repowered sites from 1.5 TWh to 8.2 TWh by 2020 (Lawson, 2013).

Most wind turbine manufacturers are concentrated in six countries (the United States, Denmark, Germany, Spain, India and China), with components supplied from a wide range of countries. Market shares have changed in the past five years. New players from China are growing and have started exporting; the six largest Chinese companies (among the top 15 manufacturers globally) together have exceeded 20% of market share in recent years.

Figure 2: Global wind map, installed capacity and production for lead countries



Note: wind speeds at 80 m height are shown with 15 km resolution.

Source: resource data from Wiser *et al.*, 2011; production and capacity data from IEA, 2013.

KEY POINT: good wind resources are found in many regions, notably in the United States, Europe and China, which lead the global market.

Denmark, the pioneering country, had about half of global markets in 2005, but Danish companies represented only 20% of operating turbines in 2012 – still a huge amount for a country that has slightly more than 1% of global installed wind capacity (Navigant, 2013a). In addition to Denmark, strong manufacturers in Spain and Germany make Europe a large exporter of wind technology; in 2010, net exports were EUR 5.7 billion (EWEA, 2012). The United States and India are also among the large manufacturing countries. The US market now comprises 559 wind-related manufacturing facilities and domestic content is 67% (up from less than 25% before 2005) while imports are down to 33% from 75% (Wiser and Bolinger, 2012). Countries with emerging manufacturers include France and Korea, while Brazil has an increasing number of manufacturing facilities.

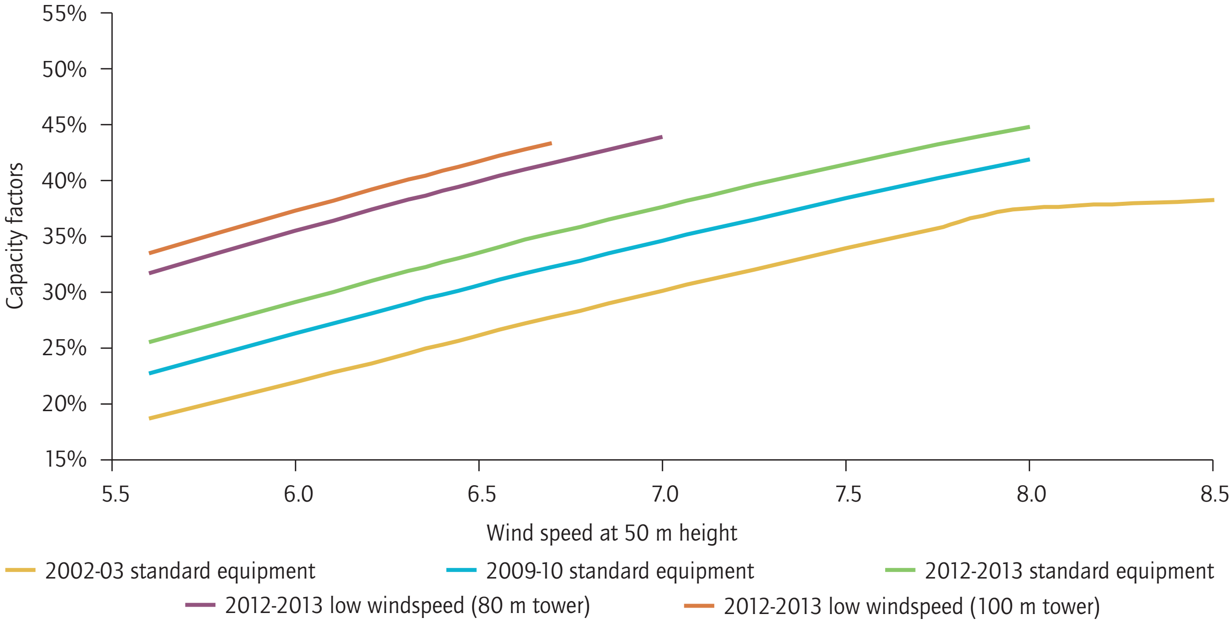
The wind industry has contributed substantially to the socio-economic development of several regions. A clear example is significant job creation in Spain during the first decade of the century, where a sound support scheme attracted several foreign industrial companies across the value chain for wind projects, together with a strong local industry. The United Kingdom is currently attracting industry because of its thriving offshore wind market (Crown Estate, 2012a): between 2007 and 2010, jobs in the sector grew by nearly 30% (EWEA, 2012). Jobs in the wind industry (both direct and indirect) reached approximately 265 000 in both China and the European Union (of which 118 000 in Germany), 81 000 in the United States, 48 000 in India and 29 000 in Brazil (REN21, 2013). Employment figures are not easy to compare across technologies, but wind generally provides more jobs per investment than generation from coal and natural gas. An estimate for the United States finds that wind provides 0.10 job-years/GWh to 0.26 job years/GWh, while the rate is 0.11 job-years/GWh for both coal and natural gas (Wei *et al.*, 2010). An estimate for Spain shows that per EUR 1 million invested, the wind industry creates 15 jobs/yr while combined cycle gas turbines (CCGT) create six jobs/yr (Ernst & Young, 2012).

Technology improvements

The general trend in turbine design has been to increase the height of the tower, the length of the blades and the power capacity. On average, however, turbines have grown in height and rotor diameter more rapidly than have their power capacities. This decrease in the specific power, or ratio of capacity over swept area, has pushed up capacity factors considerably for the same wind speeds (Figure 3). Reducing the energy cost has been the primary driver of this evolution, which might also have positive implications at system level (see *System integration: actions and time frame*).

This trend has also led to the emergence of rotors designed for lower wind speeds, having even smaller specific power, with high masts and long blades in relation to generator size – and even higher capacity factors. This allows installing wind turbines in lower-wind-speed areas, which are often closer to consumption centres than the best "windy spots". As this avoids installation in areas that are sensitive for environment and landscape integration (seashores, mountain ridges, etc.), this practice lowers the potential for opposition and conflicts (Chabot, 2013).

Figure 3: Capacity factors of selected turbine types



Source: Wiser *et al.*, 2012.

KEY POINT: turbine design advancement in ten years allows for significant increase in capacity factors.

Advances in blade design, often with better materials and also advanced control strategies, have contributed to increased yields from the turbines relative to their installed capacity. Since 2008, the share of gearless or direct-drive turbines has increased from 12% to 20%. Other design variations being pursued include rotors downwind of the tower and two-bladed rotors. Offshore wind turbines are evolving from the earlier "marinised" versions of land-based models towards dedicated offshore turbines of increased size, exploring different sub-structures such as jackets and tripods. Further improvements involving the design are anticipated.

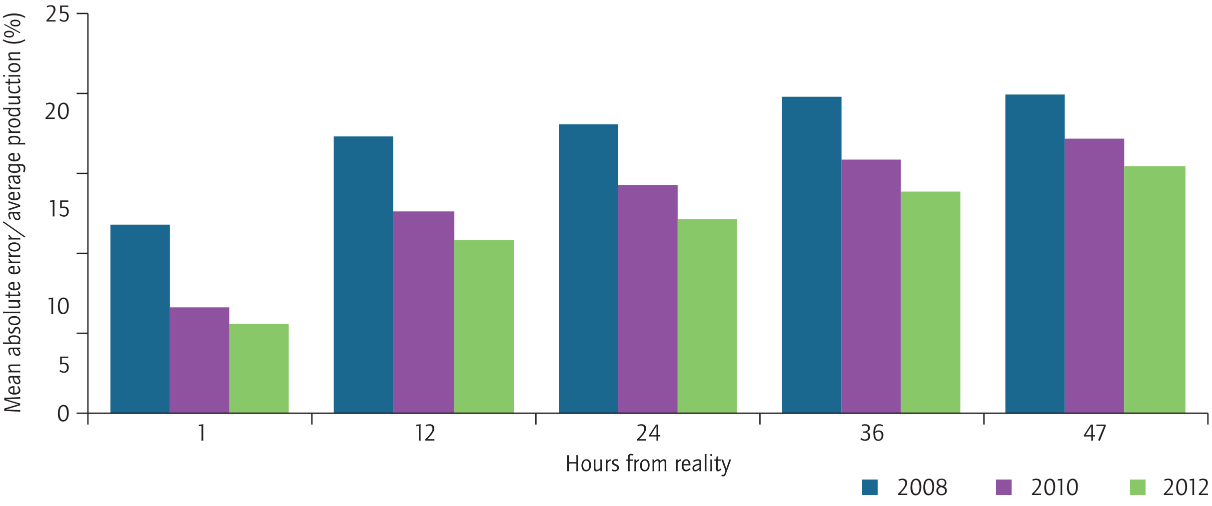
Box 1: Modern wind turbine technology: major achievements over last five years

While several technical designs are in use today, most grid-connected large turbines have three blades in a horizontal axis rotor that can be pitched to control the power output. The size of the wind turbines continues to increase; the average rated capacity of new grid-connected turbines in 2012 was about 1.8 MW compared to 1.6 MW in 2008 (Navigant, 2013a). For offshore, the average installed turbine size has grown from 3 MW in 2008 to 4 MW in 2012. As of 2012, the largest commercial wind turbine available is 7.5 MW, with a rotor diameter of 127 m, and several larger diameter turbines are available (up to 164 m). Turbines with a rated capacity ranging from 1.5 MW to 2.5 MW still comprise the largest market segment.

Wind turbines generate electricity from wind speeds ranging from 3 metres per second (m/s) or 4 m/s to 25 m/s (even 34 m/s with storm control). The *availability* of a wind turbine is the proportion of time that it is technically ready for use, a useful indication of O&M requirements, and the reliability of the technology in general. Onshore availabilities are usually more than 95%. Availability of offshore wind power plants in Denmark and Sweden have been mostly between 92% and 98%, but some years of lower availabilities have occurred. In the Netherlands and the United Kingdom, offshore power plants availabilities have been less than 90% in the first years of operation, but in most cases have recovered towards 95% (GL Garrad Hassan, 2013a).

Wind power output varies as the wind rises and falls. At low penetration levels, wind variability adds only incrementally to the existing variability in electricity supply and demand, but variability and uncertainty become significant as wind penetrations increase. Recent years have seen more countries and regions reach high penetration levels of close to 20% of yearly electricity consumption from wind power. The experience gained in wind integration shows that few physical changes to power systems are needed until penetration exceeds 20%. Considerable progress has been made since 2008 in forecasting the output of wind power plants. In Spain, for example, day-ahead errors have been reduced by one-third (Figure 4). Moreover, a vast majority of wind turbines now installed have fault ride-through capabilities and offer active and reactive power control, thanks to power electronics developments.

Figure 4: Evolution of forecasting errors since 2008



Source: Red Electrica, 2013.

KEY POINT: day-ahead errors in Spain have been reduced by one-third since 2008, a result of dramatically improved forecasting technologies.

Advancing towards competitiveness

Where the resource is good, and conventional generation costs are high, onshore wind energy may be competitive with newly built conventional power plants today. This is the case in Brazil, where recent power auctions saw wind bids as low as USD 42/MWh. Australia, Chile, Mexico, New Zealand, Turkey and South Africa also see land-based wind power competing or close to competing with new coal- or gas-fired plants. Competitiveness, however, is not yet the norm and reducing the levellised cost of energy (LCOE)[1] from wind remains a primary objective for the wind industry.[2] Pricing CO_2 emissions from fossil-fuel combustion to reflect climate change externalities would help wind achieve competitiveness more rapidly.

Investment costs

In the previous version of the IEA *Wind Roadmap* (IEA, 2009), the investment costs for onshore wind energy – including turbine, grid connection, foundations, infrastructure and installation – ranged from USD 1.45 per watt (USD/W) to USD 2.60/W. The range today is even larger, spanning from the low USD 1.10/W in China to the high USD 2.60/W in Japan (IEA, 2013); mid-range prices are found in the United States (USD 1.60/W) and Western Europe (USD 1.70/W).

Following a period of steady decline, investment costs rose considerably in 2004-09, doubling in the United States for example. This increase was due mostly to supply constraints on turbines and components (including gear boxes, blades and bearings), as well as higher commodity prices, particularly for steel and copper (the increase in commodity prices also affected conventional power production). Since 2009, investment costs have fallen along with commodity costs and the reversal of supply constraint trends as well as increased competition among manufacturers. All factors considered, investment price declined by 33% or more since late 2008 (Figure 5).

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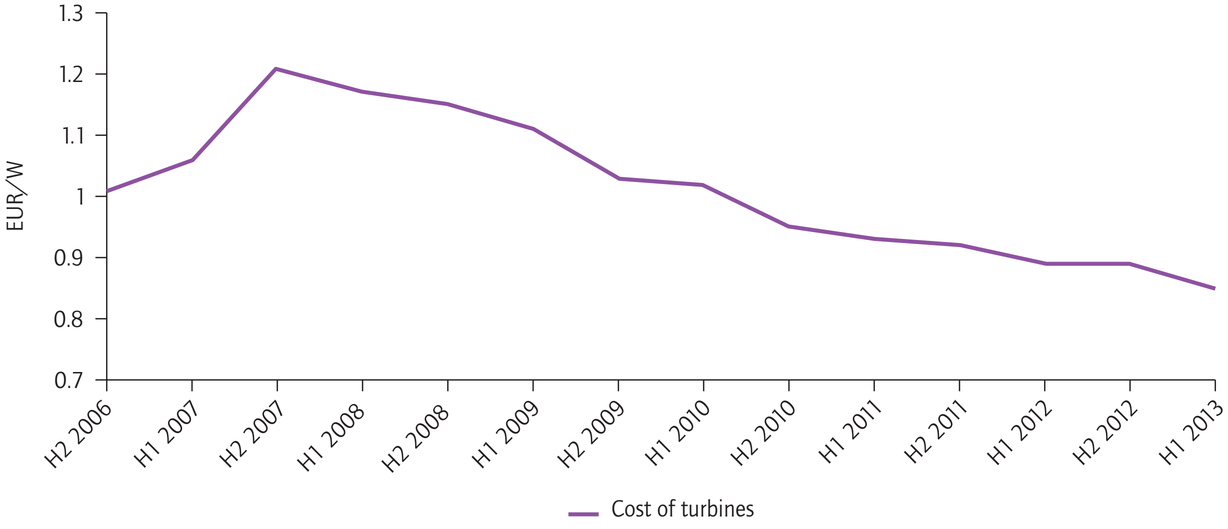
1. The LCOE represents the present value of the total cost (overnight capital cost, fuel cost, fixed and variable O&M costs, and financing costs) of building and operating a generating plant over an assumed financial life and duty cycle, converted to equal annual payments, given an assumed utilisation, and expressed in terms of real money to remove inflation.
2. The Wind IA "Task 26: Cost of Wind Energy" group has published a standard methodology to assess wind energy costs. (Schwabe *et al.*, 2011).

Figure 5: Cost trend of land-based wind turbine prices, by contract date



Note: data exclude Asian turbines.

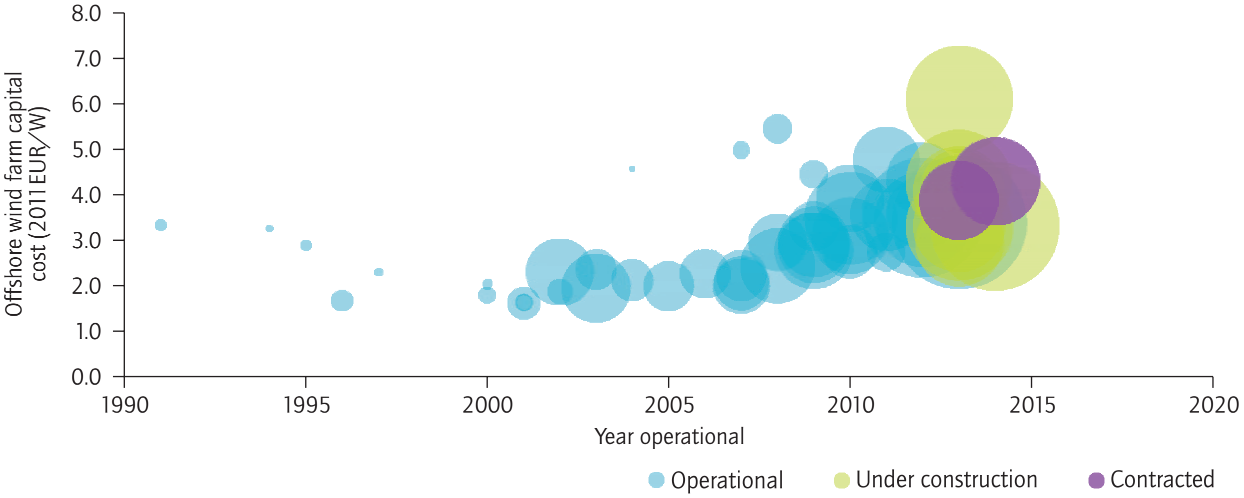
Source: Tabbush, 2013a.

KEY POINT: investment costs for onshore wind power have declined steadily since 2007.

Investment costs for offshore wind can be two to three times higher than onshore wind developments, but limited data on offshore costs make it difficult to calculate accurate estimates. It is known that in offshore projects, the turbine accounts for less than half of the investment cost, compared to three-quarters for land-based projects. Offshore projects incur additional expenses for foundation, electric infrastructure and installation costs, which vary with distance from shore and water depth. In 2008, offshore investment costs ranged from USD 3.10/W to USD 4.70/W. Costs have increased in the 2010-13 period, spanning from USD 3.60/W to USD 5.60/W (Wind IA, 2012; JRC, 2012). It should be noted that the low number is from Denmark, and does not include grid connection to the shore (Wind IA, 2012).

The investment costs of offshore wind in the United Kingdom have significantly increased since the first commercial-scale wind power plants were deployed in the early 2000s. This results from underlying cost increases, reliability concerns and deeper water sites: while earlier plants were in relatively shallow waters, most new plants since 2010 are located in water depth exceeding 20 m (Crown Estate, 2012a). Recently announced wind power plants for similar sites show that capital costs have levelled off at GPB 2.60/W to GBP 2.90/W (USD 4.00/W to USD 4.40/W) including transmission capital costs (Figure 6). This reflects several factors including a better understanding of the key risks in offshore wind construction and larger projects leading to greater economies of scale.

Figure 6: Capital costs of European offshore wind farms, by year (EUR/W)



Note: the bubble diameter is proportionate to wind farm capacity; EUR/W = EUR per watt.

Source: GL Garrad Hassan, 2013b.

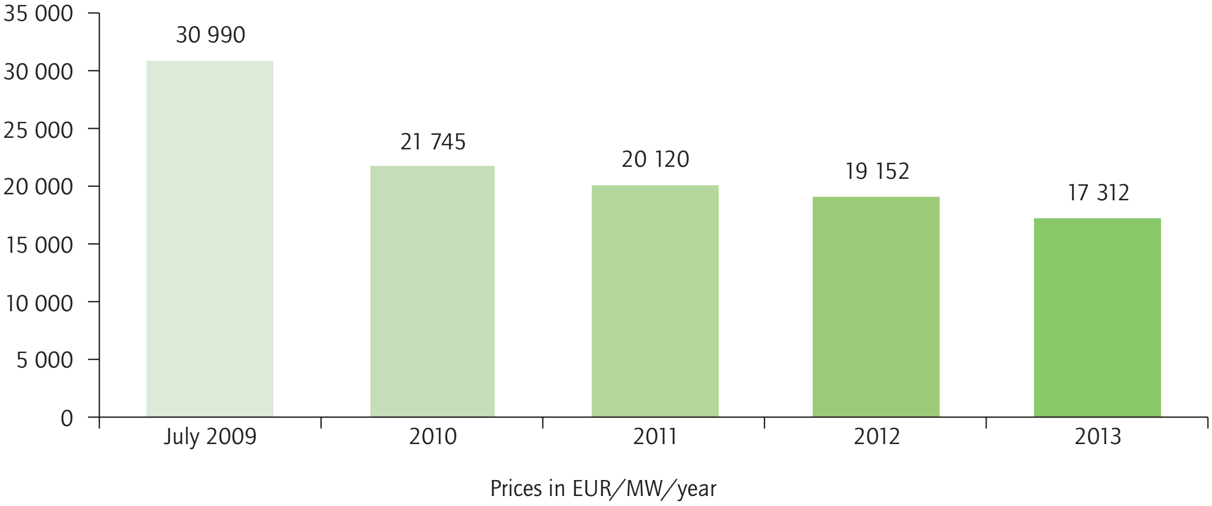
KEY POINT: while technical advances since 2008 make it possible to install in deeper water, they also drive up investment costs for offshore wind power.

O&M

The O&M costs of wind turbines represent an important component – 15% to 25% – in the cost of wind power. O&M activities typically include scheduled and unscheduled maintenance, spare parts, insurance, administration, site rent, consumables and power from the grid. Low availability of data makes it difficult to extrapolate general cost figures, as does the rapid evolution of technology: O&M requirements differ greatly, according to the sophistication and age of the turbine. Problems with electrical and electronic systems are the most common causes of wind turbine outages, although most of these faults can be rectified quite quickly. Generator and gearbox failures are less common, but take longer to fix and are more costly.

Based on recent contracts, O&M shows a 44% decrease in average prices (as EUR per MW per year [EUR/MW/yr]) from 2009 to 2013 (Figure 7). With a capacity factor of 25%, the 2013 costs for land-based would thus be EUR 7.90 per MWh (EUR/MWh) (USD 10.25/MWh). The span, however, can be large ranging from USD 5 per kilowatt hour (USD/kWh) to USD/kWh (Wiser and Bolinger, 2013). For offshore projects, O&M cost range exhibits a low of USD 20/MWh (stable since 2007), while the upper end has increased from USD 48/MWh in 2007 to USD 70/MWh (NREL, 2012).

Figure 7: Recent trends in average price for full-service O&M contracts (EUR/MW/yr)



Source: Tabbush, 2013b.

KEY POINT: O&M costs of land-based wind power have decreased by almost half since 2007.

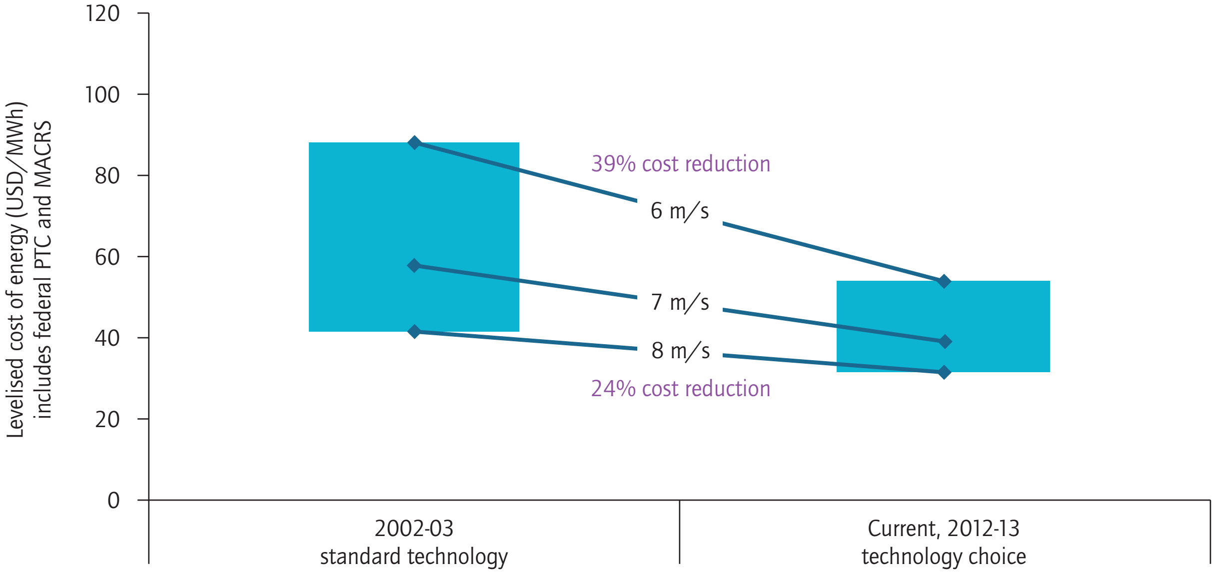
LCOE

The LCOE of wind energy can vary significantly according to the quality of the wind resource, the investment cost, O&M requirements, the cost of capital, and also the technology improvements leading to higher capacity factors.

Turbines recently made available with higher hub heights and larger rotor diameters offer increased energy capture. This counterbalances the decade-long increase in investment costs, as the LCOE of recent turbines is similar to that of projects installed in 2002/03. For some sites, LCOEs of less than USD 50/MWh have been announced; this is true of the recent Brazil auctions and some private-public agreements signed in the United States. Technology options available today for low-wind speed – tall, long-bladed turbines with greater swept area per MW – reduce the range of LCOE across wind speeds (Figure 8). More favourable terms for turbine purchasers, such as faster delivery, less need for large frame agreement orders, longer initial O&M contract durations, improved warranty terms and more stringent performance guarantees, have also helped reduce costs (Wiser and Bolinger, 2013).

Higher wind speeds off shore mean that plants can produce up to 50% more energy than land-based ones, partly offsetting the higher investment costs. However, being in the range of USD 136/MWh to USD 218/MWh, the LCOE seen in offshore projects constructed in 2010-12 is still high compared to land-based (JRC, 2012; Crown Estate, 2012b). This reflects the trend of siting plants farther from the shore and in deeper waters, which increases the foundation, grid connection and installation costs. Costs of financing have also been higher for larger deals at new sites, as investors perceive higher risk.

Figure 8: Estimated change in the LCOE between low- and high-wind-speed sites



Source: Wiser *et al*., 2012.

KEY POINT: cost of land-based wind power has fallen more rapidly at low-wind sites thanks to the use of larger rotors.

Barriers encountered, overcome or outstanding

Since the first IEA Technology Roadmap on wind power was published in 2009, stakeholders have encountered – and gained experience in addressing – several barriers that delay the deployment of wind energy and the achievement of targets set in energy policy. Permit/authorisation delays and high costs for administrative and grid connection procedures are issues in many countries. Other barriers relate to the lengthy approval of environmental impact assessments (EIAs), compliance with spatial planning, the number of parties involved, an absence of information on the grid connection capacity, a lack of planning for grid extension and reinforcements, insufficient grid capacity and land ownership. For example, the German offshore wind projects faced delays in 2011 due to financial and technical issues. Delays in grid reinforcements also led to curtailments of wind energy in China.

The permitting process for wind power plants can be complicated, long and expensive. Finding ways to simplify the process and co-ordinate among authorities can speed up considerably the building of wind power. As public acceptance is needed to avoid lengthy appeal processes, authorities need to assess safety margins to buildings, radars, roads, airports, etc., and address concerns about the presence of bats and birds (such as raptors). Still, the size of areas in which building wind power plants is forbidden has been shrinking over time, as knowledge of actual impacts improves. Some management measures – such as stopping the turbines when bird migration occurs – can also reduce negative environmental impacts and facilitate obtaining permissions to build.

Financing of wind power remains a substantial challenge, as it is relatively new territory for both companies and financial institutions. Political and regulatory stability are needed to counteract perceived high risk, particularly in times of economic crisis, when banks reduced long-term lending and have increased borrowing costs. Much discussion has explored "alternative" providers of debt (private placements, debt funds, institutional, etc.) – but so far the gap has not been closed. Efforts to make public financing available can help avoid higher cost of capital, yet is it also clear that political and regulatory instability can severely impact project viability and financing. There is evidence of market fears of government making retroactive changes to support schemes (as in Spain) or ex-post creation on taxes on existing plants, and of higher financing costs in some countries (as in India) (CPI, 2012).

Project financing is particularly challenging in the offshore wind sector, which still faces high technological and construction risks. The increasing scale and complexity of the innovative projects create a perception of higher risk, the main constraint to raising investments, but also there is a lack of capital to fulfil the growing sector needs. Funding support – grants for technology development and loans for deployment – is therefore of crucial importance. Specific measures may be needed to finance the offshore sector and avoid specific delays in:

- starting the projects and achieving financing: permitting for offshore areas may need new procedures and the establishment of public financing options; and
- grid connection: the regulator and system operators need to address future offshore plans in good time to establish planning and financing needed.

Medium-term outlook

Despite uncertainties and complications associated with the ongoing financial and economic crisis, the prospects for both land-based and offshore wind power development in the next five years remain positive (IEA, 2013).

From a global perspective, land-based wind is projected to reach an installed capacity exceeding 500 GW by 2018, despite a slow-down in 2013. China will likely have the largest cumulative capacity with a total of 185 GW, followed by the United States (92 GW), Germany (44 GW) and India (34.4 GW). Global production of land-based wind power should reach 1 144 TWh in 2018, with non-OECD countries producing over 44%, a substantial increase from less than 30% in 2012.

With strong support in some countries, offshore wind progresses significantly to 2018, but its viability over the medium term ultimately depends on tackling technical and financial challenges. By 2018, it should reach 28 GW, an impressive scaling up from 5.4 GW in 2012. Europe, led by the United-Kingdom, then Germany and Denmark, is driving much of the growth, representing almost two-thirds of total cumulative capacity by 2018. China (28%), the United States, Japan and Korea account for the rest. By 2018, offshore wind should deliver 76 TWh of electricity globally – a third of which from the United Kingdom, followed by China.

Vision for deployment and CO_2 abatement

Theoretically, wind supply could meet global energy needs several times over (Wiser *et al.*, 2011) while producing virtually no CO_2 emissions. However, the amount of wind resources that can be harvested in a cost-effective manner is currently much smaller. Although the best sites deliver the most power in relation to the level of investment, and should be developed first, the economic potential for other sites will increase over time as the technology matures, and as ways are found to increase the ability of power systems to incorporate greater wind energy production (*e.g.* through expanded transmission networks and flexibility).

CO_2 reduction targets from the *ETP 2012* Scenarios

Wind power plants installed by end 2012 are estimated to generate 580 TWh/yr of clean electricity and thus avoid the emission of about 455 $MtCO_2$/yr. In the *ETP 2012* 2DS and hiRen Scenarios (IEA, 2012a) (see Box 2), which this roadmap takes as its point of departure, deployment of wind power contributes 14% to 17% of the power sector CO_2 emissions reductions in 2050. In the scenarios, global electricity production in 2050 is almost entirely based on zero-carbon emitting energy technologies, including renewables (57% to 70%); the higher the renewable share, the lower the corresponding shares of fossil fuels with CCS (14% to 7%) and nuclear (17% to 11%). Over the complete lifecycle of wind power plants, emissions of CO_2 are negligible.

At the system level, the variable nature of wind power may require additional flexible reserves (*e.g.* combustion turbines) to respond to increased variability and uncertainty in the power system. Concerns have been expressed that this may raise the CO_2 emissions of the power sector, either as a result of cycling losses or, in the longer term and in some countries, as a result of a displacement of carbon-free but inflexible capacities (*e.g.* nuclear power in France or Germany) with flexible fossil-fuelled plants. In reality, such cycling losses are anticipated to be very small – *i.e.* less than 0.5% (GE Energy, 2012). Emission increases can be seen in some countries, but will be limited by interconnections among countries. IEA modelling scenarios indicate that related CO_2 emissions will be much less than the emission reductions achieved by wind power expansion.

Box 2: *ETP* Scenarios: 6DS, 2DS, hiRen

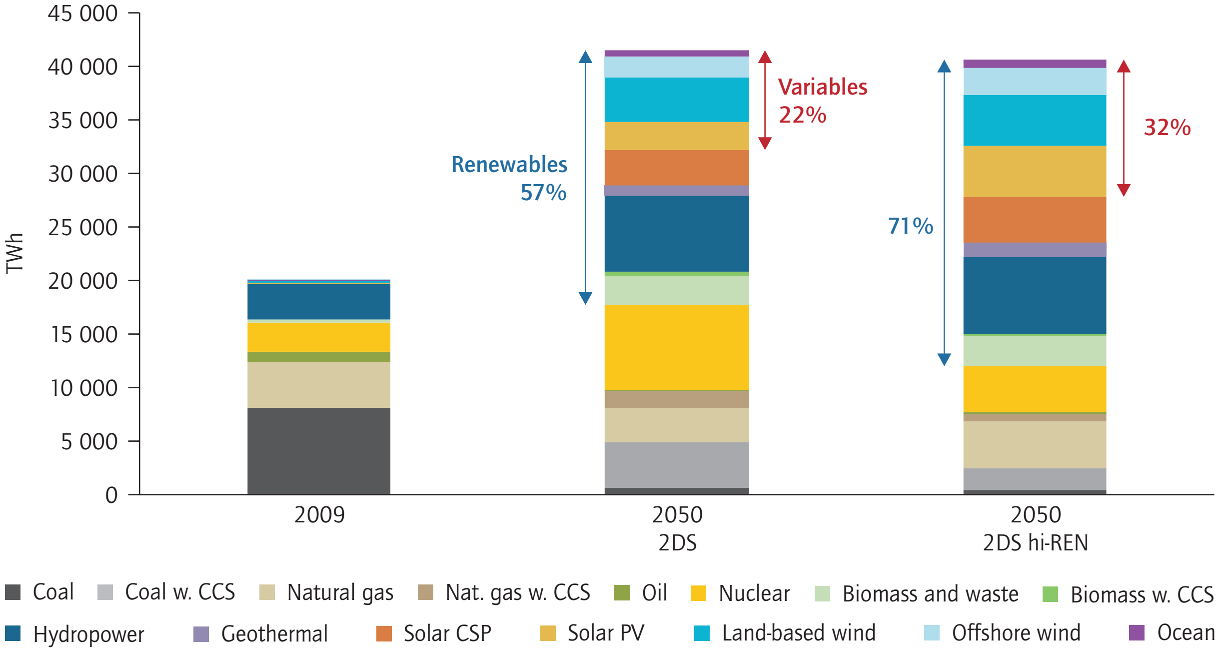
This roadmap has as a starting point the vision from the IEA *ETP 2012* analysis, which describes diverse future scenarios for the global energy system in 2050.

A Base Case Scenario, which is largely an extension of current trends, projects that energy demand will almost double during the intervening years (compared to 2009) and associated CO_2 emissions will rise even more rapidly, pushing the global mean temperature up by 6°C (the 6°C Scenario [6DS]). An alternative scenario sees energy systems radically transformed to achieve the goal of limiting global mean temperature increase to 2°C (the 2°C Scenario [2DS]). A third option, the High Renewables Scenario (hiRen Scenario), achieves the target with a larger share of renewables, which requires faster and stronger deployment of wind power to compensate for the assumed slower progress in the development of CCS and deployment of nuclear than in 2DS. This hiRen Scenario is more challenging for renewables in the electricity sector.

The *ETP 2012* analysis is based on a bottom-up TIMES[*] model that uses cost optimisation to identify least-cost mixes of energy technologies and fuels to meet energy demand, given constraints such as the availability of natural resources. Covering 28 world regions, the model permits the analysis of fuel and technology choices throughout the energy system, representing about 1 000 individual technologies. It has been developed over several years and used in many analyses of the global energy sector. Recently, the *ETP 2012* model was supplemented with detailed demand-side models for all major end-uses in the industry, buildings and transport sectors.

* TIMES = The Integrated MARKAL(Marketing and Allocation Model)-EFOM (energy flow optimisation model) System.

Figure 9: Global electricity mix by 2050 in the 2DS and hiRen scenario



Source: IEA, 2012a.

KEY POINT: renewables could provide 57% to 71% of world's electricity by 2050, of which 22% to 32% would be variable.

Wind targets revised upward compared to 2009 roadmap

To achieve the targets set out in the 2DS and hiRen Scenarios, it is necessary in this update to increase considerably the wind capacity deployment that was envisioned in 2009. Against the initial wind roadmap, the 2DS now sees a deployment of 1 400 GW in 2030 (compared to 1 000 GW) and 2 300 GW in 2050 (compared to 2 000 GW). In terms of electricity generation, the 2DS foresees 6 150 TWh in 2050 (almost a 20% increase), so that wind achieves a 15% share in the global electricity mix (against 12%).

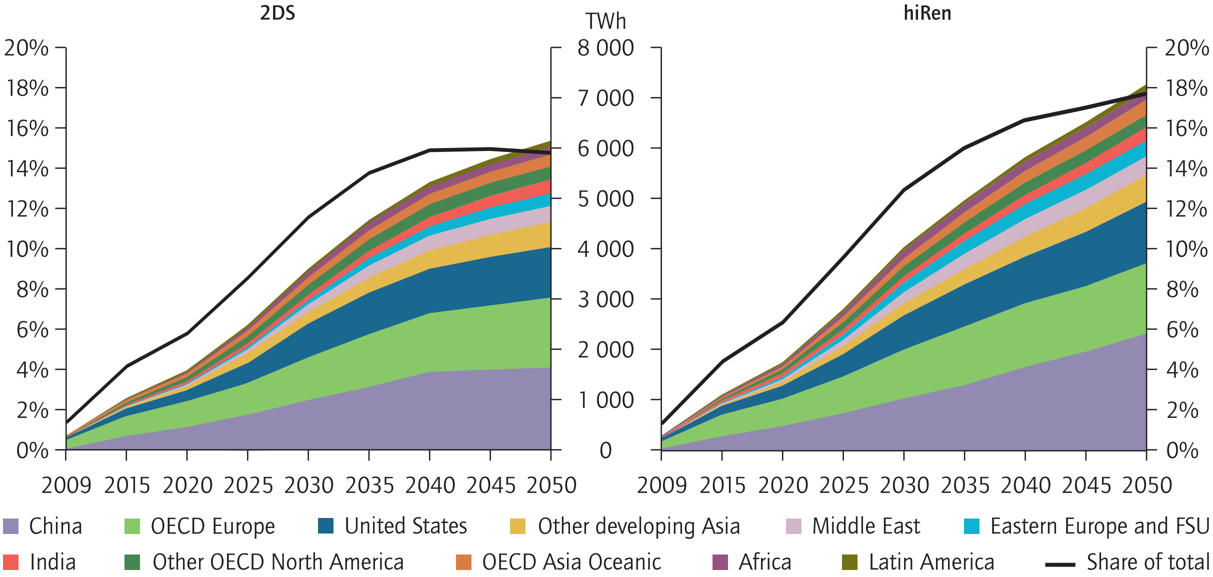
Wind capacity in the hiRen Scenario reaches 1 600 GW in 2030 and 2 700 GW in 2050, and generates 7 250 TWh, almost a one-fifth increase compared to the 2DS. In this scenario, the share of wind power in electricity generation increases to 18% in 2050. The higher penetration of wind in the hiRen is driven by a lower deployment of both CCS and nuclear power.

As offshore wind power remains more expensive, deployment is expected to take place mainly on land. Offshore will, however, provide a growing share and will increase to one-third of wind generation by 2050.

China will overtake OECD Europe as the leading producer of wind power, by 2020 in the 2DS and by 2025 in hiRen; in both cases, the United States will be the third-largest market. India and other developing countries in Asia emerge by 2020 as an important market. By 2050, China leads with 1 600 TWh to 2 300 TWh, followed by OECD Europe (1 300 TWh to 1 400 TWh) and the United States (1 000 TWh to 1 200 TWh), and then by other developing countries in Asia and the Middle East (Figure 10).

As wind penetration increases, CO_2 abatement in 2050 from wind energy under the 2DS reaches a total of 3 Gt/yr over the 6DS (see Box 2), or 4 Gt/yr if wind power was frozen at its current level (and a mix of fossil fuels being used to generate the difference in electricity). China makes the largest

Figure 10: Regional production of wind electricity in the 2DS and hiRen



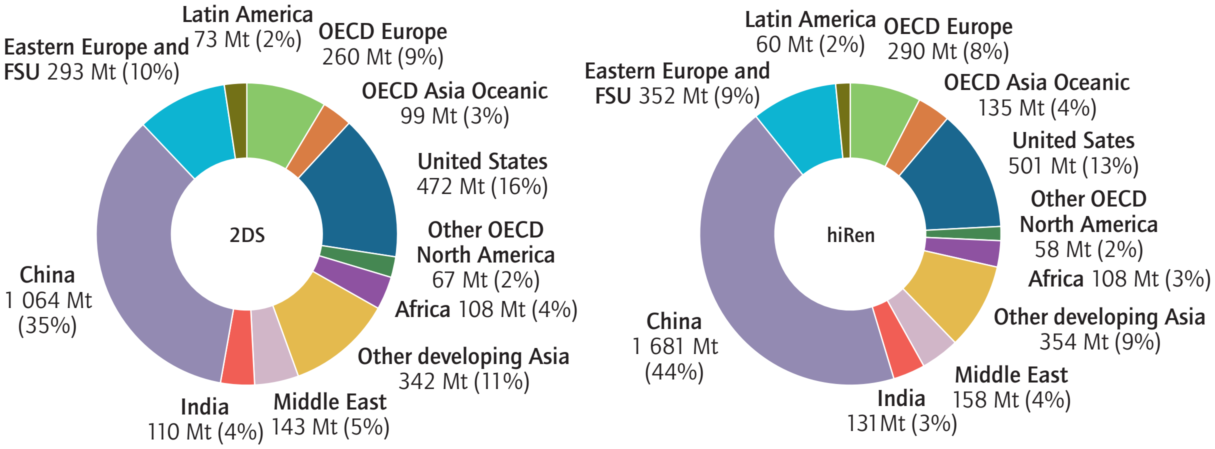
Source: IEA, 2012a.

KEY POINT: principal wind markets up to 2050 are China, OECD Europe and the United States.

contribution with 1 GtCO$_2$/yr avoided, followed by the United States at 472 Mt, and other developing Asia and Eastern Europe with 342 Mt (Figure 11).

Under the hiRen additional reductions over the 6DS reach 4 Gt CO$_2$/yr – or 4.8 Gt CO$_2$/yr if wind power was frozen at its current level.

Figure 11: Additional CO$_2$ emissions reduction in 2050 by region in the 2DS and hiRen (over the 6DS)

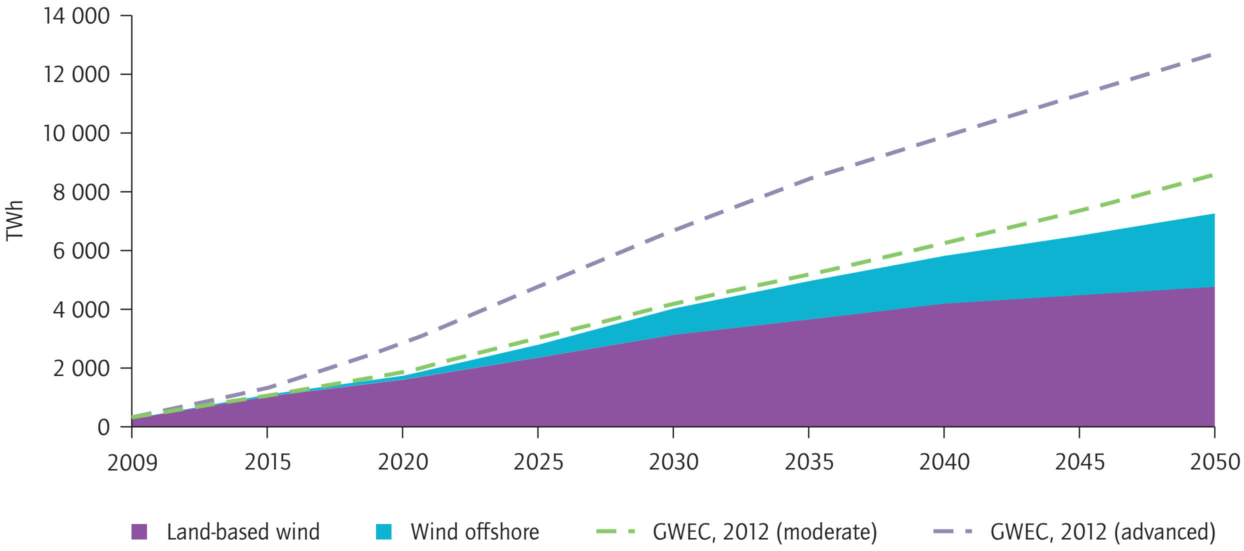


Source: IEA, 2012a.

KEY POINT: China accounts for 35% to 44% of additional CO$_2$ reductions attributed to wind power in 2050.

The wind industry suggests that production could increase even more, with deployment reaching up to 6 678 TWh from 2 500 GW capacities in 2030, and up to 12 651 TWh from 4 814 GW in 2050 (Figure 12) (GWEC, 2012). This corresponding advanced scenario would require an average annual installation rate of 250 GW, five times the present installation rate.

Figure 12: Wind electricity production in the hiRen versus industry scenarios



Sources: IEA, 2012a; GWEC, 2012.

KEY POINT: industry foresees wind electricity by 2050 as being 75% higher than in hiRen.

Potential for cost reductions

The main metric for improvements of technology is the cost for produced energy, for a certain site holding constant the quality of wind resource. This will take into account both the improvements in extraction of energy as well as in the design for producing the equipment with cost efficient material use.

The European Wind Initiative (EWI) targets competitive land-based wind by 2020 and offshore by 2030, as well as reducing the average cost of wind energy by 20% by 2020 (in comparison to 2009 levels). The cost competitiveness will depend on costs of other technologies as well, and assumes that externalities of fossil fuels are incorporated.

A compilation of trends from various publications is summarised in Wind IA Task 26 (2012) where most LCOE estimates anticipate 20% to 30% reduction by 2030.

Technology innovation, which will continue to improve energy capture, reduce the cost of components, lower O&M needs and extend turbine lifespan, remains a crucial driver for reducing LCOE (see *Wind power technology*). Larger markets will improve economies of scale, and manufacturing automation with stronger supply chains can yield further cost reductions.

Given its earlier state of development, offshore wind energy is likely to see faster reductions in cost. Foundations and grid connection comprise a larger share of total investment cost, with foundations having substantial cost-reduction potential. Greater reliability, availability and reduced O&M cost are particularly important for offshore development as access can be difficult and expensive.

The 2DS assumes a learning rate[3] for wind energy of 7% on land and 9% off shore up to 2050, leading to an overall cost reduction of 25% by 2050. Offshore

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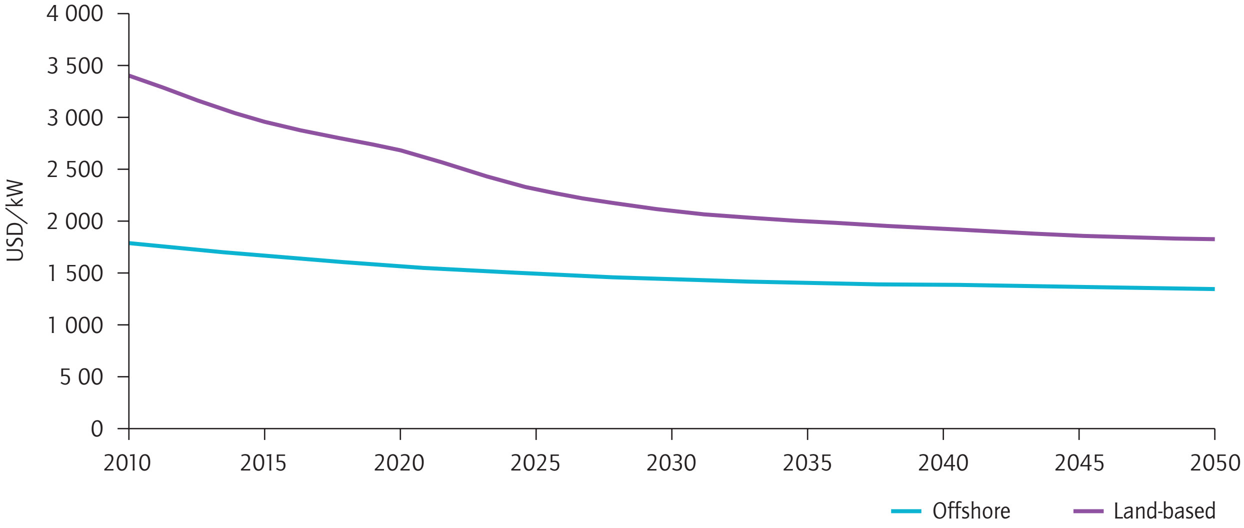
[3] Learning or experience curves reflect the reduction in capital costs achieved with each doubling of installed capacity.

investment costs are assumed to fall by 37% by 2030, and by 45% in 2050 (Figure 15). The analyses assume a 20% reduction of onshore O&M costs by 2030, rising to 23% by 2050. Larger reductions are anticipated for offshore O&M costs, of 35% in 2030 and 43% in 2050.

The cost of generating energy is expected to decrease by 26% on land and 52% off shore by 2050, assuming capacity factor increases from 26% to 31% on land and 36% to 42% off shore. All figures anticipate that improved wind turbine technology and better resource knowledge will more than offset the possible saturation of excellent sites.

Figure 13: 2DS projections for investment costs of wind turbines



Source: IEA, 2012a.

KEY POINT: investment costs for wind power would decrease by 25% on land and 45% off shore by 2050.

Global investment to 2050

Approximately USD 5.5 trillion to USD 6.4 trillion of investment will be required to reach the 2DS targets of 15% to 18% global electricity produced from wind energy in 2050. Cumulative investments in wind in the 2DS account for 15% of the total investments (USD 36 trillion) in the power sector. Close to 70% will be spent in China, OECD Europe and OECD Americas together (Table 2).

Table 2: Cumulative investment in the 2DS (USD billion)

	2010-20	*2020-30*	*2030-50*
OECD Europe	256	337	831
OECD Americas	209	455	628
OECD Asia Oceania	32	69	120
Africa and Middle East	42	173	194
China	305	385	839
India	36	38	158
Latin America	25	12	74
Other developing Asia	53	105	279
Other non-OECD	22	61	185
TOTAL	**980**	**1 635**	**3 308**

Current investment in wind power deployment is already considerable, with more and more countries getting involved: USD 76.560 billion of new investment was reported in 2012 (Liebreich, 2013). The 2DS scenarios project the sector to grow from 282 GW of installed capacity at the end of 2012 to between 2 346 GW and 2 777 GW in 2050. This would require the annual new capacity installed to grow from 45 GW in 2012 to 56 GW/yr to 65 GW/yr on average for the next 38 years, or up to 93 GW/yr taking into account repowering. On average, annual investments should double to between USD 150 billion and USD 170 billion.

Wind technology development: actions and time frames

Increased efforts in wind technology R&D are essential to realising the vision of this roadmap, with a main focus on reducing the investment costs and increasing performance and reliability to reach a lower LCOE. Good resource and performance assessments are also important to reduce financing costs.

Wind energy technology is already proven and making progress. No single element of onshore turbine design is likely to reduce dramatically the cost of energy in the years ahead. Design and reliability can be improved in many areas, however; when taken together, these factors will reduce both cost of energy and the uncertainties that stifle investment decisions. Greater potential for cost reductions, or even technology breakthrough, exists in the offshore sector.

Actions related to technology development fall into three main categories:

- **wind power technology**: turbine technology and design with corresponding development of system design and tools, advanced components, O&M, reliability and testing;
- **wind characteristics**: assessment of wind energy resource with resource estimates for siting, wind and external conditions for the turbine technology, and short-term forecasting methods;
- **supply chains, manufacturing and installation issues**.

In light of continually evolving technology, continued efforts in standards and certification procedures will be crucial to ensure the high reliability and successful deployment of new wind power technologies. Mitigating environmental impacts is also important to pursue.

This roadmap draws from the Wind IA *Long-term R&D Needs* report, which examines most technology development areas in more detail (Wind IA, forthcoming).

Wind power technology

Cost reduction is the main driver for technology development but others include grid compatibility, acoustic emissions, visual appearance and suitability for site conditions (EWI, 2013). Reducing the cost of components, as well as achieving better performance and reliability (thereby optimising O&M), all result in reducing the cost of energy.

System design	*Time frames*
1. Wind turbines for diverse operating conditions: specific designs for cold and icy climates, tropical cyclones and low-wind conditions.	Ongoing. Commercial-scale prototypes by 2015.
2. Systems engineering: to provide an integrated approach to optimising the design of wind plants from both performance and cost optimisation perspectives.	Ongoing. Complete by 2020.
3. Wind turbine and component design: improve models and tools to include more details and improve accuracy.	Ongoing. Complete by 2020.
4. Wind turbine scaling: 10 MW to 20 MW range turbine design to push for improved component design and references for offshore conditions.	Ongoing. Complete by 2020-25.
5. Floating offshore wind plants: numerical design tools and novel designs for deep offshore.	Ongoing. Complete by 2025.
Advanced components	***Time frames***
6. Advanced rotors: smart materials and stronger, lighter materials to enable larger rotors; improved aerodynamic models, novel rotor architectures and active blade elements.	Ongoing. Complete by 2025.
7. Drive-train and power electronics: advanced generator designs; alternative materials for rare earth magnets and power electronics; improved grid support through power electronics; reliability improvements of gearboxes.	Ongoing. Complete by 2025.
8. Support structures: new tower materials, new foundations for deep waters and floating structures.	Ongoing. Complete by 2025.
9. Wind turbine and wind farm controls: to reduce loads and aerodynamic losses.	Ongoing. Complete by 2020-25.

O&M reliability and testing	*Time frames*
10. Operational data management: develop standardised and automated wind plant data management processes; build shared database of offshore operating experiences.	Ongoing. Complete by 2015.
11. Diagnostic methods and preventive maintenance: develop condition monitoring, predictive maintenance tools and maintenance practices, especially off shore.	Ongoing. Complete by 2015.
12. Testing facilities and methods: develop advanced testing methods and build facilities to test large components.	Ongoing. Complete by 2020.
13. Increase technical availability: target for offshore turbines to current best-in-class of 95%; minimum O&M requirement for remote locations.	Ongoing. Complete by 2020-25.

System design

Moving towards specific **wind turbines for diverse operating conditions** requires deeper understanding of the conditions in which a wind power plant will operate over its lifetime. The aim is to develop more cost-effective turbine designs with the ability to extract more energy from the wind, over a longer lifetime and in specific operating environments. Wind turbine manufacturers planning to offer so-called "cold climate packages" will need to use special materials and components, including specialised measurement systems, heaters or pre-heaters for components and subsystems, and even nacelle heating to allow comfortable turbine maintenance. Anti- or de-icing systems for blades most often use electro-thermal heating elements. Special foundations may be needed in permafrost.

System design needs tool development to minimise loads across the components to optimise for specific conditions including offshore, cold and icy climates, tropical cyclone climates and low-wind speeds. Improving model tools requires measurement campaigns both in the field and in controlled test facilities.

Optimising power-to-swept area ratios is important to achieve lowest LCOEs, especially at low-wind-speed sites (Molly, 2012). If this optimisation includes connecting costs it may lead to different results,[4] as the reduction in connection costs might be important, especially for offshore wind farms far from shore. Also, the reduced variability offered by the weaker turbines is likely to facilitate the handling of large shares of wind power in the electricity mix.

R&D targets for **up-scaling to 10 MW to 20 MW turbines** will push the technology towards new solutions, which may help reduce costs for the 2 MW to 5 MW turbine size (seen as sufficient for most applications). Optimum size for both land-based and offshore applications is still to be solved (EWI, 2013). Further enlargement of land-based turbines is limited by logistics constraints as well as sound and visibility regulations. Offshore up-scaling will bring more direct benefits. A comprehensive evaluation by the UpWind Project (funded by the European Union) found a 20 MW turbine technically feasible, with need for significant advances in materials, design architectures, controls capabilities and other factors (UpWind, 2011). Achieving the vastly larger turbines expected in future generations will require new R&D and innovations to offset or mitigate the mass increases that would be assumed from classical scaling-up theory (Figure 14).

Advanced components

Advanced rotors, with larger swept area and higher reach, provide greater energy capture and have already reduced the cost of wind energy. As rotors become larger with longer, more flexible blades, a fuller understanding of their behaviour during operation is required to inform new designs. Noise reduction technologies are important to increase the amount of land available for wind projects. Other promising technologies can be developed to improve blade pitch control and advance blade bearing and pitch systems and hub design, materials and manufacture.

Drive-train component improvements can be realised through a comprehensive optimisation of the whole turbine. Increased controls, through **power electronics**, can reduce loads and material intensity. Hydraulic drive-train designs, in which a

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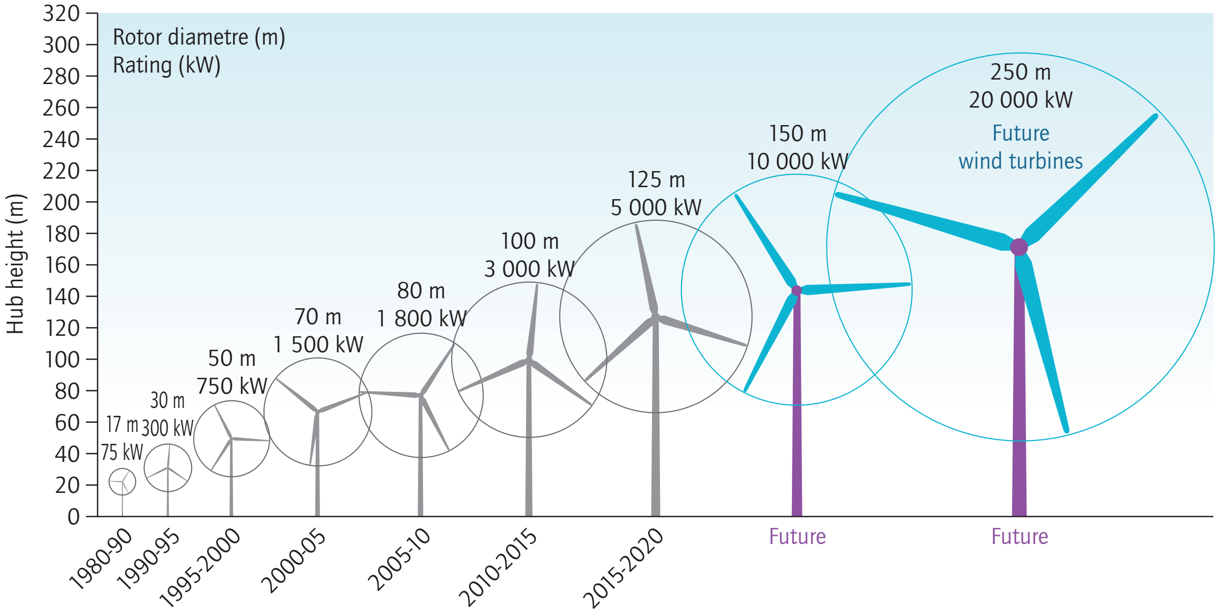
[4] Consider, for example, a "strong" turbine of specific power (relative to the swept area) of 530 W/m^2, assuming on a given site a capacity factor of 32.4%. On the same site, a "weak" turbine of only 294 W/m^2 will have a capacity factor of 48.9%. For same swept areas, the weak turbine will generate only 83.7% of the electricity of a strong turbine, but will require a connecting line of only 55.5% of the capacity of that needed for the strong turbine (Molly, 2011).

Figure 14: Growth in size of wind turbines since 1980 and prospects



Source: adapted from EWEA, 2009.

KEY POINT: scaling up turbines to lower costs has been effective so far, but it is not clear the trend can continue forever.

hydraulic system replaces the mechanical gearbox, are also a possibility. Continued development of larger and greater turbine capacities will necessitate higher capacity power electronics and enhanced grid support capabilities from wind power plants. Lower cost power conversion is expected from deployment of higher voltage power electronics (UpWind, 2011).

Box 3: Abundance of rare earths

Rare earth oxides (REOs) are used in many modern devices such as catalytic converters, LCD screens, rechargeable batteries, and wind turbine generators (about 20% of them, whether geared or direct drive) that use permanent magnets. These generators are more compact, more efficient, and require less maintenance, which is especially important off shore.

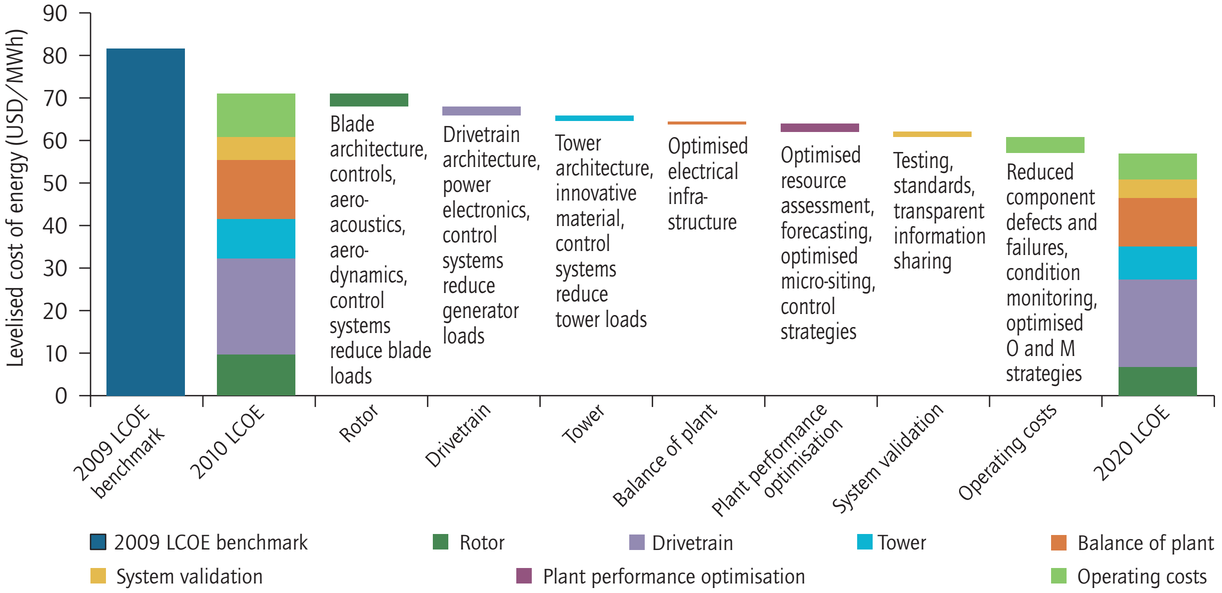
Fears have been expressed that scarcity of REOs may impede large-scale deployment of wind power. However, known reserves are estimated to represent 1 000 years of supply at current consumption levels (USGS, 2013). In fact, prices for the neodymium oxide used to produce magnets dropped from USD 195/kg to USD 80/kg during 2012 – a trend which does not suggest imminent scarcity. Extrapolations show that the wind power industry will continue to represent less than 1% of the global demand. The real issue is that 95% of current REO production occurs in China, which restricts exports but has only 30% of the world’s known reserves. Mining projects are currently being considered in more than 20 countries, and research is underway for alternative materials in many applications.

Support structures could benefit from advances in material research that might further reduce costs. Materials with higher strength-to-mass ratios (*e.g.* carbon fibre and titanium) could enable larger area rotors, lighter generators and other drive-train components, thereby reducing tower head mass. New materials could also provide solutions for taller towers and reduce the dependence of permanent magnet generators on rare earths. As turbines approach 10 MW, direct-drive superconducting generators may offer potential to lower mass and size, while also providing the reliability benefits of direct-drive platforms (Abrahamsen *et al.,* 2010).

Wind turbine and wind farm (*i.e.* plant-wide) controls are an important area for cost reduction in wind power. Industry is currently undergoing a transformation to optimise at the plant level, with individual turbines viewed as components that can be designed and operated for specific locations within the plant as a whole. Turbine-mounted Lidar (Light and radar) will be used to inform turbines of changes in wind speed, direction and turbulence, making it possible to optimally position turbines (and pitch blades) as changes occur in the approaching wind. Such capabilities offer the dual benefit of enhanced performance and reduced fatigue loads (UpWind, 2011).

All these improvements could drive about 20% cost reduction of the lcoe of land-based wind power by 2020 (Figure 15).

Figure 15: Target for cost reductions of land-based wind power in the United States



Source: US DOE, 2013.

KEY POINT: incremental progress on many fronts can reduce land-based wind power costs.

Special considerations for offshore development

Offshore challenges: the design of offshore turbines for distant offshore installations will continue to deviate from that of land-based turbines, with less focus on issues such as flicker, sound and aesthetics. Continued turbine scaling will remain critical for offshore technology, as it has already resulted in lower balance of plant and operations costs while simultaneously increasing energy capture.

The interaction of the marine atmosphere and sea waves, which places different loads on various parts of the wind turbine and its foundation, requires continued attention. As long as the real requirements of wind technology in offshore conditions remain insufficiently understood, conservative design practices – adopted from other offshore industries – are likely to be used for turbine design (Wiser and Bolinger, 2012).[5]

Offshore turbines could adopt a design other than the mainstream three-blade concept, *e.g.* two blades rotating downwind of the tower. Improved alternative-current (AC) power take-off systems or the introduction of direct-current (DC) power systems are also promising technologies for internal wind power plant grid offshore and connection to shore. Changes in design architecture and an ability to withstand a wider array of design considerations including hurricanes, surface icing, and rolling and pitching moments, are also likely to be needed.

In total, the US DOE expects a 40% reduction in the cost of electricity generated by offshore wind by 2030; the UK Crown Estate foresees similar reductions for wind projects to be decided as early as 2020 (2013b; Crown Estate, 2012b). The Crown Estate expects cost reductions from areas such as competition and installation, with the largest savings (17%) from turbine changes (Figure 16 and Box 4). Of this, increase in rated power accounts for nine percentage points, as it reduces capital costs by as much as 4% to 5%, operating costs by 10% to 15%, and increases annual energy production by up to 5%.

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[5] Assessment of a number of shallow, transitional, and deep-water offshore concepts is ongoing in the IEA Wind Task 30 Offshore OC4 group.

Box 4: UK projections for offshore cost reductions

In the United Kingdom, the government-owned Crown Estate manages all offshore sites. The Renewables Roadmap target is to cut the cost of wind power to GBP 100/MWh (USD 150/MWh) and install 18 GW capacity off the UK coasts by 2020.

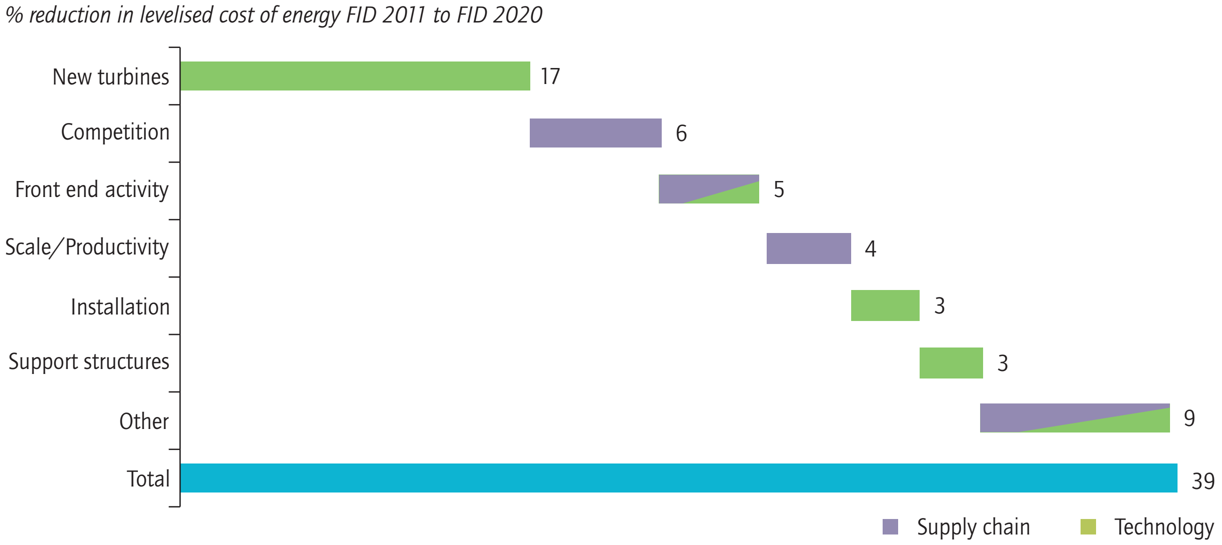
All parts of the supply chain will need to play their roles in building the industry and bolstering innovation to drive down the cost of energy in line with the seven areas identified by the roadmap:

- introduction of larger turbines with higher reliability and energy capture and lower operating costs;
- greater competition in key supply markets (*e.g.* turbines, foundations and installation) from within the United Kingdom, Europe and East Asia;
- greater activity at the front end of projects, including early involvement of suppliers and improved wind farm design;
- economies of scale and standardisation;
- optimisation of installation methods;
- mass-produced, standardised deep water foundations;
- lower costs of capital through de-risking construction, and O&M.

As cost reductions require a larger market, predictability and permanence of the market is needed to achieve maximum results. Wind farm developers and suppliers must work together to deliver continuous, end-to-end cost and risk reduction. Managing a pipeline of projects, rather than working project by project, will help to drive down cost.

The cost of capital is a key driver of LCOE for offshore wind plants. A drop of one percentage point in the weighted average cost of capital (WACC) reduces LCOE by about 6%. As the offshore industry gains experience, key risks (*e.g.* installation costs and timings, turbine availability, and O&M costs) will be better managed, and the overall risk profile of offshore projects will decline, thereby lowering the returns sought by capital providers. Moving to products specifically designed for offshore wind and industrialising the supply chain provides multiple opportunities to reduce capital and operating costs and increase power generation (Crown Estate, 2012b).

Figure 16: Cost-reduction potential of offshore wind power plants, United Kingdom



Source: Crown Estate, 2012b.

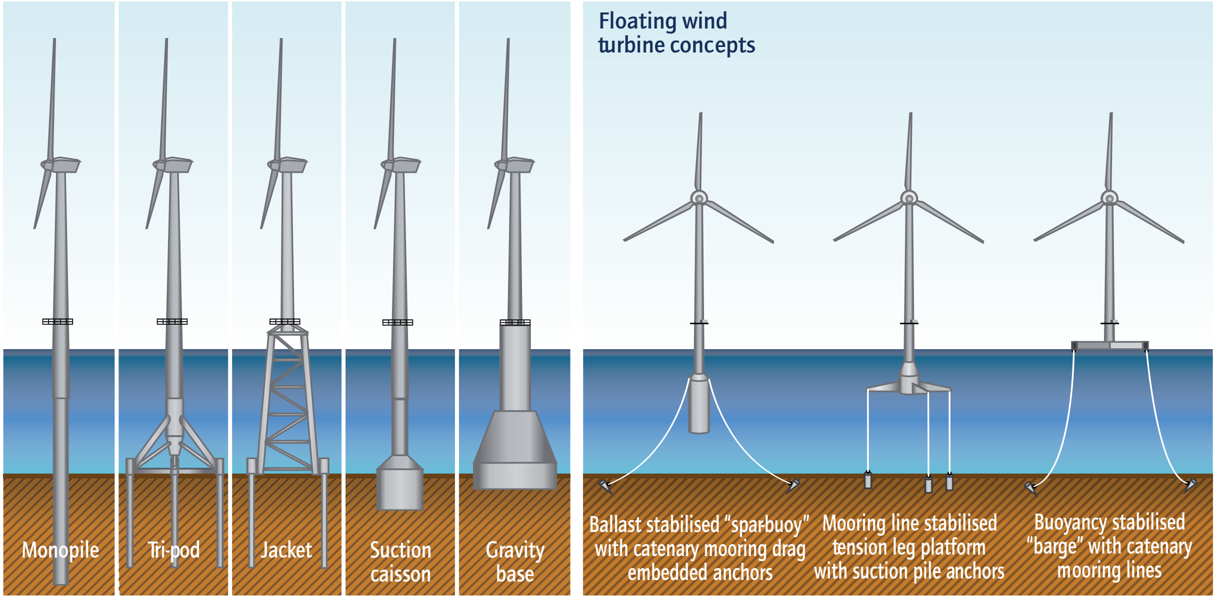
KEY POINT: progress all along the value chain can reduce the cost of offshore wind power.

The monopile's relative simplicity and low labour requirements make it an attractive platform, but the combination of diverse seabed conditions, deeper water and larger turbines will push the development for innovative alternatives such as jackets, tripods, gravity-based structures and suction caissons (Figure 17). Composite towers and foundations might offer greater corrosion protection, while integrated concrete and steel hybrid structures or entirely concrete structures might also deliver benefits (Navigant, 2013b).

Clearly, a sizable offshore wind resource can be developed with the fixed-bottom foundation technologies. Floating offshore foundations, by contrast, offer the potential for less foundation material, simplified installation and decommissioning, and additional wind resource at water depths exceeding 50 m to 60 m. Two recent first demonstrations show good performance: Hywind, a 2.3 MW prototype operating off the Norwegian coast since 2009; and US/PT, a 2 MW prototype off the Portuguese coast since 2011. Five floating turbines in Portugal received EU funding to be constructed by 2015.

The long-term cost implications of moving to floating offshore platforms are not yet clear; years of rigorous design and testing will be needed before these technologies are commercially viable. New tools will be required to capture the design criteria, which include the need to address weight and buoyancy requirements as well as the heaving and pitching moments created by wave action. Current floating concepts include the spar buoy, the tension leg platform and the buoyancy-stabilised semi-submersible platform (Figure 17). Vertical-axis turbines, which disappeared from land, may have a second chance at sea. Although they have a higher material need to cover same swept areas and have some dynamical structural issues, their lower centre of gravity and fewer parts may be suitable in offshore wind. Vertimed, an EU-funded project led by EDF-Energies Nouvelles with Nenuphar and Technip, aims to install thirteen vertical-axis wind turbines of 2 MW off Fos-sur-Mer in the French Mediterranean waters by 2017.

Figure 17: Fixed-bottom foundation and floating offshore concepts



Source: Wiser *et al.*, 2011.

KEY POINT: diverse concepts are being tested for offshore turbines.

O&M reliability and testing

Operational data management can facilitate faster and less costly O&M. High access costs to offshore turbines, often coupled with narrow weather windows, make reliability a high priority. Minimal on-site O&M can be achieved by equipping turbines with system redundancy while applying remote, advanced condition monitoring and self-diagnostic systems can reduce the duration and frequency of onsite repairs. Offshore turbine designs that create new access opportunities, potentially allowing repairs under more diverse weather and sea conditions, are also important.

Reliability and other operational improvements would be accelerated through greater sharing of operating experience among industry actors, including experiences related to other marine technologies such as wave and ocean current technologies. A database of operating experiences, currently being developed in Germany, has stimulated wider, international research co-operation. A way should be sought to make operational data available through a shared database, while taking into account commercial sensitivities. Development of public databases may need "push" from R&D funding organisations and government; *e.g.* granting of subsidies could be linked to required reporting of operational experience.

Diagnostic methods and preventative maintenance offer the possibility to use corrective maintenance with more regular and effective measures that can help to minimise unplanned maintenance – a critical factor in driving down operations expenditures. Technological advances in condition monitoring and more experience identifying failure indicators are expected to increase efficiency in diagnosing and finding appropriate mitigation in advance of failures. Advanced condition monitoring techniques might include self-diagnosing systems, real-time load response, and the ability to manipulate and control individual turbines from an onshore monitoring facility. Co-ordinating preventative maintenance efforts with improved wind and weather forecasting should allow operators to minimise turbine production losses (US DOE, 2012).

Long-term options

To date, concepts to replace the current two-to-three-bladed horizontal axis turbine have fallen short in terms of cost-effectiveness and technical reliability.

Future research is likely to explore airborne options. Kites might transmit mechanical energy to land-based generators, or fully fledged “flying machines” such as tethered autogyres with rotors run by the wind that provide both lift and power generation. Google recently bought Makani Power, a start-up that specialises in developing such devices. High-altitude winds are known to be very good and constant resources, routinely used by pilots to save time and fuel on eastbound circumpolar flights. Their potential has been said to be considerable (Archer and Caldeira, 2009), but other scientists see a greater potential for environmental perturbation than for electricity generation (see *e.g.* Miller, Gans and Kleidon, 2011).

While technologies to get electricity from offshore winds have been developing, use of winds in maritime transportation disappeared after having served mankind for centuries (except for leisure and some small fishing activities). An array of new or modernised technologies (*e.g.* automated sails and kites) can save fuel and emissions in maritime transportation, either through direct mechanical energy or through electricity generation or both (see *e.g.* Fagiano *et al.*, 2012). A full description of these still immature options is beyond the scope of this roadmap.

In the future, innovative combinations of renewable energies and storage options could prove to be cost-effective. There is strong interest in the energy island proposed in the Netherlands, which will combine wind power, pump-storage and potentially tidal power (IEA, 2012b). Other options would tie individual submarine pumped storage systems with offshore turbines (see, *e.g.,* Slocum *et al.*, 2013).

Wind characteristic assessment

Accurate assessment of wind characteristics is needed for choosing the right turbines for given sites and selecting the specific locations for turbines within a wind farm (micro-siting). More precise measurements and modelling of external conditions (*e.g.* climate) can significantly enhance the turbine design process. Ultimately, efforts in both areas contribute to more precise power production forecasts, whether five days or five minutes ahead.

One risk factor that influences investments in wind power relates to the anticipated output from a given plant with turbines located over many square kilometres. Better understanding of the numerous uncertainties in current wind resource assessment processes could result in lower financing costs. Both models and measurements are needed to estimate the long-term average wind resource and the turbine output: measurements offer precision and allow benchmarking models, which offer depth in both time and space.

Resource assessment and siting

Regional wind atlas and databases, based on models that try to capture the wind resource for a certain grid cell, offer a starting point. Such atlases are already used for potential analyses when setting targets for deployment and regional planning. They can also help wind developers to find the best sites for projects, but more detailed modelling and measurements are needed for actual investments.

A shared database of information on the availability of wind resources in all countries with significant deployment potential would greatly facilitate the development of new projects. Many countries have already published wind atlas maps and detailed data, including measurements, would also be valuable to share, but commercial sensitivity concerns need to be addressed. Resource data are particularly sparse in developing countries and for wind at heights above 80 m and off shore. The database should include details of wind variability, average speeds, wind shear, turbulence and extreme speeds. Ideally, it would also link to other databases of the solar resource, site topography, air temperature, lightning strikes and seismic activity, as well as off shore relevant external conditions. The International Renewable Energy Agency (IRENA), in collaboration with the Clean Energy Ministerial (CEM) Multilateral Wind and Solar Working Group, recently posted an online compilation of resource data for wind.[6]

As turbines become taller, it becomes more costly to acquire measurements using standard anemometry masts – particularly off shore. **Remote sensing** using sonic detection and ranging (Sodar) or light

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[6] www.irena.org/globalatlas.

Resource assessment and siting	***Time frames***
1. International wind atlases: develop publicly accessible databases of land-based and offshore wind resources and conditions.	Ongoing. Complete by 2015.
2. Remote sensing techniques: high spatial resolution sensing technology and techniques for use in high-fidelity experiments and siting wind power plants.	Ongoing. Complete by 2015.
3. Siting optimisation of turbines in a wind power plant: develop tools based on state-of-the-art models and standardised micro-siting methods; refine and set standards for modelling techniques for wind resource and micro-siting.	Ongoing. Complete by 2020.
4. Measurement campaigns and model improvement for multi-scale complex flow: improve understanding of complex terrain, offshore conditions and icy climates; develop integrated models linking large-scale climatology, meso-scale meteorological processes, micro-scale terrain and wind farm array effects.	Complete by 2025.
Assess conditions to improve turbine design	***Time frames***
5. Measurement campaigns and model improvement for turbine rotor inflow: experimentation to couple blade loading conditions to rotor inflow, including computational fluid dynamics and wake effects.	Complete by 2020.
6. Marine environment design conditions: design case development for complex interactions among wind, waves, turbulence and current, including handling of extreme conditions such as typhoons and icing.	Complete by 2025.
Improve short-term forecasting accuracy	***Time frames***
7. Wind forecasts: meteorological wind forecasts, with feed-back loop from wind power plant online data to weather forecasting.	Complete by 2020. Weather forecasting takes input data from wind power plants.
8. Power production forecasts: for use in power system operation, with storm and icing forecasts.	Complete by 2020.

and radar (Lidar) technologies, and computational fluid dynamics (CFD) techniques to model air flow, have recently been developed but still need validation especially for complex terrains.[7] Remote sensing is also a future option in turbine nacelles to improve the control of turbines.

Siting optimisation of wind turbines in a plant could help address the wake effect (*i.e.* the influence of one turbine on the airflow incident on another turbine), one of the more poorly understood phenomena in wind power. Wake effect is particularly significant off shore, where wind power plants comprise hundreds of turbines, and can reduce energy capture by as much as 10% while often increasing structural loading and O&M costs.[8] Future research is critical to improve micro-siting and increase the lifespan of the turbines, as is validation of wake models. Reducing array losses and optimising plant layout by modelling the wake effect can improve total wind power plant efficiency.

Efforts are underway to standardise methods for **measurement campaigns and computer modelling** of the resource, on-site measurement and data gathering. Uncertainty remains highest for new types of sites, such as off shore, complex and forested terrains, and those with icy conditions.[9] Additional work is needed to develop measurement and modelling techniques, and to standardise best practices. Improving the models further requires measurement campaigns in diverse terrains; to achieve multi-scale models for complex flow, it will be necessary to combine regional and micro-siting models.

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[7] The Wind IA Task 11 has recently published recommended practices using SODAR and LIDAR to assess the wind resource.

[8] Work for a new IEC standard on wind plant siting IEC 61400-15 has started in 2013.

[9] The Wind IA Task 19 Wind Energy in Cold Climates has published Recommended Practices and State-of-the-art reports including also measurements http://arcticwind.vtt.fi/.

Assess conditions to improve turbine design

Measurement campaigns to improve models for turbine rotor inflow are needed to improve knowledge about turbine loading. Coupling blade loading conditions to rotor inflow requires use of CFD and modelling of wake effects. Improving accuracy of external meteorological conditions more broadly is vital to better turbine design. More precise estimates of extreme winds, for example, can reduce the uncertainty of loads for turbines. Moreover, understanding wind characteristics at specific locations within the wind farm can support selection of turbines to the site and optimise turbine design for operations within that plant, using full plant control algorithms (instead of single machine controls) to optimise the output of the whole plant.

For offshore, work is needed on **marine environment design conditions** to improve understanding of the complex interactions among wind, waves, turbulence and current conditions and apply such learning to better turbine design. Knowledge of extreme conditions, such as typhoons or icing, will be important for certain sites.

Improve short-term forecasting accuracy

Improving the accuracy of **short-term wind forecast** is needed for the operation of wind power plants, especially for electricity markets and the power system. Better predictability of wind resources will help producers meet delivery commitments, thereby increasing the economic value of wind-generated electricity in the power market. Forecasts will enable the power system to schedule and dispatch other power plants as cost effectively as possible, and to ensure adequacy of balancing reserves in real-time operation.

Improved accuracy of **power production forecasts** on various time scales will support power system operation and enable wind power producers to act in electricity markets. Depending on market gate closure times and system operation practices, time scales of one to two days ahead, four to eight hours ahead and one to two hours ahead can be used.[10] In the future, forecast accuracy will allow wind power producers to operate also in the system (ancillary) services markets and offer balancing services.

Supply chains, manufacturing and installation

Rapid growth rates of wind energy have given rise to occasional bottlenecks in supply of key components, including labour. Supply chain complexity for onshore wind has increased with the deployment of higher towers and larger blades, and supply chain readiness is a particular issue for offshore wind. Strong supply chains will provide stability and predictability for investors.

Manufacturing and installation	***Time frames***
1. Advanced manufacturing methods: accelerate automated, localised, large-scale manufacturing for economies of scale, with an increased number of recyclable components.	Ongoing. Continue over 2013-50 period.
2. Offshore installation and logistics: make available enough purpose-designed vessels; improve installation strategies; make available suitably equipped large harbour space.	Sufficient capacity by 2015.
3. Develop workforce: develop curricula for wind workforce in industry and academia.	Ongoing. Continue over 2013-50 period.

Advanced manufacturing methods offer pathways to increase manufacturing efficiency. Strategies such as improvements in serial production and automation, and in locating factories nearer to installation sites can reduce transport costs and import taxes, and provide more efficient means of turbine delivery.

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[10] In the United States, several large power markets are very effectively integrating wind into real-time markets using forecasts that are within ten minutes ahead, taking advantage of much lower wind forecast errors.

Economies of scale and cost reductions from actual project deployment are anticipated when projects can be delivered at a quicker pace. At present, severe supply chain pressures are seen in the offshore market segment. Governments should consider support for testing, manufacturing and assembly processes located in specially designed harbours in the vicinity of resource-rich areas (as in the Bremerhaven area development in Germany). Cross-country co-operation on project installation and grid development may also trigger more R&D co-operation in this area.

Rising steel prices affect the entire supply chain; bottlenecks for cabling have contributed significantly to delays for offshore wind projects in Germany.

Depending on weather and local conditions, **installation and logistics of offshore turbines** can be a costly and iterative process, constrained to defined periods by nature protection (*e.g.* breeding animals in spring and summer) and strict weather windows. Staging, assembly, transport and installation account for a substantial fraction of offshore wind costs. Installation vessels (*e.g.* jack-up barges and lifting equipment) are costly and more will be needed to meet demand. Co-operative measures such as sharing vessels between projects could help. Significant upgrades are needed in ports that were not designed for the offshore wind industry.

To lower costs, installation strategies need to reduce the amount of work done at sea or with large cranes. To reduce O&M costs, sufficiently robust access systems for staff could widen the current weather windows.

A large, skilled workforce is needed to develop new designs, establish new manufacturing plants in new locations, develop installation technologies, and to build, operate and maintain wind power plants. The EU Wind Technology Platform estimates a gap of 18 000 qualified staff entering the European wind energy workforce in 2030, if the rate of graduation from industry-relevant courses is not increased (TPWind, 2013). The nature of this shortage changes over time to become dominated by a lack of qualified O&M personnel.

Governments and state/province authorities could help establish the necessary education and training activities. For example, the American Recovery and Reinvestment Act (ARRA) designated USD 500 million for projects that prepare workers for careers in energy efficiency and renewable energy (US DOL, 2010). In Europe, the European Academy of Wind Energy hub links several training programmes provided by centres of excellence at specific universities. In the United Kingdom, the Renewables Training Network facilitates the transition of professionals from other sectors into the offshore wind industry. A Talent Bank project, hosted by EU Skills, is designed to make it easier for businesses to access and organise apprenticeship schemes.

System integration: actions and time frames

Effective mechanisms for integrating wind power into transmission grids are a key challenge for achieving this roadmap's goals. Specific actions are needed to promote transmission grid development and to improve the operation of power systems.

Transmission planning and development

Improve transmission development	*Time frames*
1. Develop long-term interconnection transmission infrastructure plans in concert with power plant deployment plans; advanced planning tools.	Complete plans by 2015 and tools by 2020.
2. Establish workable mechanisms for transmission cost recovery and allocation; provide incentives for accelerated permitting and construction of transmission capacity.	Complete by 2015-20.
3. Identify agencies to lead large-scale, multi-jurisdictional transmission projects or a "one-stop shop" approach to regulatory approval of major transmission infrastructure projects.	Complete by 2015-20.
4. Develop and implement plans for regional-scale transmission overlays to link regional power markets.	Complete plans by 2015. Achieve deployment by 2030.
5. Develop and implement plans for offshore grids, linking transmission lines, offshore wind resources and power market zones; develop tools to co-optimise offshore grid and wind turbine design (incl. power-to-swept area ratios).	Complete plans by 2015 and tools by 2020. Achieve deployment by 2030.

Improve transmission development

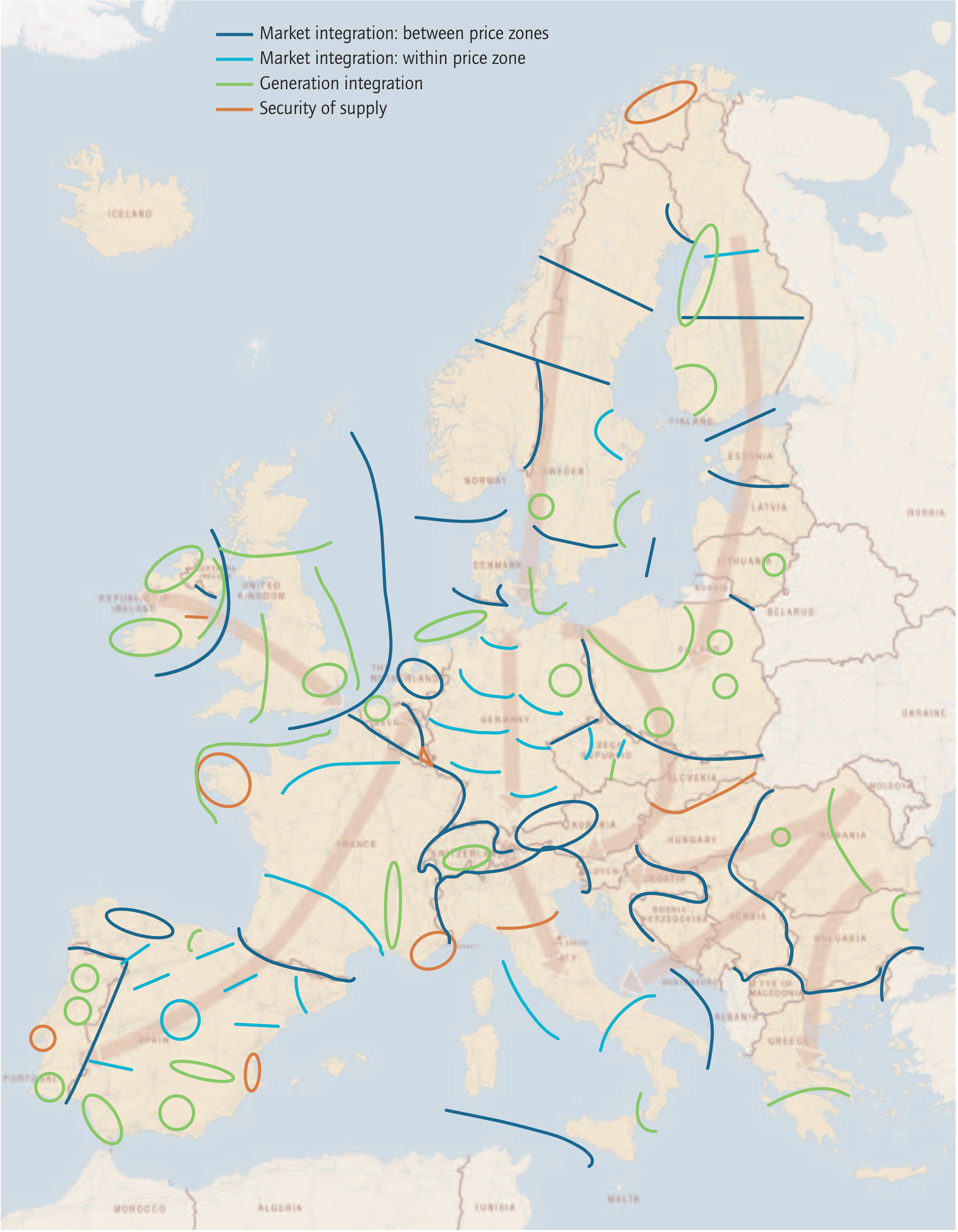
Long-term, interconnection transmission infrastructure plans require mechanisms to optimise existing and future grids. Much of the best wind resource lies some distance from energy demand centres: delivery of wind-generated electricity to end-users requires use of existing transmission and distribution (T&D) systems (grids). In some cases, the best wind speeds may be just off shore and relatively close to major (coastal) demand centres – but transmission entails higher costs per kilometre of connecting lines. Even wind resources close to existing grids create challenges: much of the transmission infrastructure is at least 40 years old and needs upgrades or reinforcement.

In this regard, wind is one among other drivers for grid strengthening, such as enhancing the integration of electricity markets and increasing security of supply. The European Network of Transmission System Operators for Electricity (ENTSO-E) has identified about 100 bottlenecks in the European transmission grid (Figure 18). Although many are identified as security of supply or market integration issues, about 80% have some link to the deployment of renewables (ENTSO-E, 2012).

Emerging underground cable technology may help overcome local public opposition and ecological concerns – though at a cost. Strong support for R&D initiatives towards new transmission technology will be a key enabler. Developing transmission planning, grid modelling and power market tools are needed to take into account variability and lower utilisation time of resources like wind power. Operational and planning time scales will both be incorporated in the planning task in future where renewables are increasingly at the core of long-term planning strategies.

Full utilisation of existing grids is also important to avoid unnecessary curtailments of wind power. Dynamic line ratings is one promising technology to help increase transmission capacity over existing lines, but requires more R&D on how it can be applied more widely.

Figure 18: Bottlenecks in the European electricity network



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Source: ENTSO-E, 2012.

KEY POINT: stronger grids would help integrate markets, secure supply and deploy renewables.

Box 5: Co-ordinated transmission planning in Europe

The European regulation EC 714/2009 led to the founding of two bodies, the European Network of Transmission System Operators (ENTSO-E), and the Agency for the Co-operation of Energy Regulators (ACER). ENTSO-E co-ordinates the 41 national transmission systems operators (TSOs) from 34 countries. Every two years, it publishes a non-binding Ten-Year Network Development Plan (TYNDP), partly with the aim of increasing transparency of the European transmission network.

The TYNDP 2012 comprises eight documents: six regional reports, one scenario outlook and system adequacy report, and the pan-European document, which extracts the most important pan-European projects from the regional reports.

The TYNPD 2012 identifies more than 100 projects adding up to 52 300 km of new transmission lines – an annual grid length development of 1.3% for investment costs of EUR 104 billion (USD 135 billion) (ENTSO-E, 2012). The drivers for new transmission include renewable energy sources (RES) integration (80%), market integration (47%) and security of supply (33%). In Europe, these project costs are not allocated to energy producers. As transmission is seen as a "common good", costs are allocated to consumers, with national regulators being responsible for authorising the projects.

Governments and energy regulators should accelerate the development of integrated, economically optimal plans for new transmission; doing so across the whole of an interconnected power system is a critical enabler.

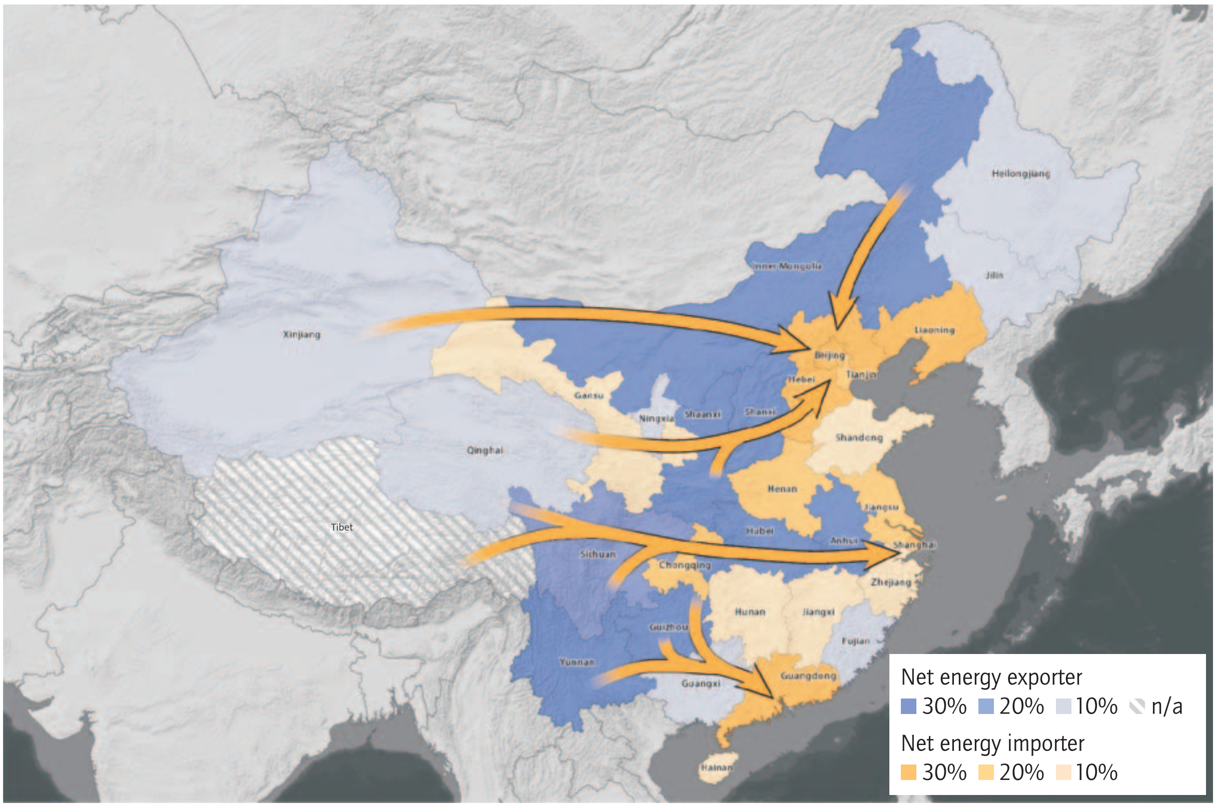
China is further developing its West-East electricity transfer project with the building of three electricity transmission corridors that connect demand centres on the coast with newly built generation capacity in the north, central and south regions (Figure 19). Each corridor of HVDC lines is expected to exceed 40 GW in capacity by 2020, and will transport electricity from coal, hydro, land-based wind and solar power to large onshore load centres. Wind power curtailment for lack of transmission capacity has been a serious impediment to wind power deployment in China.

Transmission cost recovery and allocation mechanisms are needed to expand capacity. Lack of transmission capacity is a major obstacle in several EU countries (Ireland, the United Kingdom and Germany), the United States and China. This reflects that it often takes more time to permit and build transmission lines than to permit and build wind power plants. In fact, lack of transmission needed to connect new wind power plants is a potential barrier delaying wind energy deployment.

Cost allocation is often the most important policy consideration for allowing new transmission to be built. In general, the approach is that costs should be shared among all beneficiaries, capturing the broadly distributed benefits of reduced electricity costs, improved security of supply and stronger competition in the electricity market. In Europe and in some parts of the United States (including Texas), the costs are broadly allocated instead of any single category of stakeholders – *e.g.* wind power developers – paying them entirely (ENTSO-E, 2012).

Texas offers an example of successfully combining broad transmission cost allocation policies with pro-active transmission planning. The Electric Reliability Council of Texas (ERCOT) provided development scenarios for the Public Utility Commission (PUC) of Texas, and PUC confirmed (July 2008) the development of transmission to deliver 18.5 GW of wind power to demand centres from five competitive renewable energy zones located in west Texas, using the state's long-standing policy of broadly allocating all transmission costs to load. The new lines, expected to be in service by end 2013, will reduce the volume of curtailments currently needed for the 10 GW wind installed and increase opportunities to build 8 GW more. The project is expected to cost USD 6.9 billion (PUC Texas, 2013).

Figure 19: China's West-East electricity transfer project



Note: this is an indicative map figuring the concept of the West-East electricity transfers. The exact localisation of corridors is still under discussion and subject to possible changes.

Source: D. Tyler Gibson and James Conkling/China Environment Forum at the Woodrow Wilson Center.

KEY POINT: the vast majority of power sources in China – including wind resource – are far from demand centres.

Incentives may be needed to encourage TSOs to build transmission; such measures must take into account the capital constraints of most TSOs and the return expectations of financial investors. Investors, including infrastructure funds, could then become more involved in the equity funding of transmission projects, as this asset class is considered attractive at an acceptable return. Offering to TSOs a premium on normal WACC for "new built" is one way to create such incentives.

Effective planning, however, should seek to minimise total system costs, rather than focusing solely on maximising wind power dispatch. As penetration increases, it may be necessary to adjust capacities of wind turbines, grids and entire systems.

The siting and permitting of transmission expansion often involves multiple jurisdictions (local, state, federal), each with different regulations and methods of assessing costs, benefits and environmental impacts. A stalemate often arises in that no-one wants to be the first to invest: both the wind plant developer and transmission developer want to be certain the other party will commit in order to avoid the risk of being left with a stranded asset (*i.e.* unusable and of no monetary value). Where generation and transmission assets are separated by regulation, integrated planning and investment are even more critical.

Policy makers may consider the merits of **mandating a single agency to lead the planning and permitting process** when several jurisdictions are involved, or of implementing a "one-stop shop" approach to regulatory approval of major transmission infrastructure projects. Germany recently shifted responsibilities between counties and federal authorities for lines crossing county borders: the National Grid Expansion Acceleration Act (NABEG) of 2011 aimed to simplify and accelerate permitting procedures of national and cross-border lines while ensuring a high level of public participation. In 2013, a second law containing a "Federal Requirement Plan for Transmission Networks", identified 36 power line projects as "necessary and urgent" and gave sole authority for any related dispute to the Federal Administrative Court in Leipzig.

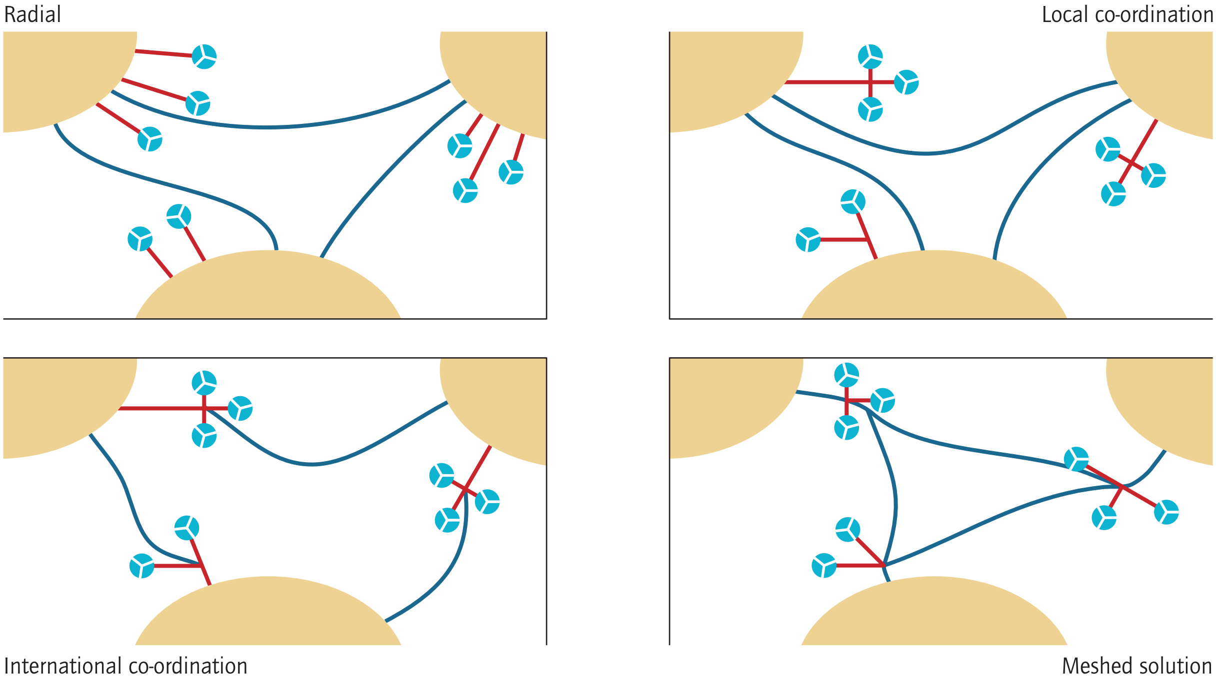
In the United States, new regional and interregional transmission planning and cost allocation policies are required under the Federal Energy Regulatory Commission (FERC) Order 1000, which also mandates that transmission planning processes take into account the states' RPS. Ongoing state, regional and federal co-operation is needed to ensure that cost allocation policies will support the necessary transmission upgrades.

Plan and deploy regional super grids and offshore grids

High-voltage direct-current (HVDC) lines reduces energy losses during transmission, and is increasingly used worldwide for bulk power transmission over long distances, for interconnecting power systems and for systems that require long lengths of cable. From a cost perspective, the break-even point between high-voltage alternative-current (HVAC) and HVDC, which is several hundred kilometres on land, is less than 100 km off shore. Continued evolution of HVDC conversion technology, improvements in cable-laying vessels, increased marine cable-laying capacity and innovative trenching equipment will help reduce costs (Wiser and Bolinger, 2012). One recent HVDC technology, voltage source converter (VSC), is usually preferred over the more mature current source converter (CSV) for offshore connections.

Distance is a key factor in **developing and implementing plans for offshore grids**. The North Sea Countries' Offshore Grid Initiative (NSCOGI) is a co-operative framework among ten countries,

Figure 20: From radial to fully meshed options for offshore grid development



Source: NSCOGI, 2012.

KEY POINT: offshore, meshed solutions might be preferable but require more planning and higher certainty.

the European Commission, ACER, ENTSO-E and national regulatory authorities. It has published a study analysing the possible effects of developing a meshed grid versus a radial approach by 2030 (Figure 20), which shows some advantages of the meshed option. This approach would, however, require a higher level of certainty on offshore wind deployment – of 42 GW by 2020 and 52 GW by 2030 (NSCOGI, 2012).

In the United Kingdom, the total capacity of offshore wind power plants having connection agreements with National Grid is 35.2 GW. A key industry issue during 2011/12 was how to move toward a more co-ordinated onshore/offshore grid, which could reduce costs and speed up the connection process. The feasibility of a co-ordinated grid network has been explored, showing that a meshed grid network could save between GBP 0.5 and GBP 3.5 billion (USD 0.77 billion to USD 5.4 billion) compared to a purely radial approach. Continued work will be needed to resolve issues arising from a co-ordinated grid approach, including unlocking barriers to enable developers to connect to grids off shore (Crown Estate, 2012a).

Reliable system operation with large shares of wind energy

Variability and uncertainty are not new characteristics of power systems. As demand for power varies by hours, days, and seasons, all power systems must have sufficient firm capacity to respond to load, with some safety margin (*i.e.* operational reserves) to respond to unforeseen events and forecasting errors. Experiences in Western Europe and the United States suggest that at low-wind energy shares (5% to 10%), the increase in variability "seen" by the system will be small and existing reserve margins are sufficient. As wind penetrations rise, greater amounts of operational reserves will be needed to ensure that combined (forecast/actual) production from wind and dispatchable power plants can continue to be reliably balanced against (forecast/actual) demand.

The main challenge for wind integration is as follows: once the targeted amount of wind energy has been captured and converted into electricity, and sufficient transmission capacity has been secured to deliver it to market, the electricity available must be cost-effectively integrated into the power system while ensuring the security of supply. Existing T&D networks and the physical power markets they support were designed around dispatchable, centralised power generation that can typically be turned off and on according to demand. In contrast, the generation of electricity from wind energy depends on a variable resource that cannot be scheduled, as is possible with conventional plant.

Enable wind integration	***Time frames***
1. Enable larger balancing areas and use of wind forecast and online data in control rooms of system operators. 2. Assess grid codes and ensure that independent power producers can access grids.	Ongoing. Complete by 2015-20.
Develop electricity markets	***Time frames***
3. Accelerate development of larger-scale, faster and deeper trading of electricity through evolved power markets and advanced smart grid technology. 4. Enable wind power plants taking part in electricity markets, also for system services. 5. Incentivise timely development and use of flexible reserves, innovative demand-side response and storage.	Ongoing. Market development by 2020 and wind power in ancillary services market by 2025.
Increase power system flexibility	***Time frames***
6. Develop methods to assess the need for additional power system flexibility to enable variable renewable energy deployment. 7. Carry out system studies to examine the challenges, opportunities, costs and benefits of high shares of wind power integration. 8. Prepare strategies for managing wind curtailments.	Ongoing. Complete by 2020.

Enable wind integration

The first step in wind integration is **enabling forecast**. Acquiring online data to control rooms means accessing also distribution-system connected plant data. In Spain and Portugal, this is organised through centres for compiling distributed data, which also manage any control orders from the TSOs. Forecasting on a one-to-two day horizon is a primary tool in managing uncertainty. In system operation, it is also important to be ready for extreme events (storms and other events with large ramps). In the United States, the FERC expects that forecasting and intra-hour scheduling be part of any proposal for charging integration costs. In addition, generators providing variable energy resources must provide meteorological and forced-outage data, which the transmission provider can use for forecasting their output

Enabling larger balancing areas and trade with neighbouring areas are important measures to support higher shares of wind power. Co-ordination between balancing areas allows for more spatial diversity, thereby reducing the impact of variable renewable energy, and also provides synergies between diverse flexible supply-side and demand-side resources. Experience from Germany and the Nordic countries reveals the value of larger balancing areas in decreasing reserve needs for individual system operators. The Nordic power market, which covers the whole Scandinavia, has facilitated the trade of Danish wind for Norwegian hydropower, helping wind energy to reach 30% of the Danish market with moderate balancing costs from the day-ahead market.

Grid codes represent the requirements of system operators on power producers, and typically include specifications such as voltage and frequency. Most modern wind turbines have the required capabilities to comply with these codes, but further co-operative efforts to standardise the content, definitions, terminology and compliance-test methods of grid connection requirements can support smoother grid operation.

In the early days of wind power deployment, turbines were mostly connected to distribution grids – and simply disconnected in case of grid disturbances to simplify the corrective measures of grid operators. At larger deployment, (*e.g.* in Germany and Spain) it became evident that disconnecting turbines that represent several gigawatts of power can undermine system reliability. The development of fault-ride-through capabilities of wind power plants has become an industry standard.

Grid code harmonisation, if carefully defined and coherent with each technology capability, could lead to more cost-effective turbines. Regulators should ensure that grid codes are equitable and provide a level playing field for all entrants while avoiding excessively stringent requirements and uselessly expensive features. In Europe, network codes are being elaborated by ENTSO-E according to guidelines provided by ACER. Once approved by the Parliament and the Council, these codes will be legally binding. The network code in Europe is based on "envelopes of requirements" that leave national TSOs free to choose an appropriate requirement inside these values.

Develop electricity markets

Larger-scale, faster and deeper trading of electricity requires evolved markets and smart grid technologies. Improved operational practices, such as electricity trading rules, can be a powerful enabler of flexibility. Regulators tasked with market design may wish to consider characteristics, such as: allowing shorter time windows; adjusting balance of portfolios with enhanced trading options; and extending balancing and provision of other system services into demand response, storage and wind generation. Increasing intraday trading and including cross-border trading will facilitate wind deployment. Grid operators should be ensured the ability to assess grid operation challenges and uncertainty.

Dispatching energy at short intervals is also useful for reducing wind integration costs and enabling more efficient operation of the power system. This allows dispatch schedules to be updated within the operating hour in response to demand and supply deviations, thus accommodating total system variability at far lower costs than when using only expensive reserve generation to accommodate intra-hour variability.

Integrating wind more tightly in the real-time dispatch process has proven a very effective strategy for independent system operators (ISOs) such as the Midcontinent ISO (in the Midwest United States) and the ERCOT. These ISOs are dispatching wind every five minutes, just as they do with coal, natural gas and other conventional generators. Because the ISOs tell the wind producers how much wind power they expect to receive every five minutes, wind plants fit into markets and operations just like any other generating capacity. Using a very short-term forecast (updated within ten minutes of real time) to dispatch the wind plants makes this work: even a simple persistence forecast reduces the forecast error towards zero as real time approaches.

With wind power already participating in electricity markets, some experience with managing imbalances has been gained. In Nordic countries, for example, wind power producers have been exposed to imbalance costs that have been quite moderate, USD 3/MWh to USD 4/MWh, even if they do not reflect the real costs that wind power causes for system balancing at all hours.

System support services from wind power plants are still being developed to provide both voltage and frequency control to system operators when needed. Technical requirements on wind turbines (*e.g.* remote control) to participate in power markets are increasing in importance. Market rules will need to develop to take advantage of these services in future, in times when more cost effective services are not available from other power plants.

Getting sufficient remuneration from market prices at high wind (and solar) penetration levels is a future challenge for wind power in electricity markets. Energy-only markets will react to high winds (or strong sunshine) with very low electricity spot prices, making the transition from subsidised variable renewables to market exposure a complex task – even when wind (or solar) power offer competitive electricity costs.

Increase power system flexibility

Timely deployment and use of flexible reserves is vital at higher penetration levels of wind power. Markets need to be designed such that price signals encourage investment in and subsequent operation of all flexible resources in the region. Timely investment in flexibility should be incentivised, recognising the tendency for large shares of renewable energy to depress spot electricity market prices. Conventional generation, from thermal plants (to different degrees) to hydropower, already provide some flexibility. Enhancing system flexibility from thermal plants relates to faster starts and greater ramp rates and ramp ranges; reduced minimum generation; balancing and response capability; better part-load efficiency; and low emissions to meet environmental requirements during cycling. Deeper trade with adjacent markets and connecting diverse energy sectors (*e.g.* heat, transport and gas) can further increase flexibility available for balancing. Using dynamic marginal costs to develop such incentives would be essential to efficiently integrate wind power.

Other options for flexibility include the use of deferrable and responsive demand (*i.e* demand-side management) through smart meters, and investment in energy storage as well as electric and hybrid vehicles. Smart grids that enable both demand and supply agents to interact in real time create the potential for an exponential increase in the number of market participants, which implies both benefits and challenges.

Box 6: Geographic “smoothing” of variable output

As distances between wind power plants increase, their collective output is generally less correlated. An uncongested grid connected to many dispersed plants will therefore “see” a smoother aggregated wind output profile than if all the wind plants were in the same place. The capacity of interconnected markets to share dispatchable reserve capacity increases the extent to which wind plants can displace conventional energy production. Larger, deeper and more liquid electricity markets can be achieved by merging balancing areas and increasing trade among systems. Europe has a political target to merge regional balancing markets by the end of 2014.

Carrying out system-wide studies to identify challenges that system operators need to consider as wind power becomes an integral part of power system evolution, rather than being developed in isolation. System operators should receive early notice of targeted wind energy shares in order to plan accordingly, and should collaborate with wind power developers and manufacturers regarding the capabilities that wind power plants can offer to system support as well as wind forecasting and on-line data for operator control rooms. TSOs and regulators should co-ordinate actions to avoid situations of sudden oversupply of new wind capacity that the TSO would be unable to absorb. Detailed system-wide studies, assessing the existing flexibility and options to increase it, are important to advancing towards high renewable energy shares. Good examples include the *All Island Grid Study* in Ireland (and its continuation studies) and the east and west interconnect studies carried out in the United States (DCEN, 2008; Ecofys and DIgSILENT, 2010; Enernex, 2011; GE Energy, 2010).[11]

At higher penetration levels of wind power it is foreseeable that conventional, synchronous generation may sometimes provide less than 50% of the load, which raises questions about how the system might behave and associated stability concerns for which TSO have little or no experience. Research is needed to answer questions about model accuracy and the extent to which HVDC transmission reinforcement can be used to stabilise AC transmission lines.

Curtailments of wind power are an emerging concern. In northern Germany and Texas, some curtailments were caused by delayed transmission reinforcement; in Spain, the issue was a lack of fault-ride-through capabilities at wind power plants. These situations were largely temporary and have been reduced through updates to transmission systems and requirements. China's more serious curtailment problems, however, reflect inflexibility in the operation of the power system. Integration studies show that curtailments will become a more serious challenge at wind power penetration levels of about 30%. Addressing this issue, which may require compensation for curtailments, is vital to enabling investors to consider future energy production options.

Further information on integration of variable renewables will be provided in a forthcoming IEA publication on grid integration of variable renewables (forthcoming1).

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[11] Wind IA Task 25 is preparing Recommended Practices for Wind Integration studies, to be published in 2013 (www.ieawind.org).

Policy, finance, public acceptance and international collaboration: actions and time frames

Strong market pull is needed to complement the technology push that will support higher shares of wind in electricity markets. Action in this area is more associated with policy, finance, public acceptance and international collaboration that fosters more rapid deployment of wind power. Sharing the lessons learned from past activities and experience in different countries can enhance awareness, acceptance and deployment.

Incentivising investment

A principal role of government is to attract investment in clean energy technologies by facilitating a predictable and transparent policy framework, including integrating renewable energy policy into an overall energy strategy. Without government incentives or equivalent support, in most cases the rates of return would be too low and markets would stagnate.

To finance the higher amounts of investments needed to expand wind penetration, it is essential to move from limited resources for risk financing towards more abundant resources for mainstream activities and more conservative financing (such as pension funds). These investors seek adequate risk-adjusted returns and stable inflation-adjusted income streams. A predictable policy environment is a prerequisite to minimise the perceived risk; by contrast, regulatory uncertainty, including retroactive changes, can drive up the cost of finance to prohibitive levels.

Attract investment to wind power	***Time frames***
1. Set short- and long-term deployment targets for wind power (where not already in place).	Complete by 2015.
2. Implement incentives and support mechanisms that provide sufficient confidence to investors; create a stable, predictable financing environment to lower costs for financing.	Complete by 2015.
3. Internalise the external costs of electricity production into market prices.	Complete by 2020.
4. Encourage national and multilateral development banks (MDBs) to target clean energy deployment.	Continue over 2013-50 period.
5. Further develop mechanisms to attract investment in wind deployment (such as the Clean Development Mechanism [CDM]).	Continue over 2013-50 period.

Binding **deployment targets** with near-term milestones provide a clear pathway for technology development and confirm government support, both of which further encourage private sector investment. For instance, the European Union targets 20% of all energy to be from renewables by 2020 (about one-third of all electricity) with binding targets for member states, further detailed in their national renewable energy action plans (EEA, 2011). Importantly for the longer term, consultations are ongoing about possible targets post-2020.

National roadmaps could be created to support wind development and implementation at the country level. The first of these was the *China Wind Energy Development Roadmap 2050* published by the Energy Research Institute of China's National Development and Reform Commission together with the IEA (IEA and ERI, 2011). National roadmaps would help countries to identify priorities based on the energy and industrial policy they choose. A detailed process for developing national wind roadmaps will soon be published as a *How2Guide* (IEA, forthcoming2)

Establishing incentives and support mechanisms for wind deployment can build investor confidence. At present, government support and incentives for renewable energy producers vary from country to country. Common mechanisms include fixed FiTs, feed-in premium (FiPs), production tax credits, RPS or quotas (with or without tradable green certificates), capital grants and loan guarantees. Most mechanisms seek to establish a return per megawatt hour of electricity that is competitive with other energy sources and sufficient to attract private investment; loan guaranties in the United States focus on reducing risks for investors. Importantly,

Box 7: Attracting private finance

Raising sufficient finance for investments in low-carbon energy technologies depends on governments setting a domestic policy framework that is responsive to evaluation of risk and return profiles on which the private sector makes investment decisions. Investor confidence can be strengthened in several ways.

In the case of wind development, potential investors need a solid understanding of the full range of both perceived and real risks, which can include wind resource uncertainty, technology risk (*e.g.* unforeseen O&M costs and down-time), predictability and longevity of government incentives, instability in the carbon price, and uncertainty regarding the reliability and credit-worthiness of other parties.

Partnerships enhance financing, as different players have different risk appetites and financing possibilities. Public-private partnerships (PPPs) can reduce the risk to private investors, and should be used to maximise leverage. PPPs may be effective, for example, to secure the construction of new grid infrastructure, wherein the grid company provides the investment capital against a governmental assurance that the lines will be used, thereby guaranteeing a return on the investment.

government policies must have flexibility to adjust the subsidy level as the cost of wind energy gets closer to conventional technologies. However, such adjustments must apply only to new plants, as any retroactive changes to remuneration of existing plants would undermine investor confidence.

Internalising the external costs of electricity production is viewed as one way to level the playing field across primary energy sources. Subsidies might serve to reflect the value of clean energy production – including the avoided costs of reduced GHG emissions and pollutants, the positive impact on health, less energy dependence, etc. – that is not yet effectively internalised in electricity prices. A more straightforward method of internalising the cost of GHG emissions in the price of electricity – which may have more weight in investment decisions – would be to put a price on emissions through carbon taxes or emissions trading systems. A carefully designed scheme is paramount to ensure meaningful and stable prices. Even with a carbon price, emerging renewable energy technologies with good prospects for cost cuts could be given additional incentives to unlock their long-term potential (Philibert, 2011).

The critical barriers that can deter or slow down deployment tend to change as the market for a technology develops. Policy makers need to take a dynamic approach, adjusting priorities as deployment expands. Above all, support mechanisms should aim to reduce project risks and stimulate deployment, while encouraging the technology to reduce costs. A policy must also be easy to implement and enforce (IEA, 2011).

Public financing by government or quasi-government agencies has been critical to development of larger wind power projects. Most offshore projects in Europe have received support from the European Investment bank (EIB), Eksport Kredit Fonden (EKF) the Danish export credit agency, Euler Hermes (EH) the German export credit agency, or a combination of them. Financing offshore wind projects in Germany has been facilitated by the availability of EUR 5 billion from the German Development Bank (Kreditanstalt für Aufwiederbau). The Meerwind project in Germany included financing from US-based private equity firm, Blackstone. In 2011, DONG Energy sold 50% of the Anholt project to two Danish pension funds, a new source of financing in the sector. Parties are exploring alternative forms of financing such as project bonds. The European experience shows that many different regulatory regimes work as long as the overall price level is compatible with the current installation costs of offshore wind and the regulatory framework is sufficiently stable to cover the relatively long development and construction process.

MDBs are an important source of financing for joint development efforts. Financing facilities can be designed on a case-by-case basis to support differing needs. The Turkish Clean Technology Fund (CTF) is a business plan established among the Turkish government, the World Bank, the International Finance Corporation and the European Bank for Reconstruction and Development, worth approximately USD 1.9 billion.

Alongside policy support, efforts should be made to identify and address barriers to deployment. For example, off-taker risk can be a serious impediment to investment. A project's risk profile is considerably higher prior to the signature of a power-purchase agreement and reduces substantially once an off-taker has been securely identified to buy the electricity to be produced. In India, China and elsewhere, power-purchase agreements are habitually signed at project completion – long after financing has been secured. This practice makes it more difficult to attract investors early, when the bulk of financing is needed. It should be noted that the financial reliability of potential off-takers may be in question. In such a case, disincentives to investment could be reduced by a regulated requirement for off-takers to contract for electricity when projects are at the financing stage, or by developing a mechanism to shield investors from subsequent failure to secure a power-purchase agreement.

Increased effort should be made to **develop mechanisms to attract investment.** The **CDM** within the United Nations Framework Convention on Climate Change (UNFCCC), which is pursuing global agreements to cap GHG emissions, has shown some success in building clean energy capacity in developing economies. Early in 2013, there were 2 616 wind projects in the CDM pipeline, 29% of the total amount of projects. Wind ranks first with respect to the number of projects, followed by hydro (26%). Wind power projects are expected to yield 19% of total certified emissions reductions (CERs) issued per year. China and India dominate among wind CDM projects. China has 1 511 projects totalling almost 84 GW, and India 810 projects totalling about 14 GW. Brazil, Mexico, South Korea, South Africa and Chile follow. The rapid increase in wind deployment in China and India has coincided with the development of the CDM incentive mechanism for clean energy projects. This growth has contributed to the development of domestic wind manufacturing bases, particularly in China. However, current uncertainty on the future of the climate negotiations has put into question the future of CDM.

Public engagement and the environment

Prominent environmental groups are squarely behind the large-scale deployment of wind power, while international, national and regional policies targeting GHG emission reductions have wide public support. Yet local groups often oppose individual projects or the installation of transmission lines, often because of visual impacts, effects on property values, health concerns, or impacts on avian, bat and offshore ecology. In some European cases, local opposition has delayed important transmission interconnector projects by as much as 15 years. Even as knowledge is gained regarding how wind power affects the natural environment, uncertainty remains over impacts on local species. If studies from other regions are difficult to find, this lack of information often leads decision makers to reject a wind proposal or take no action at all, forcing developers to less-desirable sites that result in higher energy costs.

Mitigate impacts and increase public engagement	*Time frames*
1. Improve techniques to assess, minimise and mitigate social and environmental impacts and risks.	Complete by 2020.
2. Increase public involvement and understanding, and community engagement, on the basis of best practices.	
3. Promote wind energy as part of a portfolio of abatement technologies for GHG emissions and pollution.	Continue over 2013-50 period.

Rigorous effort is needed to **assess, minimise and mitigate the social and environmental concerns** associated with wind power – particularly in response to the sometimes polarised public debate. Local EIAs can identify and allay real public concerns, as well as avoid subsequent, unforeseen project delays. Government agencies and the wind power community should work together to build improved understanding of local impacts, and to ensure that the planning of wind power and related transmission infrastructure is based on transparent, fair and equal criteria.

To avoid duplications of environmental impact analyses for every wind power project, where feasible, environmental/radar studies that benefit a large number of projects could be financed with public or shared funding. Overall, a better understanding of impacts and mitigation solutions will increase the certainty of development outcomes and ultimately lead to more deployment.

Increase public involvement and understanding of the full value of wind

Public involvement is essential to enable efficient project development. As a tool to help the industry address stakeholder questions on wind energy, the Swedish wind energy industry introduced its first code of conduct for the sector in July 2012 (Svensk Vindenergi, 2012). The Wind IA has published best practice recommendations (Wind IA Task 28, 2013), outlining methods to identify and minimise negative local impacts, reduce project uncertainty and risk due to local attitudes, accelerate project development, and establish strategies and communication activities to express the full value of wind power. Support can be built via the provision of reliable and balanced information, and with community participation at the earliest stages of a project, including open public hearings. In cases where negative environmental effects from wind are likely, means to minimise and mitigate these effects need to be identified and developed.

It is also important that the general public and local populations in the vicinity of a proposed development understand the full value of wind energy. The variability of wind power is taken by some as a measure of unreliability while its contributions to climate change mitigation and energy security are often underestimated. Effective public information campaigns that highlight quantifiable benefits of wind power can address these concerns.

Planning and permitting

Improve planning and permitting	***Time frames***
1. Include wind power in long-term regional planning, taking into account other likely power plant developments and transmission deployment.	Complete by 2020.
2. Harmonise, accelerate and streamline permitting practices.	Complete by 2015.

The need to **include wind power in the long-term regional planning process is clear:** wind power developments typically reflect a wide range of potentially conflicting attributes and interests, and thus require very careful consideration. Early, integrated, long-term planning for deployment of wind power and associated infrastructure will help long-term wind deployment. Identifying pre-screened zones that offer quicker permitting to wind deployment will lighten the burden on developers by avoiding likely obstacles. Large-scale development zones should take into account wind resources and existing and planned grid infrastructure. Where a large wind resource is located in an area lacking sufficient transmission to bring electricity to market, transmission planning should be co-ordinated. Development zones must also be allocated on an equitable basis with socio-environmental requirements, as well as defence (radar) and other industrial interests.

Examples of effective national strategic planning for the offshore sector exist across Europe (Denmark, Germany, the United Kingdom, the Netherlands and Belgium). The Dutch government's 2009 National Water Plan includes 6 000 MW wind power development potential by 2020 alongside the ongoing development of fisheries, shipping, sand extraction, oil and gas extraction, nature conservation and coastal defences. The plan designates areas in which permits for wind energy parks can be granted.

Efforts to **streamline permitting procedures** face an inherent challenge in that a key aspect of many permitting procedures is to ensure that deployment takes into account diverse local needs. However, if responsibility is divided among several agencies at different levels of government, permitting can be subject to delays and create uncertainty for developers and investors. A more holistic approach that identifies and integrates the various approvals required can effectively address any planning, environmental or safety distance concerns during wind project development. Standardised, more transparent permitting procedures reduce project uncertainty.

For example, the US Department of the Interior (US DOI) and the FERC are now partnering to oversee deployment of wind, wave and tidal power on the outer continental shelf. In Denmark and in the United Kingdom, offshore permitting procedures have been streamlined into a "one-stop-shop" system in which the Danish Energy Agency and Crown Estate serve as the co-ordinating authorities. In Denmark, the system operator is involved in selecting sites and initiating the lease process. It then holds a competitive bid process to select a wind farm developer while the system operator permits and constructs the interconnection to the onshore grid and negotiates a power purchase agreement. This model is effective in that it includes interconnection support to facilitate financing the projects.

The UK government recognised the importance of spatial planning and the need to streamline the consenting process and a created "one-stop shop" approach for permitting for its Round 2 offshore tendering. The Crown Estate (which is the seabed owner and manager) charged successful applicants a one-time fee based on the spatial area of their respective sites. Once plants are operational, owners of Round 2 projects will be required to make lease payments on the order of 1% of gross power sales, including incentives. In 2009, an offer was announced to extend site leases to 50 years, affording developers greater certainty when considering life-extension and repowering of their projects. This move was also designed to instil greater confidence in the supply chain. For Round 3, initiated in 2008, the Crown Estate established a strategic spatial planning process and identified nine zones prior to running the tender process. Additionally, the UK government implemented a new infrastructure planning process for the permitting of offshore projects, providing an improved and timely consenting regime.

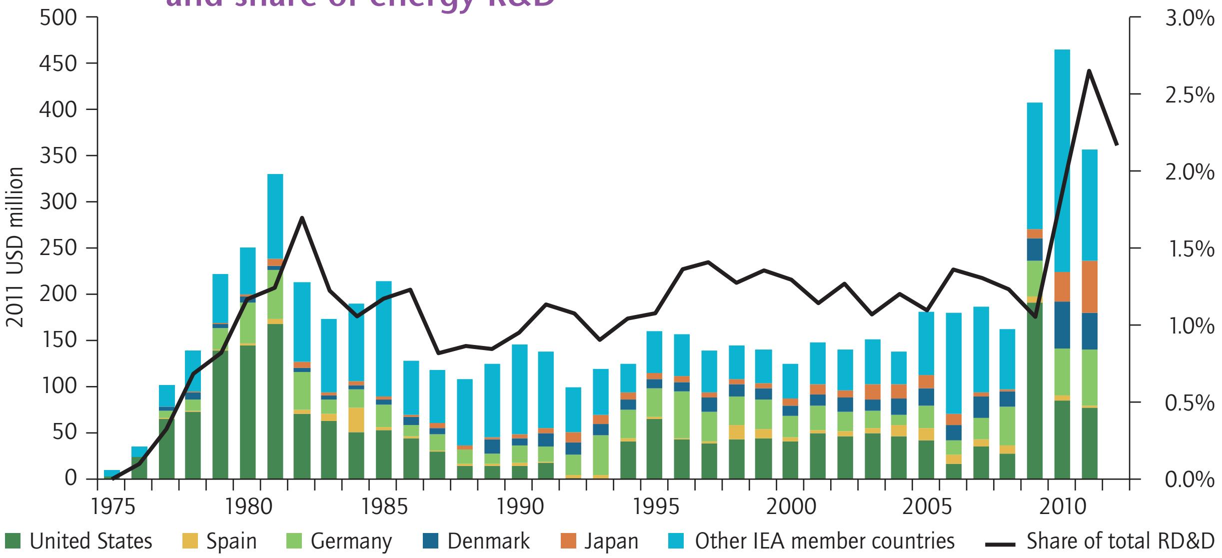
Increased funding for RD&D

Support R&D and demonstrations	***Time frames***
1. Establish funding commitment levels for the next decade for wind energy R&D.	Complete by 2015-20.
2. Provide demonstration funding for innovative concepts that would not be pursued without extra support.	Ongoing. Complete in 2020.

Achieving the technology development needed for the roadmap targets will require increased funding for RD&D.

Establishing clear **financial support for RD&D** sends a clear strong message that public and private sectors are engaged for the long term. This helps attract more investors. For the last three decades, research funding in OECD member countries for wind power has mostly fluctuated between 1% and 2% of all energy R&D funding. Stimulus programmes in the European Union and the United States increased funding in 2009-2010. In 2011, the figure stood at estimated 2.2%, equalling about USD 357 million (Figure 21).

Figure 21: OECD member country funding for wind energy R&D and share of energy R&D



KEY POINT: public finance of wind energy R&D has been comparatively low against investment in other energy technologies.

By contrast, the wind industry invested 5% of its income (about USD 4 billion) into R&D between 2007 and 2010. But private companies tend to privilege short-term R&D efforts that deliver more certain returns on investment. Long-term, fundamental research is usually the role of the public sector and the primary focus of public R&D initiatives. Increased co-ordination among the full community to support R&D and demonstration efforts, particularly in offshore wind, could bring additional benefits.

Given the substantial role that wind power is expected to play in achieving climate change and energy goals, the strong consensus view of the roadmap participants is that wind's portion of funding for all energy sources should be increased substantially, to two to five times the current funding levels. Wind energy R&D should be prioritised and allocated a dedicated budget amount, to ensure its full potential can be met.

Establishing large test sites is another key area for public investment. Examples of ongoing work include the German offshore test field, Alpha Ventus, which started operation in 2009 at sea depths of 30 m to 40 m and distances of up to 40 km from shore. New test facilities for large component have been developed for blades in Boston (United States) and Bremerhaven (Germany), and are under development for drive trains in Charleston (United States) and Narec (United Kingdom).

International collaboration: actions and time frame

Efforts to spread deployment of wind and other clean energy technologies worldwide will contribute to the effective use of the best resources and will have a global benefit in terms of GHG emissions abatement. International collaboration can help more countries develop their use of renewable sources and decrease their dependence on fossil fuels.

Increase international collaboration	*Time frames*
1. Expand international RD&D collaboration, making best use of national competencies.	Continue over 2013-50 period.
2. Build capacity in emerging economies by developing new mechanisms to encourage technology exchange and sharing of best practice for wind deployment.	Continue over 2013-50 period.
3. Assess and express the value of wind energy in economic development, poverty alleviation and efficient use of fresh water resources.	Continue over 2013-50 period.

Expanding international RD&D collaboration is an important means of ensuring greater co-ordination among national approaches to wind energy RD&D. It could help to ensure that key aspects are addressed according to areas of national expertise, taking advantage of existing RD&D and testing activities and infrastructure. Long-term harmonisation of wind energy research agendas would also be beneficial.

One example of international collaboration is the Wind IA, which is one of 42 such agreements covering the complete spectrum of energy technology development. More than 20 countries participate in the Wind IA: together, their national experts have developed a coherent research programme including offshore, cost of energy, social acceptance, wind modelling, aerodynamics and wind integration.[12] This may provide the focus for greater collaboration among OECD and non-OECD countries.

In addition, in Europe, the Wind Energy Technology Platform (TPWind) builds collaboration among industry and public sector participants; it is one of a range of technology platforms with cross-cutting activities established in partnership with the European Commission. TPWind has developed a research agenda and market deployment strategy up to 2030, which provides a focus for the European Union and national financing initiatives. In the offshore sector, Norway joined the German-Danish-Swedish Co-operation Agreement with specific focus on offshore wind energy RD&D.

China has been participating for several years in international collaboration on standards, testing and certification of wind power plants, which led to a revision of the Chinese grid code in 2012 and development of a testing centre for wind turbines.

The need to **build capacity in emerging economies** cannot be overstated. Strong wind resources exist in many countries where deployment has yet to begin to approach its potential. By 2050, according to the 2DS, more than half of cumulative global investment in new capacity will have taken place in non-OECD countries. In China alone, building the 611 GW of installed capacity envisaged in the 2DS would at today's prices cost around USD 690 billion by 2030 and USD 1.5 trillion by 2050.

Rapid economic growth, limited energy supply and abundant conventional resources are factors that cause key countries to turn first to conventional energy supply. Without sufficient incentive to do otherwise, many emerging economies are likely to pursue a carbon-intensive development path (UNEP, 2009). Bilateral and multilateral efforts, such as the Sino-US Co-operation in Clean Energy, are underway to address this challenge.

Governments of OECD member countries are encouraged to assist developing economies in the early deployment of renewable energy. The exchange of best practice in terms of wind technology, system integration, support mechanisms, environmental protection, approaches to mitigating water stress, and the dismantling of deployment barriers are important areas. Dynamic mechanisms will be required to achieve successful technology and information transfer. Poorer and more slowly developing economies (such as many in Africa) are lagging behind more quickly industrialising nations; specific, tailored actions will be necessary.

The value of wind energy for reasons in addition to climate protection should be emphasised – even when based on developed economies' experience. Benefits related to innovation, employment, fresh water conservation and environmental protection should be accurately quantified and expressed to developing economy partners, particularly in terms of wind energy's ability to contribute towards the fundamental benefits of energy provision and poverty alleviation.

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[12] See www.ieawind.org.

Roadmap action plan and next steps

The main milestones to achieve the target of 15% to 18% global electricity from wind power in 2050 are:

- Stimulate cost reductions to achieve cost competitiveness with new conventional power production (including carbon prices) by 2020 for onshore and by 2030 for offshore wind power. This means increasing funding allocation for wind energy RD&D between two- and five-fold by 2020.
- Reduce uncertainty of resource assessment to 3% of projected output of wind power plants and increase technology reliability to 95% by 2020 also for offshore.
- By 2020: publish and encourage broad use of best practice guidelines for project development, system integration and community engagement.
- By 2020: include wind power in long-term regional planning with clear ways to address deployment barriers from transmission and safety distances to built environment.
- By 2020: increase cost competitiveness by setting a price on emissions through an emissions trading system, with careful design to ensure the emissions price is meaningful (fully cost-reflective) and stable.

Near-term actions for stakeholders

The most immediate actions are listed below by lead actors.

Governments include policy makers at international, national, regional and local levels. Their underlying roles are to: remove deployment barriers; establish frameworks that promote close collaboration between the wind industry and the wider power sector; and encourage private sector investment alongside increased public investment.

Governments should take the lead on the following actions:

- Set or update long-term targets for wind energy deployment, including short-term milestones.
- Ensure a stable, predictable financing environment. Where market arrangements and cost competitiveness do not provide sufficient incentive for investors, make sure that predictable, long-term support mechanisms exist.
- Address existing or potential barriers to deployment from land-use restrictions, public resistance and lack of co-ordination among different authorities (*e.g.* environment, building, traffic, defence).
- Launch work on regional land-use and marine spatial planning, taking into account wind power and its transmission needs. Harmonise and streamline permitting practices.
- Identify and provide a suitable level of public funding for wind energy R&D, proportionate to the cost reduction targets and potential of the technology in terms of electricity production and CO_2 abatement targets.
- Enable increasing international R&D collaboration to make best use of national competencies.
- Provide incentives for accelerated construction of transmission capacity to link wind energy resources to demand centres; identify agencies to lead large-scale, multi-jurisdictional transmission projects together with regulators and system operators.
- For offshore deployment, make available sufficient and suitably equipped large harbour space.
- Work with R&D funding organisations to establish the technology push (*e.g.* compulsory reporting when getting subsidies) needed to establish public databases (O&M and wind resources).
- Launch maritime spatial planning that includes areas for offshore wind energy deployment and develop appropriate offshore planning regimes.

Wind industry includes turbine and component manufacturers, developers of wind plants and associated infrastructure, with strong collaboration with the research sector. One main objective is to lower the lifecycle cost of energy production and reduce the uncertainties of wind output estimates and reliability.

Wind industry actions on R&D for short-term results by 2015 should focus on:

- wind characteristics: develop a publicly available database of onshore and offshore wind resources and environmental conditions; develop and implement international standards for wind resource assessment and siting; further develop remote sensing technology; and develop short-term forecast models, for use in power system operation (working together with system operators);
- wind turbine technology: build a shared database of offshore operating experiences; develop dedicated designs for different site conditions;

for offshore deployment, make available sufficient purpose-designed vessels and improve installation strategies;

- work with funding agencies to establish targeted R&D support programmes, then launch long-term programmes for new materials; improve design tools; and increase knowledge of offshore, complex terrain and icing climates, aerodynamics, and of offshore turbine and foundation designs.

Power system actors include transmission companies, system operators and independent electricity sector regulators as established by governments, as well as vertically integrated utilities (where they exist). Their key role is to invest in transmission infrastructure needed to connect wind power (and other generators) and move electricity to load centres. They also play a role in enabling physical power markets to evolve in a manner that cost-effectively reduces the impact of variability and increases the value of wind power while ensuring security of supply.

Power system actors should focus their short-term efforts on the following areas:

- develop wide-area transmission plans that support interconnection, anticipating wind power deployment and the linking of regional power markets, to ensure security of supply;
- establish mechanisms for cost recovery and allocation from new transmission build-outs for wind-rich areas, in case transmission costs are not covered by customers;
- where not already available, implement grid codes that ensure open access to transmission networks for wind power plants; collaborate with neighbouring areas to enhance balancing;
- continue to advance progress on the evolution of market design and system operating practices to enable integration of large shares of renewable energy;
- improve wind forecasting and include online data in control rooms of system operators;
- work for offshore grid improvements such as meshed grids connecting several countries and combining offshore connections with interconnectors where regionally and socio-economically reasonable;
- develop methods to assess the need for additional power system flexibility; carry out grid studies to examine costs and benefits of high shares of wind power;
- exploit power system flexibility to increase the value of RES;
- support standards development to ensure government-funded R&D is translated into industry best practice.

Implementation

The implementation of this roadmap could take place through national roadmaps, targets, subsidies and R&D efforts. Based on its energy and industrial policies, a country could develop a set of relevant actions. To facilitate this process at national levels, the IEA is also publishing a *How2Guide* for the development of wind roadmaps, which includes information and guidance related to:

- resource availability;
- technology status and costs;
- policy costs and effectiveness;
- barriers that would need to be addressed;
- stakeholder engagement and public acceptability.

Ultimately, international collaboration will be important and can enhance the success of national efforts. This roadmap update identifies approaches and specific tasks regarding wind energy research, development, demonstration and deployment, financing, planning, grid integration, legal and regulatory framework development, public engagement, and international collaboration. It also updates regional projections for wind energy deployment from 2010 to 2050 based on *ETP 2012*. Finally, this roadmap details actions and milestones to aid policy makers, industry and power system actors in their efforts to successfully implement wind energy.

The wind roadmap is meant to be a process, one that evolves to take into account new developments from demonstration projects, policies and international collaborative efforts. The roadmap has been designed with milestones that the international community can use to ensure that wind energy development efforts are on track to achieve the GHG emissions reductions required by 2050. As such, the IEA, together with government, industry and non-governmental organisation (NGO) stakeholders will report regularly on the progress that has been achieved toward this roadmap's vision. For more information about the wind roadmap inputs and implementation, visit www.iea.org/roadmaps.

Abbreviations and acronyms

2DS	2°C Scenario
6 DS	6°C Scenario
AC	alternative current
ACER	Agency for the Co-operation of Energy Regulators
ARRA	American recovery and reinvestment Act
CCS	carbon capture and storage
CDM	Clean Development Mechanism
CEM	Clean Energy Ministerial
CER	certified emission reduction
CFD	computational fluid dynamics
CO_2	carbon dioxide
CPI	Climate Policy Initiative
CSP	concentrating solar power
CSP	current source converter
CTF	Clean Technology Fund
DC	direct current
EDF	Électricité de France
EH	Euler Hermes
EKF	Eksport Kredit Fonden (Denmark)
EIA	environmental impact assessment
EIB	European Investment Bank
ENTSO-E	European Network of Transmission System Operators for Electricity
ERCOT	Electric Reliability Council of Texas
ETP	*Energy Technology Perspectives*
EU	European Union
EUR	euro
EWEA	European Wind Energy Association
EWI	European Wind Initiative
FERC	Federal Energy Regulatory Commission (United States)
FID	final investment decision
FiT	feed-in tariff
FiP	feed-in premium
G8	Group of Eight
GBP	Great Britain pound
GHG	greenhouse gas(es)
Gt	gigatonnes
GW	gigawatt (1 million kW)
GWh	gigawatt hour (1 million kWh)
GWEC	Global Wind Energy Council
hiRen	high renewables (Scenario)
HVDC	high-voltage direct current
IA	implementing agreement
IEA	International Energy Agency
IFI	international financial institution
Irena	International Renewable Energy Agency
ISO	independent system operator
JRC	Joint Research Centre
kW	kilowatt
kWh	kilowatt hour
LCD	liquid-crystal display
LCOE	levelised cost of electricity
Lidar	light and radar, or light detection and ranging
MW	megawatt (1 thousand kW)
MWh	megawatt hour (1 thousand kWh)
NABEG	National Grid Expansion Acceleration Act (Germany)
NGO	non-governmental organisation
NREL	National Renewable Energy Laboratory (United States)
NSCOGI	North Sea Countries' Offshore Grid Initiative
OECD	Organisation for Economic Co-operation and Development
O&M	operation and maintenance
PPA	power purchase agreement
PPP	public-private partnership
PUC	Public Utility Commission
PV	photovoltaic
R&D	research and development
RD&D	research, development and demonstration
REN21	Renewable Energy Network for the 21st Century
REO	rare earth oxide
RES	renewable energy source
RPS	renewable energy portfolio standard
Sodar	sonic detection and ranging
T&D	transmission and distribution

TIMES	The Integrated MARKAL (Marketing and Allocation Model)-EFOM (energy flow optimisation model) System.
TSO	transmission system operator
TWh	terawatthour (1 billion KWh)
TYNDP	Ten-Year Network Development Plan
UK	United Kingdom
UNEP	United Nations Environment Programme
US	United States (of America)
USGS	United States Geological Survey
USD	United States dollar
US DOE	United States Department of Energy
US DOI	United States Department of Interior
VSC	voltage source converter
WACC	weighted average cost of capital

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[13] The values utilised for the chart are based on published information - typically contractor or developer press releases and/or guidance from the relevant project owner through direct consultation. The values have been adjusted for currency, inflation and scope differences. Currency adjustments (principally between sterling, euro and Danish krone) have been made using historical inter-bank data from oanda.com, referenced from the approximate date of financial close or signing of major construction contracts. Inflation adjustments before 1998 have been based on UK Retail Price Index (excluding all housing) using data obtained from the Office for National Statistics. For 1998 onwards, the average of RPI and euro area inflation (Harmonised Indices of Consumer Prices) has been taken - the latter being obtained through the European Commission Eurostat portal. Adjustment for scope differences has been made in cases where grid connection including offshore substation have been provided by a third-party. In these instances, an increase of 15% to 25% has been added which based on GL GH experience is a realistic reflection of the cost of such works. In addition, reductions have been made in cases where Warranty, Operational and Maintenance costs have been included in the published value at a rate of EUR 150 000 per wind turbine per year which, again, is based on GL GH experience and is broadly representative of current and historical levels.

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