Technology Roadmap

Wind energy

International Energy Agency

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The Agency aims to:

- 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.
- Find solutions to global energy challenges through engagement and dialogue with non-member countries, industry, international organisations and other stakeholders.

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Foreword

Current trends in energy supply and use are patently unsustainable – economically, environmentally and socially. Without decisive action, energy-related emissions of CO_2 will more than double by 2050 and increased oil demand will heighten concerns over the security of supplies. We can and must change our current path, but this will take an energy revolution and low-carbon energy technologies will have a crucial role to play. Energy efficiency, many types of renewable energy, carbon capture and storage (CCS), nuclear power and new transport technologies will all require widespread deployment if we are to reach our greenhouse gas (GHG) emission goals. Every major country and sector of the economy must be involved. The task is also urgent if we are to make sure that investment decisions taken now do not saddle us with sub-optimal technologies in the long-term.

There is a growing awareness of the urgent need to turn political statements and analytical work into concrete action. To spark this movement, at the request of the G8, the International Energy Agency (IEA) is developing a series of roadmaps for some of the most important technologies. These roadmaps provide solid analytical footing that enables the international community to move forward on specific technologies. Each roadmap develops a growth path for a particular technology from today to 2050, and identifies technology, financing, policy and public engagement milestones that need to be achieved to realise the technology's full potential. Roadmaps also include special focus on technology development and diffusion to emerging economies. International collaboration will be critical to achieve these goals.

Wind energy is perhaps the most advanced of the "new" renewable energy technologies, but there is still much work to be done. This roadmap identifies the key tasks that must be undertaken in order to achieve a vision of over 2 000 GW of wind energy capacity by 2050. Governments, industry, research institutions and the wider energy sector will need to work together to achieve this goal. Best technology and policy practice must be identified and exchanged with emerging economy partners, to enable the most cost-effective and beneficial development. As the recommendations of the roadmaps are implemented, and as technology and policy frameworks evolve, the potential for different technologies may increase. The IEA will continuously update its analysis of future potentials for wind and other low-carbon technologies, and welcomes stakeholder input as the roadmaps are taken forward.

Nobuo Tanaka

Executive Director, IEA

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Key Roadmap Findings

- This roadmap targets 12% of global electricity from wind power by 2050. 2 016 GW of installed wind capacity will annually avoid the emission of up to 2.8 gigatonnes of CO_2 equivalent.[1] The roadmap also finds that no fundamental barrier exists to achieving these goals or even to exceeding them.
- Achieving these targets requires investment of some USD 3.2 trillion (EUR 2.2 trillion) over the 2010 to 2050 time period. 47 GW will need to be installed on average every year for the next 40 years, up from 27 GW in 2008 – amounting to a 75% increase in annual investment from USD 51.8 bn (EUR 35.2 bn) in 2008 to USD 81 bn (EUR 55 bn).
- Wind energy is a global renewable resource. While market leaders today are OECD member countries with China and India, by 2030 non-OECD economies will produce some 17% of global wind energy, rising to 57% in 2050.
- Onshore wind technology is proven. Wind power can be competitive where the resource is strong and when the cost of carbon is reflected in markets. Wind generation costs per MWh range from USD 70 to USD 130 (EUR 50 to EUR 90).
- Investment costs are expected to decrease further as a result of technology development, deployment and economies of scale – by 23% by 2050. Transitional support is needed to encourage deployment until full competition is achieved.
- Offshore wind technology has further to go in terms of commercialisation. Investment costs at present can be twice those on land, although the quality of the resource may be 50% better. This roadmap projects cost reductions of 38% by 2050.
- To reliably achieve high penetrations of wind power, the flexibility of power systems and the markets they support must be enhanced and eventually increased. Flexibility is a function of access to flexible generation, storage, and demand response, and is greatly enhanced by larger, faster power markets, smart grid technology, and the use of output forecasting in system scheduling.
- To engage public support and allay socio-environmental concerns, improved techniques are required for assessing, minimising and mitigating social and environmental impacts and risks, and more vigorous communication is needed of 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 market-based mechanisms to drive investment, while pursuing cost reductions; set mechanisms for appropriate carbon pricing.
- Advance planning of new plants to attract investment, taking account of other power system needs and competing land/sea-usage.
- Appoint lead agencies to coordinate advance planning of transmission infrastructure to harvest resource-rich areas and interconnect power systems; set incentives to build transmission; assess power system flexibility.
- Increase social acceptance by raising public awareness of the benefits of wind power (including strategic CO_2 emissions reductions, security of supply and economic growth), and of the accompanying need for additional transmission.
- Exchange best practice with developing countries; target development finance at wind power deployment bottlenecks; further develop carbon finance options in developing regions.

1 Or 2.1 Gt CO_2 equivalent annually over and above the emission reductions from wind in the Reference Scenario.

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. This challenge was acknowledged by the ministers from G8 countries, China, India and South Korea, in their meeting in June 2008 in Aomori, Japan, where they declared the wish to have IEA prepare roadmaps to advance innovative energy technology.

> *We will **establish an international initiative with the support of the IEA** to develop roadmaps for innovative technologies and cooperate upon existing and new partnerships* [...] *Reaffirming our Heiligendamm commitment to urgently develop, deploy and foster clean energy technologies, we recognize and encourage a wide range of policy instruments such as transparent regulatory frameworks, economic and fiscal incentives, and public/private partnerships to foster private sector investments in new technologies...*

To achieve this ambitious goal, the IEA has undertaken an effort to develop a series of global technology roadmaps covering 19 technologies, under international guidance and in close consultation with industry. These technologies are evenly divided among demand side and supply side technologies. This wind roadmap is one of the initial roadmaps being developed by the IEA.

The overall aim is to advance global development and uptake of key technologies to reach a 50% CO_2 equivalent emission reduction by 2050 over 2005 levels. The roadmaps will enable governments and industry and financial partners to identify steps needed and implement measures to accelerate required technology development and uptake.

This process starts with a clear definition of what constitutes a "roadmap" in the energy context, and the specific elements it should comprise. Accordingly the IEA has defined its global technology roadmap as:

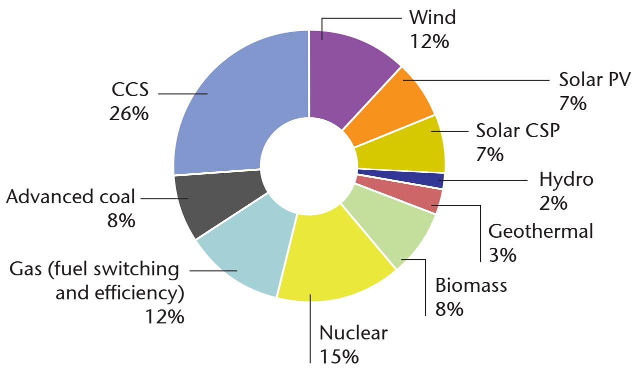
> *... a dynamic set of technical, policy, legal, financial, market and organisational requirements identified by the stakeholders involved in its development. The effort shall lead to improved and enhanced sharing and collaboration of all related technology-specific research, design, development and deployment (RDD&D) information among participants. The goal is to accelerate the overall RDD&D process in order to deliver an earlier uptake of the specific technology into the marketplace.*

Rationale for wind energy

The IEA's *Energy Technology Perspectives 2008* (ETP) publication projects that energy sector emissions of greenhouse gases (GHGs) will increase by 130% over 2005 levels, by 2050, in the absence of new policies (IEA, 2008).

Addressing this increase will require an energy technology revolution involving a portfolio of solutions: greater energy efficiency, renewable energy, nuclear power and the near-decarbonisation of fossil-fuel based power generation. The ETP BLUE Map scenario, which assessed the most cost effective strategies for reducing GHG emissions by half in 2050, concluded that wind power could contribute 12% of the necessary reductions from the power sector (Figure 1). This scenario is used as the basis of targets in this roadmap.

Figure 1: Shares in power sector CO_2 emissions reductions in the BLUE Map scenario by 2050



Source: IEA (2008a).

KEY POINT: Wind power accounts for 12% of global CO_2 emissions reductions in the power sector by 2050.

Additional to the CO_2 benefit of wind power, power sector emissions of pollutants such as oxides of sulphur and nitrogen are reduced. Issues such as water quality and air pollution are high-priority concerns for many countries, and wind energy is attractive because of the local environmental benefits that it provides. Wind energy, like other power technologies based on renewable resources, is widely available throughout the world and can contribute to reduced energy import dependence, entailing no fuel price risk or constraints.

Extensive use of fresh water for cooling of thermal power plant is becoming a serious concern in hot or dry regions. A principal advantage of wind energy for water-stressed areas is its very low consumption of water in comparison with thermal generation. This is already an important issue in China, and a growing concern in India, as well as in OECD member countries such as the (western) United States of America.

The purpose of the roadmap

This roadmap aims to identify the primary tasks that must be addressed in order to reach its vision for wind energy deployment. The cost of wind generation is not the only major barrier to wind power deployment. Broader, systemic issues governing reliable transmission and system integration, social acceptance of infrastructure, and energy market structures are at least as important, and are discussed here.

The roadmap does not attempt to cover every aspect of wind technology and deployment. For example, small wind power and off-grid systems are not addressed. This reflects only a constraint on IEA resources and not the importance or otherwise of such omissions. Neither does the roadmap serve as a beginner's guide to wind energy. For the sake of brevity, only explanatory text that is essential is included. The roadmap website provides links to further background information and reading.

The roadmap was compiled using inputs from a wide range of stakeholders from the wind industry, power sector, research and development (R&D) institutions, finance, and government institutions. Two workshops were held to identify technological and deployment issues and a draft roadmap was subsequently circulated to participants and a wide range of additional reviewers.

Previous roadmaps were identified and constituted important inputs to the process. These include the Unites States Department of Energy's report "20% Wind Energy by 2030", the Japanese Agency for Natural Resources and Energy's "Energy Technology Strategy Map 2007", and the European Wind Energy Technology Platform's "Strategic Research Agenda" of 2008.

The roadmap should be regarded as a work in progress. As IEA analysis moves forward and a new edition of *Energy Technology Perspectives* is published in 2010, new data will emerge, which may provide the basis for updated scenarios and assumptions. More importantly, as the technology, market, power sector and regulatory environment continue to evolve, additional tasks will come to light.

Finally, the objective of this roadmap is to identify actions to accelerate wind deployment globally. In some markets, certain actions will already have been achieved, or will be underway; but many countries, particularly those 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.

Roadmap content and structure

This roadmap is organised into seven major sections. First, the current state of the wind industry is discussed, followed by a section that describes the targets for wind energy deployment between 2010 and 2050 from the *Energy Technology Perspectives 2008* BLUE Map scenario. The discussion on wind deployment targets includes information on the regional distribution of wind generation projects as well as investment needs to deploy these projects, operational costs of wind plants and the total cost of wind energy.

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

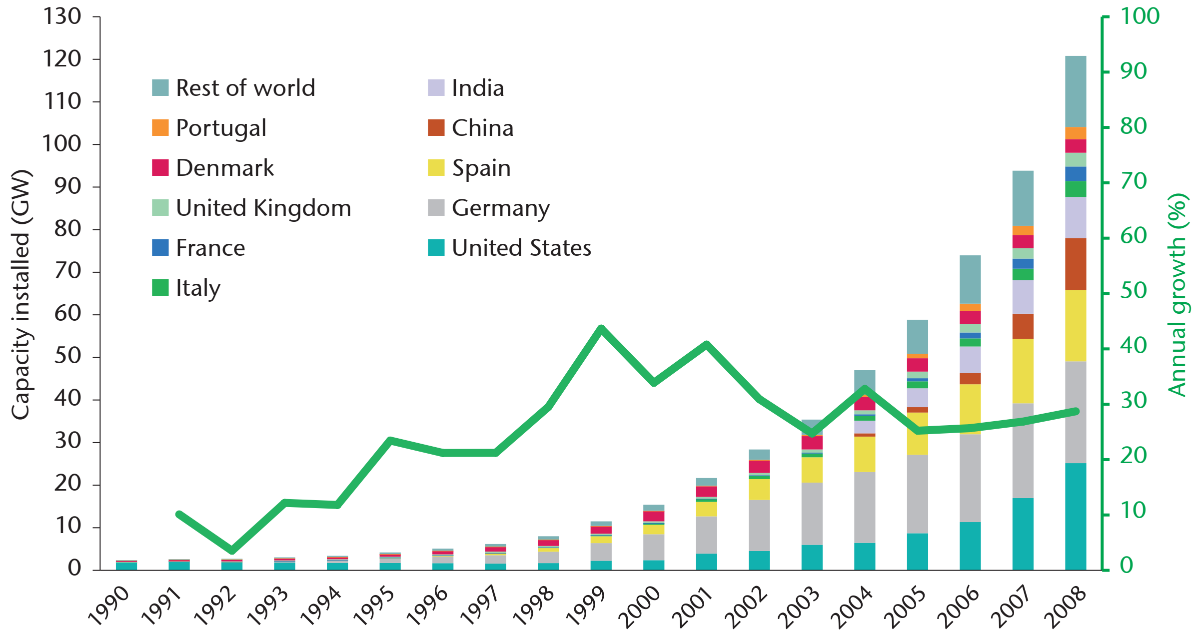
The final section discusses next steps and categorises the actions and milestones from the previous sections by stakeholders (policy makers, industry and power system actors) to help guide them in their efforts to successfully implement the roadmap activities and achieve the global wind deployment targets.

Wind Energy Today

Far from its beginnings in the late 1970s, wind power has become a global industry bearing the logos of established energy giants. In 2008, new investment in wind energy reached USD 51.8 bn (EUR 35.2 bn) (UNEP, 2009). Thriving markets exist where the deployment conditions are right.

In 2008, wind energy provided for nearly 20% of electricity consumption in Denmark, more than 11% in Portugal and Spain, 9% in Ireland and nearly 7% in Germany, over 4% of all European Union (EU) electricity, and nearly 2% in the United States (IEA Wind, 2009).

Figure 2: Global cumulative capacity growth of wind power, showing top ten countries 1990 – 2008 (GW)

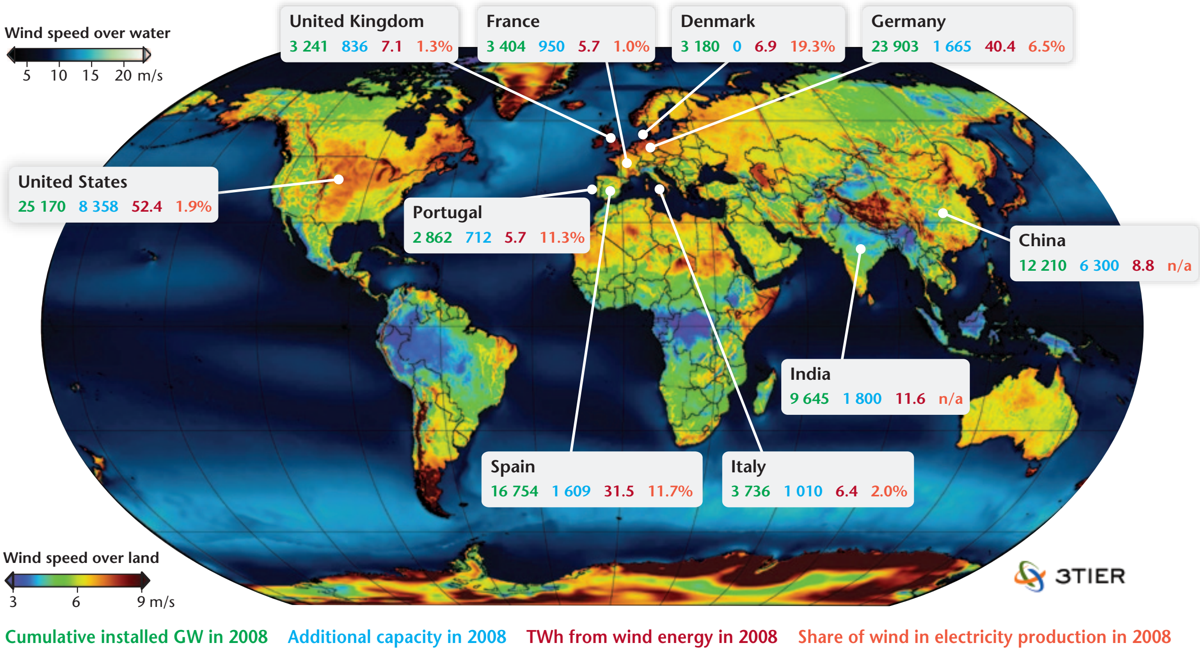


Source: IEA (2008a).

KEY POINT: Wind power capacity continues to grow exponentially.

Since 2000, cumulative installed capacity has grown at an average rate of around 30% per year (Figure 2). In 2008, more than 27 Gigawatts (GW) of capacity were installed in more than 50 countries, bringing global capacity onshore and offshore to 121 GW. Wind energy in 2008 was estimated by the Global Wind Energy Council to have generated some 260 million megawatt hours (260 terawatt hours) of electricity.

Figure 3: World wind resource map with installed capacity and production data for leading countries



Note: 80 m height and 15 km resolution.

Source: Resource data from 3Tier; production and capacity data from IEA, IEA Wind.

KEY POINT: Market leaders include the United States, Germany, Spain, China and India.

In contrast to the situation on land, deployment offshore is at an early stage. The world's first plant, in shallow water, was installed in 1991, about 3 km off the Danish coast. By the end of 2008, approximately 1.5 GW had been installed, mainly in the Baltic, North and Irish Seas: off the coasts of Denmark, the United Kingdom, the Netherlands, Ireland, Sweden and Belgium. Additional offshore turbines are in operation off China, Germany, Italy and Japan, while additional projects are planned in Canada, Estonia, France, Germany, Norway and the United States (Offshore Centre, 2009).

Just six countries worldwide account for almost all wind turbine manufacturing. Although Denmark contains only a little over 3% of global installed wind capacity, at the end of 2008, more than one-third of all turbines operating in the world were manufactured by Danish companies. Other principal turbine manufacturing countries include Germany, Spain, the United States, India and China, with components supplied from a wide range of countries.

Modern wind turbine technology

The average grid connected turbine has a rated capacity of about 1.6 MW. It extracts energy from the wind by means of a horizontal rotor, upwind of the tower, with three blades that can be pitched to control the rotational speed of a shaft linked via a gearbox to a generator, all housed in the "nacelle" atop the tower. Other design variations being pursued include two-bladed rotors, and drive trains with large-diameter low-speed generators in place of the conventional gearbox and high-speed generator. Today's offshore wind turbines are essentially marinised versions of land turbines with, for example, enhanced corrosion protection.

Wind turbines generate electricity from wind speeds ranging from around 15 km/h, (4 metres per second [m/s], corresponding to force three on the Beaufort Scale or a "gentle breeze") to 90 km/h (25 m/s, force nine, or "strong gale").

The *availability* of a wind turbine is the proportion of time that it is ready for use. Availability thus provides a useful indication of operation and maintenance (O&M) requirements, and the reliability of the technology in general. Onshore availabilities are more than 97%. Availability of offshore turbines ranges from around 80% to 95%, reflecting the youth of the technology (Garrad Hassan, 2008).

An important difference between wind power and conventional electricity generation is that wind power output varies as the wind rises and falls. Even when available for operation, wind plants will not operate at full power all of the time. This characteristic of variability will become increasingly significant as wind penetrations of energy rise above around 10%, at which level power system operation and, eventually, design, need to be modified to maintain reliability.

For a comprehensive study of wind energy technology, readers might consult the recent publication *Wind Energy - The Facts*, produced by the European Wind Energy Association (EWEA, 2009).

Economics

Under specific conditions, onshore wind energy is competitive with newly built conventional power plants today, for example where the carbon cost is effectively internalised, the resource is good, and conventional generation costs are high, as in California. In Europe, with a stable, meaningful carbon price under the European Emission Trading System, competition with newly built coal plants would be possible at many sites. However, competitiveness is not yet the rule, and reduced life cycle cost of energy (LCOE) from wind is a primary objective for the wind industry. Therefore, this roadmap targets competitiveness with conventional electricity production as a key goal, the achievement of which is necessary so that market forces can be more heavily relied upon to incentivise investment in new wind power deployment.[2]

2 The IEA Wind "Task 26 - Cost of Wind Energy" group has recently begun work to develop a standard methodology to assess wind energy costs. See www.ieawind.org

A fully representative assessment of the costs of all types of electricity production technologies and fuel sources would take into account external (socio-environmental) costs. Integrating the cost of induced climate change, as well as pollutants, into electricity markets can generate new revenues for clean energy production, and increase the competitiveness of clean energy, including wind.

Investment costs

In 2008, reported investment costs for wind generation (including turbine, grid connection, foundations, infrastructure, etc.) for European projects on land ranged from USD 1.45 to USD 2.6 million/MW (EUR 1 to EUR 1.9 million). In North America, investment costs ranged from USD 1.4 to USD 1.9 million/MW (EUR 0.98 to EUR 1.3 million); and in Japan from USD 2.6 to USD 3.2 million (EUR 1.8 to EUR 2.2 million) (IEA Wind, 2009). Costs in India and China stand at just under and just over USD 1 million/MW (EUR 1.45), respectively (GWEC, 2009).

Following a period of steadily declining investment costs, from the late 1980s, investment costs rose considerably in 2004, 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) that made it difficult to meet the increasing demand for these parts; as well as, to a lesser extent, higher commodity prices, particularly for steel and copper. While the current recession has loosened the turbine market, supply bottlenecks are likely to recur when markets fully recover, particularly if new investment in manufacturing has stagnated in the meantime, and may lead to re-inflated investment costs.

Lifecycle cost of energy

The lifecycle cost of energy (LCOE) of wind energy can vary significantly according to the investment cost, the quality of the wind resource, operation and maintenance (O&M) requirements, turbine longevity and the date of commissioning, and the cost of investment capital. Regional differences such as geography, population density and regulatory processes contribute to variations in development and installation costs and ultimately the LCOE of wind energy. For the purposes of this roadmap, wind LCOE is considered to range from a low of USD 70 (EUR 50)/MWh, under the best circumstances, to a high of USD 130 (EUR 90).

The recent US Department of Energy *Wi nd Technologies Market Report* estimates that the nation-wide capacity-weighted average price paid for wind power in 2008 (generated by projects commissioned during the period 2006 to 2008) was around USD 47/MWh. This price includes the benefit of the federal production tax credit, which has a value of at least USD 20/MWh according to the report, and other state level incentives (US DOE, 2009).

Operations and maintenance

The operations and maintenance (O&M) cost of wind turbines including service, spare parts, insurance, administration, site rent, consumables and power from the grid, is an important component in the cost of a wind power project. It is difficult to extrapolate general cost figures due to low availability of data. Additionally, because the technology is evolving so fast, O&M requirements differ greatly, according to the sophistication and age of the turbine. A sample of projects examined recently in the United States suggested that O&M costs since 2000 range from USD 32/MWh (EUR 22) for projects built in the 1990s to USD 12/MWh (EUR 8) for projects built in the 2000s (US DOE, 2009).

Offshore costs

There are limited data on offshore costs making it difficult to estimate an average cost since projects vary greatly in nature. In offshore projects, the turbine makes up only half of the investment cost, compared to three-quarters for land-based projects. The remaining costs consist mostly of foundation and cabling costs, which vary with distance from shore and water depth. Investment costs for offshore wind can be more than twice those for onshore wind developments. In 2008 offshore investment costs reached USD 3.1 million (EUR 2.1 million)/MW in the United Kingdom and USD 4.7 million (EUR 3.2 million)/MW in Germany and the Netherlands (IEA Wind, 2009).

The lifecycle cost per megawatt hour of electricity generated by offshore projects constructed between 2005 and 2008 is estimated to range from USD 110 to USD 131 (EUR 75 to EUR 90)/MWh (EWEA, 2009). Higher wind speeds offshore mean that plants can produce about 50% more energy than their counterparts on land, offsetting the higher investment costs to some extent. Reported O&M costs for offshore projects in the United Kindgom built from 2005 onwards range from USD 21 (EUR 14)/MWh in 2005 to USD 48 (EUR 33)/MWh in 2007 (JRC, 2009).[3]

3 Although not within the scope of this report, it is important to note that the variable nature of wind output, at high shares, will incur additional costs to the power system in the form of balancing costs. A range of studies assessing balancing costs are summarised and contrasted in the recently completed report from the IEA Wind Implementing Agreement Task 25 "Design and operation of power systems with large amounts of wind power" (IEA Wind, 2009b).

Table 1: Onshore and offshore wind costs

	Onshore wind	Offshore wind
Investment costs	USD 1.4 to USD 2.6 million/MW (EUR 0.98 to EUR 1.9 million/MW) (*Europe, US costs*)	USD 3.1 to USD 4.7 million/MW (EUR 2.1 to EUR 3.2 million/WM)
Operation and maintenance costs (O&M)	USD 12 to USD 32/MWh (EUR 8 to EUR 22/MWh)	USD 21 to USD 48/MWh (EUR 14 to EUR 48/MWh)
Lifecycle cost of energy (LCOE)	USD 70 to USD 130/MWh (EUR 50 to EUR 90/MWh)	USD 110 to USD 131/MWh (EUR 75 to EUR 90/MWh)

Source: IEA analysis

Vision for Deployment and CO_2 Abatement

Recent estimates suggest that sufficient energy is available in the wind to supply the planet's needs for energy several times over (EEA, 2009; Lu *et al.*, 2009). A recent assessment carried out by the European Environment Agency suggests that the potential in the European Union is about 30 400 TWh, seven times projected electricity demand in 2030 (EEA, 2009). A similar report for the United States concluded "more than 8 000 GW of wind energy is available in the United States at $85/MWh or less ... equivalent to roughly eight times the existing nameplate generating capacity in the country" (US DOE, 2008).

Within this raw potential of wind to supply our power needs, however, the amount of wind resource that can presently be harvested in a cost effective manner is much less. This economically cost-effective potential will increase over time as the technology matures, the cost of energy falls, and power systems evolve the ability to incorporate greater wind energy production.

Blue Map Scenario: CO_2 Reduction Targets

Wind power plants installed by the end of 2008 are estimated to avoid the emission of some 230 megatonnes of CO_2 per year (BTM, 2009).

In the IEA *Energy Technology Perspectives* BLUE Map scenario, which this roadmap takes as its point of departure, deployment of wind power contributes 12% of the power sector CO_2 emissions reductions in 2050. In that scenario, global electricity production in 2050 is almost entirely based on zero-carbon emitting energy technologies, including renewables (46.5%), fossil fuels with carbon capture and storage (26%), and nuclear (23%).

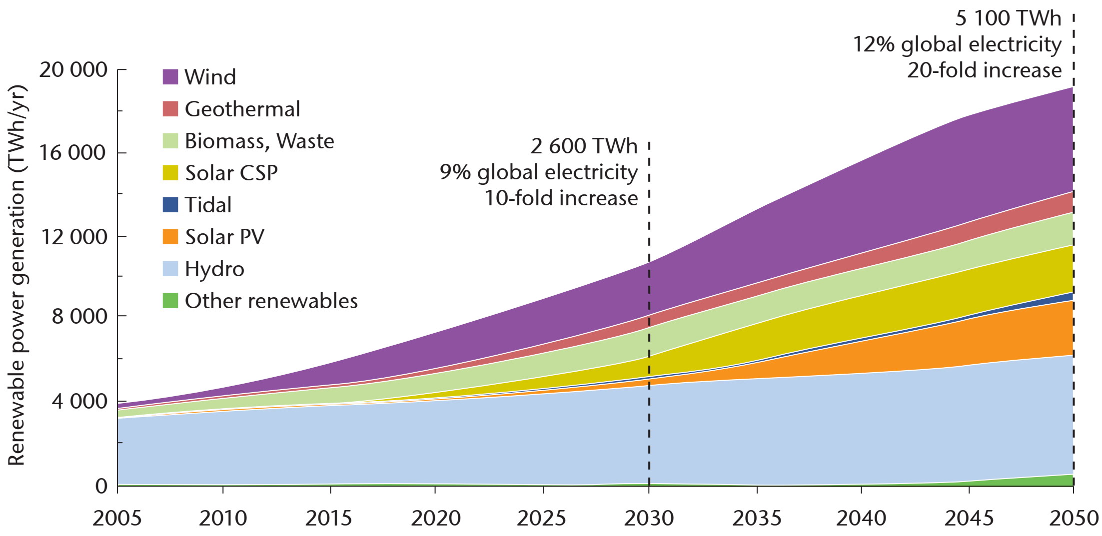
Over the complete life-cycle of wind power plants, emissions of CO_2 are negligible. While the variable nature of wind power presents challenges, it does not negate its role in emissions reductions. The emissions generated by the flexible reserves required for when variable renewables such as wind power are not generating are greatly outweighed by the emissions avoided from increasing wind capacity. In the ETP BLUE scenario, gas capacity supporting variable renewables operates for just 440 full load hours per year, or eight and a half hours per week (IEA, 2008a).

Energy Technology Perspectives BLUE Map scenario

This roadmap outlines a set of quantitative measures and qualitative actions that define one global pathway for wind deployment to 2050. This roadmap starts with the IEA *Energy Technology Perspectives* (ETP) BLUE Map scenario, which describes how energy technologies may be transformed by 2050 to achieve the global goal of reducing annual CO_2 emissions to half that of 2005 levels. The model is a bottom-up MARKAL 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. The ETP model is a global fifteen-region model that permits the analysis of fuel and technology choices throughout the energy system. The model's detailed representation of technology options includes about 1 000 individual technologies. The model has been developed over a number of years and has been used in many analyses of the global energy sector. In addition, the ETP model was supplemented with detailed demand-side models for all major end-uses in the industry, buildings and transport sectors.

By 2030, approximately 2 700 terawatt hours (TWh) of wind electricity is estimated to be produced annually from over 1 000 GW of wind capacity, corresponding to 9% of global electricity production. This rises to 5 200 TWh (12%, over 2 000 GW) in 2050 (Figure 4). An essential message of the ETP study is that there is no single energy technology solution that can solve the combined challenges of climate change, energy security and access to energy. The ETP model is based on competition among a range of technology options, and the resulting technology portfolio reflects a least cost option to reduce CO_2 emissions, rather than the maximum possible wind deployment. Figure 4 illustrates the role of renewable energy in the global power portfolio to 2050.

Figure 4: Electricity from renewable energy sources up to 2050 in the ETP 2008 BLUE Map scenario

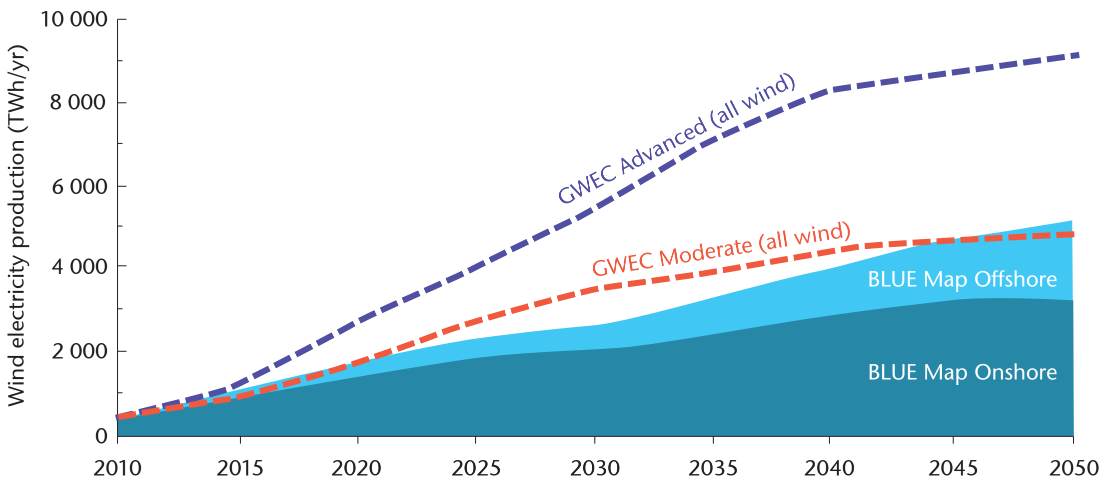


Source: IEA (2008a).

KEY POINT: Wind production increases ten-fold in 2030, and twenty-fold in 2050, over the 2008 level.

The wind industry suggests that production could increase considerably more if strong, early action is taken by governments worldwide to support deployment. Industry projections for wind energy deployment reach 5 400 TWh in 2030, and 9 100 TWh in 2050, shown in the broken lines in Figure 5 (GWEC, 2008).

Figure 5: Wind electricity production in ETP 2008 BLUE Map scenario and industry analysis



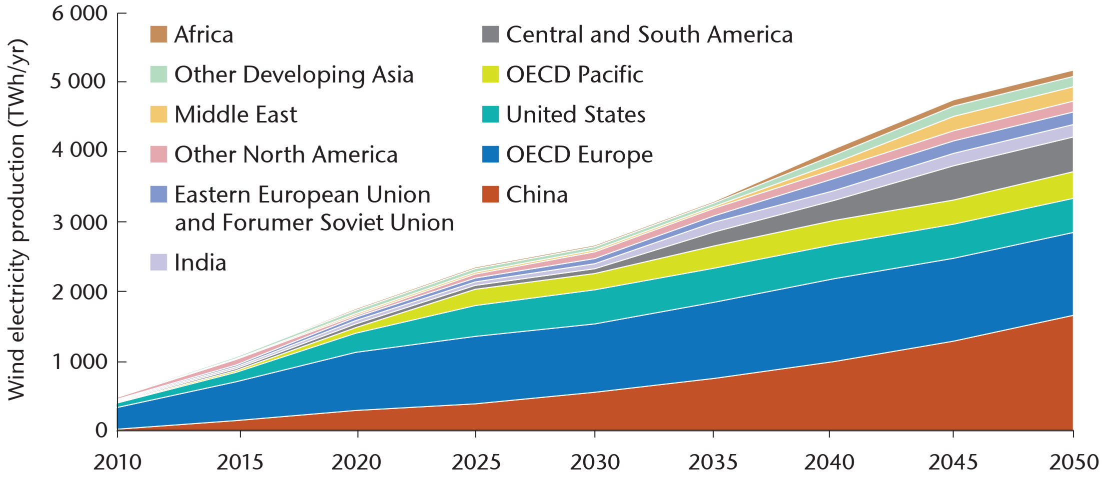
Source: IEA (2008a), Global Wind Energy Council (GWEC) (2008).

KEY POINT: Industry estimates suggest that wind potential in 2050 could be 80% greater than the BLUE Map scenario.

While offshore wind power remains more expensive, deployment is expected to take place mainly on land. The present offshore industry is located almost entirely in Northern Europe where land resources with good wind conditions are scarcer than in regions like North America and China. Moreover, water depth is a principal cost factor in offshore development, and the majority of offshore deployment is taking place in the North, Baltic and Irish Seas, which are areas of continental shelf (shallower seas) and so are currently less costly for wind development than in deeper oceans. It will be critical to place greater emphasis on offshore technology R&D to achieve roadmap targets for cost effective wind energy.

According to the BLUE Map scenario, in 2020 OECD Europe remains the leading market for wind power, followed by the United States and then China. By 2030 China overtakes the United States (557 TWh and 489 TWh respectively), and OECD Pacific countries emerge as an important market at 233 TWh. By 2050, China leads with 1 660 TWh, followed by OECD Europe and the United States, which are shown to remain steady from 2030, and then by OECD Pacific countries and Central and South America. The remaining regions, including India, Africa and the Middle East, provide nearly one-fifth of wind electricity in 2050 (Figure 6).

Figure 6: Regional production of wind electricity in the ETP 2008 BLUE Map scenario



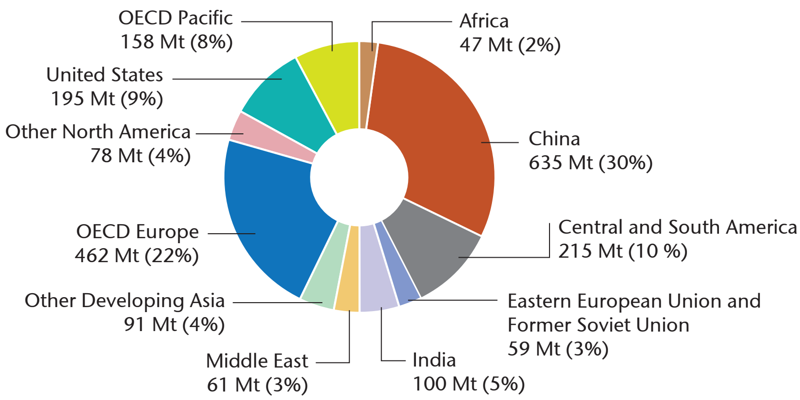
Source: IEA (2008a).

KEY POINT: Leading markets over the period are China, OECD Europe and the United States. OECD Pacific countries gain importance after 2020, and Central and South America after 2030.

CO_2 abatement from wind energy under the BLUE Map scenario reaches a total of 2 100 Mt per year over the Reference Scenario in 2050 (2 800 Mt in total[4]). China makes the largest contribution with 635 million tonnes (Mt) avoided, followed by OECD Europe at 462 Mt, and Central and South America with 215 Mt (Figure 7).

4 This figure represents CO_2 emissions savings due to wind power plants in both the BLUE and Reference Scenarios.

Figure 7: CO_2 emissions reductions in 2050 (over emissions abated by wind in the IEA Reference Scenario) (Mt)



Source: IEA (2008a).

KEY POINT: Smaller wind markets make an important contribution to CO_2 abatement.

Comparisons with other scenarios

There are important differences between the ETP BLUE Map scenario and the Global Wind Energy Council (GWEC) Advanced Scenario, in terms of global growth projected. In particular, the scenarios have different pathways for the accelerated growth of wind power in regions that currently have little installed wind energy capacity. For example, the GWEC Advanced Scenario projects over 630 GW of installed capacity in India, Eastern Europe and former Soviet Union countries, the Middle East, other developing Asian countries and Africa combined in 2030. In contrast, the ETP BLUE Map scenario estimates just over 100 GW. Markets in North America and China are also twice the size projected in BLUE Map, with 520 GW and 451 GW respectively.

The recent US DOE report, *20% Wind Energy by 2030*, projects 300 GW of installed capacity in 2030, compared with 211 GW in the ETP BLUE Map scenario (US DOE, 2008). For the European Union, the wind industry projects from 300 GW to 350 GW in its "moderate" and "high" scenarios respectively. ETP BLUE Map for OECD Europe projects 360 GW. China is likely to adopt an official target of 100 GW wind power by 2020, less than the 128 GW envisaged in ETP. So, while it is clear there are different pathways for wind deployment, this roadmap, and the ETP BLUE Map scenario on which it is based, represents a realistic pathway for major expansion in global wind energy.

Potential for cost reductions

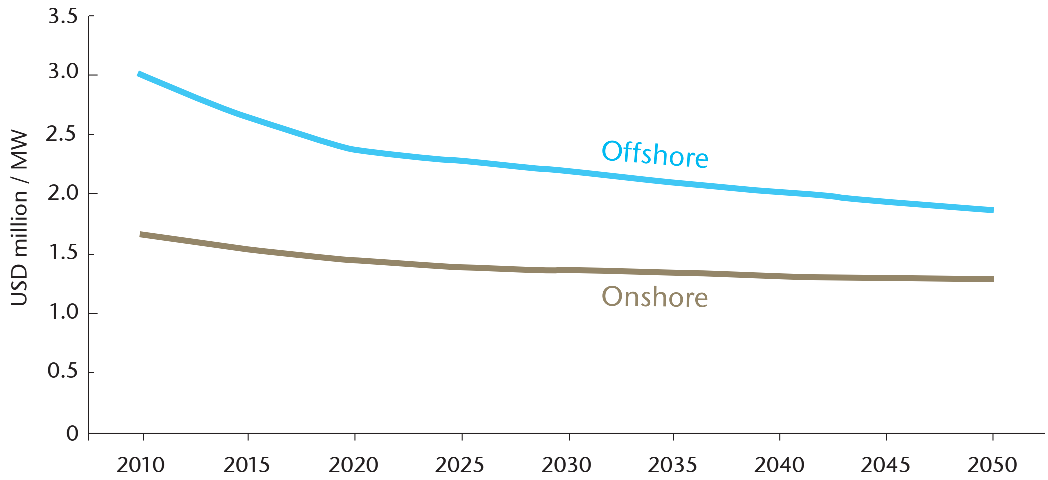
Technology innovation remains a crucial driver for reduced LCOE of wind energy. The cost of onshore wind turbines (about 75% of the total onshore investment cost) has decreased by around a factor of three since the early 1980s, although since 2004 cost reductions have not been fully realised due to inflated prices from supply constraints and higher commodity prices among other factors.

Until recently, the scaling up of turbines was an important driver for cost reductions but affordable materials with higher strength to mass ratios are necessary before turbines will grow much further cost-effectively. Nonetheless, with sufficient research efforts, technological innovation will continue to improve energy capture by the rotor (particularly at low speeds, in complex terrain and under turbulent conditions); increase the time offshore plants are available for operation; reduce O&M requirements; extend turbine lifespans; and reduce the cost of components. Additionally, the opening of new markets and resulting economies of scale, as well as stronger supply chains, have the potential to yield further cost reductions.

The ETP BLUE Map scenario assumes a learning rate[5] for wind energy of 7% onshore and 9% offshore up to 2050. Starting from USD 1.7 million (EUR 1.2 million)/MW in 2010, onshore investment costs decrease to USD 1.4 million (EUR 0.95 million)/MW in 2030, and to USD 1.3 million (EUR 0.88 million)/MW in 2050 (Figure 8). Over the period, this would be a total cost reduction of 23%. The analysis assumes a 17% cost reduction in onshore O&M costs by 2030, and by 23% in 2050.

The US DOE assumes a 10% reduction in onshore LCOE is possible by 2030 (alongside an average capacity factor increase of six percentage points). The report assumes a 14% reduction in overall O&M costs (37% of variable O&M costs) (US DOE, 2008).

Figure 8: ETP BLUE Map scenario projections for development of onshore and offshore wind investment costs (USD/MW)



Source: IEA (2008a).

KEY POINT: The BLUE Map scenario projects an onshore investment cost reduction of 23%, and 38% offshore by 2050, from 2010.

Given its state of development, offshore wind energy, especially deep offshore, is likely to see faster reductions in cost. Offshore investment costs in the ETP BLUE Map scenario fall by 27% by 2030, and by 38% in 2050. Greater reliability, availability and reduced O&M cost are particularly important for offshore development as access can be difficult and expensive. The roadmap assumes that offshore O&M costs will have fallen by 25% in 2030, and by 35% in 2050.

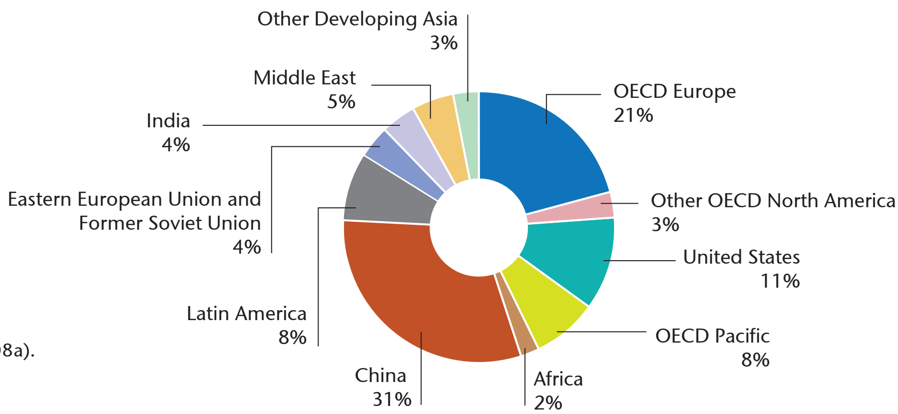
5 In retrospect, past cost reductions can be seen to demonstrate a steady "learning" or "experience" rate. Learning or experience curves reflect the reduction in the cost of energy achieved with each doubling of capacity – known as the progress ratio.

Global investment to 2050

Approximately USD 3.2 trillion of investment (EUR 2.2 trillion) will be required to reach the BLUE Map finding of 12% global electricity produced from wind energy in 2050. While this number seems large, it is just 1% of the additional investment needs required to achieve the BLUE Map goal of reducing CO_2 emissions 50% by 2050.

Current investment in wind power deployment is considerable, but not sufficient. Wind power saw nearly USD 52 bn (EUR 35 bn) of new investment in 2008, of which asset finance, investment in new generation assets, made up 92% (UNEP, 2009). The BLUE Map scenario projects over 2 000 GW of installed capacity in 2050, up from 120 GW in 2008. This would require an average annual installation of 47 GW for the next 40 years, up from 27 GW in 2008. This is equal to an additional 75% over present investment, to around USD 81 bn per year (EUR 55 bn).[6] [7]

Figure 9: Regional shares of cumulative wind energy investment by 2050 in the BLUE Map scenario[7]



Source: ETP (2008a).

KEY POINT: More than half of global cumulative investment will take place outside OECD countries.

6 The most ambitious global industry projection considers 3 498 GW installed by 2050, which would require an average annual installation rate of 84 GW, the equivalent of trebling the present installation rate.

7 Based on cost of USD 1.77 million (EUR 1.2 million) per MW.

Wind Technology Development and Deployment: Actions and Milestones

Increased efforts in wind technology R&D are essential if the vision of this roadmap is to become reality. Wind energy technology is proven but not yet fully mature. No single element of onshore turbine design is likely to dramatically reduce cost of energy in the years ahead, but there are many areas where design can be improved, which, taken together, could considerably reduce the life cycle cost of wind energy. Notably, this road mapping exercise concluded that greater potential remains for technology breakthrough in the offshore sector than in the land-based wind sector.

Three technology areas specific to wind energy require particular attention and apply to both onshore and offshore wind. These areas include wind energy resource assessment, including characterisation and forecasting methods; wind turbine technology and design; and supply chain issues. In the light of continually evolving technology and to ensure high reliability, standards and certification procedures will be crucial to the successful deployment of new wind power technologies.

Metrics for quantifying technology improvements

One way to quantify efficiency improvements in wind energy extraction is by measuring the increase in electricity production while holding the rated power of the turbine and the quality of the wind resource constant. In other words, for the same installed capacity, in the same place, the additional energy produced (via, for example, operation over a wider range of wind speeds, or reduced losses) represents the increased efficiency gained, for example, by implementing a new technology.

The capacity factor is a measure of energy production, and represents the ratio of the actual output of a power plant over a period of time and its output if it had continuously operated at full capacity over that same period. For wind generation it is typically used to express the quality of wind resources in different locations. However, it can also be used as a metric to measure improvements in energy extraction as described above.

An advantage of using the capacity factor metric to measure efficiency improvements is that it is used for all electricity generating technologies, and so enables comparisons to be made across a large scope of technologies. The US DOE has developed a summary of wind turbine performance improvements expressed in terms of capacity factors, which is reproduced in Table 2.

Table 2: Potential improvements in capacity factor from advances in wind turbine technology

Technical area	Annual energy production (% increase of existing capacity factors) – best/expected/least
Advanced tower concepts	+11/+11/+11
Advanced rotors	+35/+25/+10
Reduced energy losses and improved availability	+7/+5/0
Drive-train (gearboxes, generators and power electronics)	+8/+4/0

Source: US DOE (2008).

Wind energy resource assessment

This roadmap recommends the following actions:	Milestones
1. Refine and set standards for wind resource modelling techniques, and site-based data measurement with remote sensing technology; improve understanding of complex terrain, offshore conditions and icy climates.	Ongoing. Complete by 2015.
2. Develop a publicly accessible database of onshore and offshore wind resources and conditions, with the greatest possible coverage taking into account commercial sensitivities.	Complete by 2015.
3. Develop more accurate, longer-horizon forecast models, for use in power system operation.	Ongoing. Complete by 2015.

Set standards for resource assessment

There is a need for standardised methods for computer modelling of the resource, data gathering and onsite measurement of wind resources. Resource data are particularly sparse in developing countries as well as for wind at heights above 80 metres. Standardised data collection and analyses near demand centres and existing transmission infrastructure are of particular value in the near-term.

A computer model of the wind resource alone is insufficient basis for building a wind plant. Modelled data must be compared against real data gathered in the field. Anemometry masts, which measure the wind speed at a certain height, are the usual method, but are costly, particularly offshore. Remote sensing using SODAR or LIDAR technologies, and computational fluid dynamics (CFD) techniques to model air flow, have the potential to provide a reliable alternative in time. These technologies are already available but need to be refined and validated to be a realistic alternative to mast anemometry.[8]

Models are needed to accurately depict wind patterns in different types of land features such as ground cover, coastlines and hills, which greatly complicate the way wind behaves. In 1982, the IEA Wind Implementing Agreement coordinated an important field experiment that examined the effect of low hills on the flow of wind. The Askervein Hill Project in the Outer Hebrides, off Scotland, comprised 50 measurement masts and yielded data that remained the basis for modelling for the next 25 years. Japanese research is ongoing to develop wind models for complex terrains, based on analysis of meteorological data at more than 300 locations, and the use of remote sensing in mountainous terrain.

Data are also needed on wake effects, the influence of one turbine on the air flow incident on another turbine. This phenomenon can have serious implications for energy capture, which can be reduced by as much as 10% within a wind power plant. Wake effects are particularly persistent offshore, and can influence energy capture among neighbouring wind plants. This is likely to become a more serious factor by 2030 as larger numbers of offshore wind plants are installed in greater proximity to each other.

Share wind resource data

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. The compilation of wind characteristics over large areas – greater than a 200 km radius – could also significantly increase understanding of the extent to which distance can smooth the aggregated output profile of widely dispersed plants.

8 The IEA Wind Implementing Agreement Task 11 is developing recommended practices using SODAR and LIDAR to assess the wind resource.

Commercial sensitivity concerns need to be addressed by the industry to establish which data can realistically be included. The database should include details of wind variability, average speeds and extreme speeds, and link to other databases of the solar resource, site topography, air temperature, lightning strikes, and seismic activity.

Improve wind forecasting accuracy

Improving the predictability of wind resources will increase the economic value of wind-generated electricity in the power market by helping producers meet delivery commitments. Discrepancy between the volume of electricity scheduled for delivery to the market and the amount actually delivered results in a supply imbalance that must be offset by flexible plants and other resources, and which in some cases incurs a penalty to the producer.

The most flexible, rapidly dispatching plants, such as open cycle gas turbines (OCGT), have expensive fuel requirements. More accurate, longer term output forecasts would increase the extent to which plants with less rapid dispatch times but cheaper fuel requirements, such as coal and combined-cycle gas turbines, can be scheduled to balance fluctuating wind output on the system.

Advanced forecasting models should be developed that use meteorological data, online data from operating wind plants, and remote sensing technology. Once validated, it is important that such models are implemented by power system operators.

Improved wind turbines

This roadmap recommends the following actions:	Milestones
1. Develop stronger, lighter materials to enable larger rotors, lighter nacelles, and to reduce dependence on steel for towers; develop super-conductor technology for lighter, more electrically efficient generators; deepen understanding of behaviour of very large, more flexible rotors.	Ongoing. Continue over 2010-2050 time period.
2. Build shared database of offshore operating experiences, taking into account commercial sensitivity issues; target increase of availability of offshore turbines to current best-in-class of 95%.	Complete by 2015.
3. Develop competitive, alternative foundation-types for use in water depths up to 40 m.	Ongoing. Complete by 2015.
4. Fundamentally design new generation of turbines for offshore application, with minimum O&M requirement.	Commercial scale prototypes by 2020.
5. Develop deep-water foundations/sub-surface structures for use in depths up to 200 m.	Ongoing. Complete by 2025.

Accelerate reduction of turbine cost

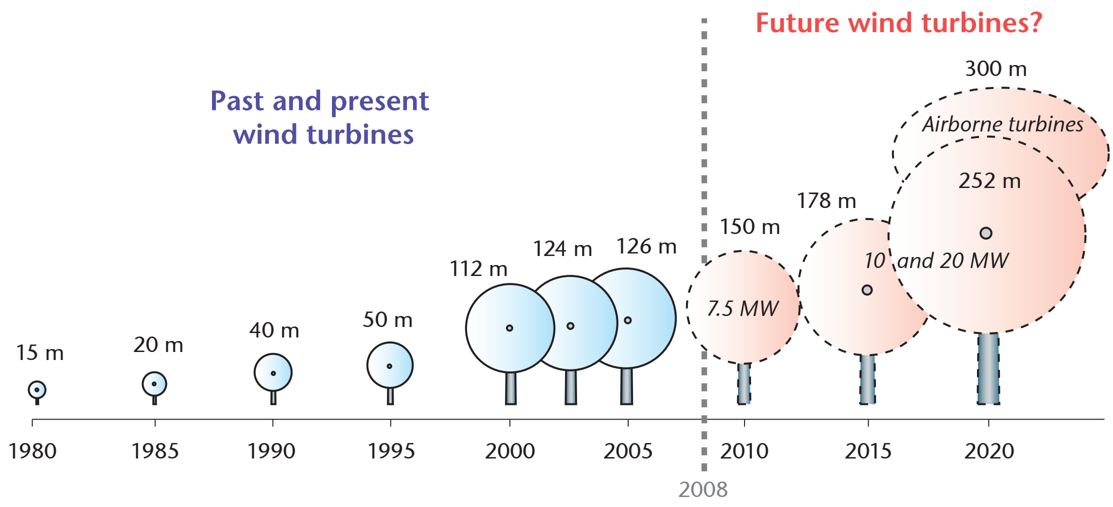
Onshore wind turbine development is now characterised by incremental reductions in the cost of energy, rather than by single, disruptive technology leaps. Deeper understanding of the conditions to which a wind power plant will be subjected over its lifetime will facilitate the development of improved turbine designs with the ability to extract more energy from the wind, more of the time, over a longer lifetime, and in specific operating environments (*e.g.,* areas of higher typhoon activity or extreme cold).

Energy capture in the rotor holds the greatest potential for long-term reduction of the cost of wind energy. The larger the area through which the turbine can extract that energy (the swept area of the rotor), and the higher the rotor can be installed (to take advantage of more rapidly moving air), the more power that can be captured. However, a larger swept area typically means a heavier rotor, which is needed to cope with increased loading during high wind events, and increased costs. This factor has effectively set an economically optimum rotor size, based on cost-effective materials available today.

Advanced materials with higher strength to mass ratios, such as carbon fibre and titanium, could enable larger area rotors to be cost-effective, but their usage has yet to be made commercially feasible. Additional cost reductions could be achieved through lighter generators and other drive train components, which would reduce tower head mass. New materials could also encourage a transition away from industry's current dependence on steel for taller towers (see Figure 10).

As rotors become larger with longer, more flexible blades, a fuller understanding of their behaviour during operation is required to inform new designs. Notable rotor-research areas include advanced computational fluid dynamics models; methods to reduce loads or suppress their transmission to other parts of the turbine, such as the gearbox or tower head; innovative aerofoil design; nanotechnology to reduce icing and dirt build-up; and lower aerodynamic noise emission.

Figure 10: Growth in size of wind turbines since 1980



Source: Adapted from EWEA (2009).

KEY POINT: Affordable materials with higher strength-to-mass ratios are needed to enable larger turbines.

Additional cost savings can be achieved through technology developments that reduce electrical losses in the generator and attendant electrical/electronic components. Enabling technologies include innovative power electronics, use of permanent magnet generators, and super conductor technology.

Improve offshore turbine performance

Greater reliability of all components, such as gear boxes and generators, is an important objective in the offshore context. High access costs and often narrow weather windows mean that a new balance needs to be struck between upfront investment costs and subsequent O&M costs – a balance that places a higher premium on reliability. Reliability and other operational improvements would be accelerated through a greater sharing of operating experience among industry actors, including experiences related to other marine technologies such as wave and ocean current technologies.

Unlike the early stages of the offshore oil and gas industry, to date there is little evidence of information sharing among entities in the offshore wind industry; however a database of operating experiences is currently under development at the German Institute for Wind Energy Research and System Integration (IWES), which could represent a potential nucleus for wider, international research cooperation.

Again, commercial sensitivities will be important, but a way should be sought to make operational data available through a shared database, possibly facilitated by government actors, to accelerate learning industry-wide. Current "best in class" operating availability of 95% should be adopted as a target for the offshore sector as a whole.

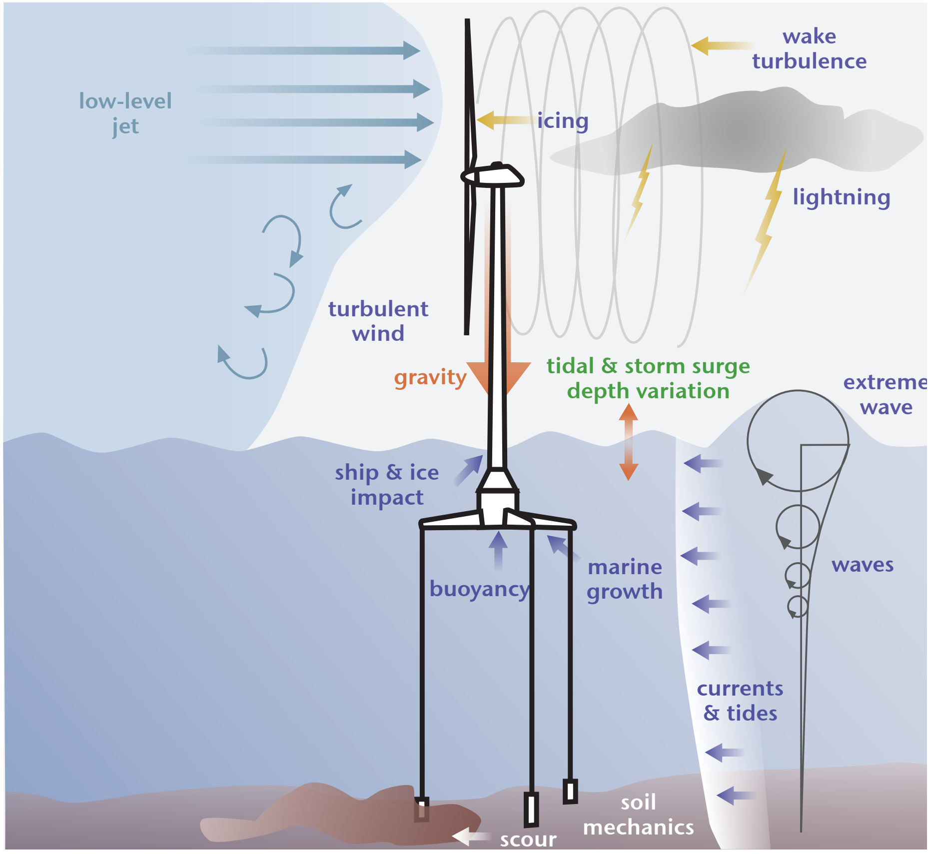
Design dedicated offshore turbines

Although a number of companies are field-testing turbines purpose-built for the offshore environment, most offshore wind turbines today resemble "marinised" onshore wind turbines. Because the real requirements of wind technology in offshore conditions remain insufficiently understood, conservative design practices have been adopted from other offshore industries for use in turbine design. These persisting uncertainties need to be resolved so design processes can build in more appropriate (potentially lower) safety margins.[9]

A new generation of more robust turbines should be developed that are designed from the very beginning for the offshore environment. The design of "dedicated" offshore turbines would be based on specific offshore operating conditions. The combined effects of different loads on all parts of the wind turbine and foundations, as the marine atmosphere interacts with sea waves and currents (Figure 11), is worthy of particular focus.

9 Assessment of a number of shallow, transitional, and deep-water offshore concepts is ongoing in the IEA Wind Task 23 Offshore Wind Technology and Deployment group.

Figure 11: Offshore operating conditions



Source: US DOE.

KEY POINT: Greater understanding is required of the complex range of forces acting on offshore wind turbines.

One possible development pathway could be a turbine with two blades rotating downwind of the tower, with a direct-drive generator (no gearbox), and simplified power electronics. Turbine capacity could be as much as 10 MW, with a rotor 150 m in diameter. It should require minimal onsite O&M. To achieve this, it could be equipped with system redundancy and remote, advanced condition monitoring and self-diagnostic systems, which would reduce the duration and frequency of on-site repairs. Such approaches would also help prevent the escalation of minor faults into serious failures that result from delayed access to the site owing to poor weather conditions.

Design new deep-water foundations

The foundations of most offshore projects to date consist of a single pile driven into the seabed, called a monopile. Current monopile designs make up about 25% of the total investment and installation costs.

New types of foundations, developed with improved knowledge of the sub-surface environment, may present significant potential for cost reduction. At this time, apart from the experimental offshore turbines off the Scottish coast (at 44 m), no offshore wind farms are known to be operating in depths greater than 30 m which is where some of the best offshore wind resources are found. Other designs using tripod, lattice, gravity-based and suction bucket technologies should be developed for use in water depths up to around 40 m.

For deeper water, new floating designs will need to be demonstrated and readied for commercial deployment. Again there may be opportunity for technology transfer from the offshore oil and gas industry. Development of new designs has already begun. In December 2007, a floating platform prototype was deployed off Sicily, while another prototype is scheduled for deployment off the Norwegian coast in 2009.

Supply chains

This roadmap recommends the following actions:	Milestones
1. Develop internationally standard education and training strategies for the complete range of skills needed, from design to deployment.	Complete by 2015.
2. Accelerate automated, localised, large-scale manufacturing for economies of scale, with an increased number of recyclable components.	Ongoing. Continue over 2010-2050 period.
3. For offshore deployment, make available sufficient purpose-designed vessels; improve installation strategies to minimise work at sea; make available sufficient and suitably equipped large harbour space.	Sufficient capacity by 2015.

As a result of successful growth and policy support, wind energy has grown tremendously over the past decades. However, this has given rise to bottlenecks in supply of key components, including labour. These must be resolved if the hundreds of thousands of new turbines necessary to meet this roadmap's vision are to be made a reality. Strong supply chains will provide stability and predictability for investors. The roadmap has identified several areas where the industry and public partners can make significant progress.

Develop wind workforce

To achieve the vision of this roadmap, a large, skilled workforce will be needed to develop new designs, establish new manufacturing plants in new locations, develop installation technologies, and to build, operate and maintain the resulting wind power plants.

However, trained personnel are in short supply. For example, in the United States, the number of engineers graduating from power engineering programmes today is one-quarter of its level in the 1980s. The US national Science and Technology Council currently predicts that the number of graduates in science and engineering degrees will continue to fall for the next 40 years (NSTC, 2000). This reflects a trend that is occurring in a number of other industries and will need to be reversed.

Strong governmental support can help the establishment of education and training activities to create the needed workforce. For example, in June this year the US Department of Labor announced the designation of USD 500 million (EUR 340 million) for clean energy job training (US DoL, 2009). In Europe, a number of training programmes are provided, with centres of excellence located at specific universities. The European Academy of Wind Energy hub links the key institutions. However, the wind industry needs a more concerted and coherent training framework that offers comparable qualifications from a wide range of institutions and regions.

Make stronger supply chains

Pathways to increase manufacturing efficiency include improvements in serial production and automation of manufacturing as well the location of factories nearer to installation sites. These strategies reduce transport costs and import taxes and provide for more efficient means of turbine delivery. Serial production can in some cases hinder technology development since large-scale, automated manufacturing can be an impediment to quick implementation of recent innovations. A balance needs to be struck between expanded production and technology innovation.

Supply chain pressures are severe in the offshore market segment. At present, the offshore market is closely linked to the land market; *i.e.,* demand for more land turbines restricts the supply of offshore turbines. At least one major manufacturer has reserved part of its manufacturing capacity for offshore production. Governments should consider supporting testing, manufacturing and assembly processes located in specially designed harbours in the vicinity of resource rich areas.

Improve efficiency of offshore installation

Depending on weather and local conditions, installation of offshore turbines can be a costly, iterative process, constrained to defined periods by strict weather windows. Specially designed installation vessels and jack-up barges, which can address the specific needs of offshore installation, are in short supply. Increasing the availability of such vessels will be necessary.

Installation vessels currently cost between USD 145 and USD 360 million (EUR 100 and EUR 250 million). Manufacturers will only have sufficient incentive to build such vessels if they have rental leases scheduled for five to ten years ahead. Once there is sufficient long-term demand, significant economies of scale will be activated, and vessels and lifting equipment will become cheaper and more readily available instead of on a case-by-case, semi-experimental basis, as is often the case today.

Experiences from the wider offshore sector suggest that significant cost reductions can be realised by increasing onshore preparatory work and reducing the amount of work done at sea. Installation strategies need to evolve accordingly. Installation that can be done without the need for large cranes will also reduce cost. Specialised access systems for O&M personnel that are sufficiently robust to widen current weather windows also need to be developed.

Increased research and development

This roadmap recommends the following actions:	Milestones
Identify and provide a suitable level of public funding for wind energy R&D, proportionate to the potential of the technology in terms of electricity production and CO_2 abatement.	From 2010.

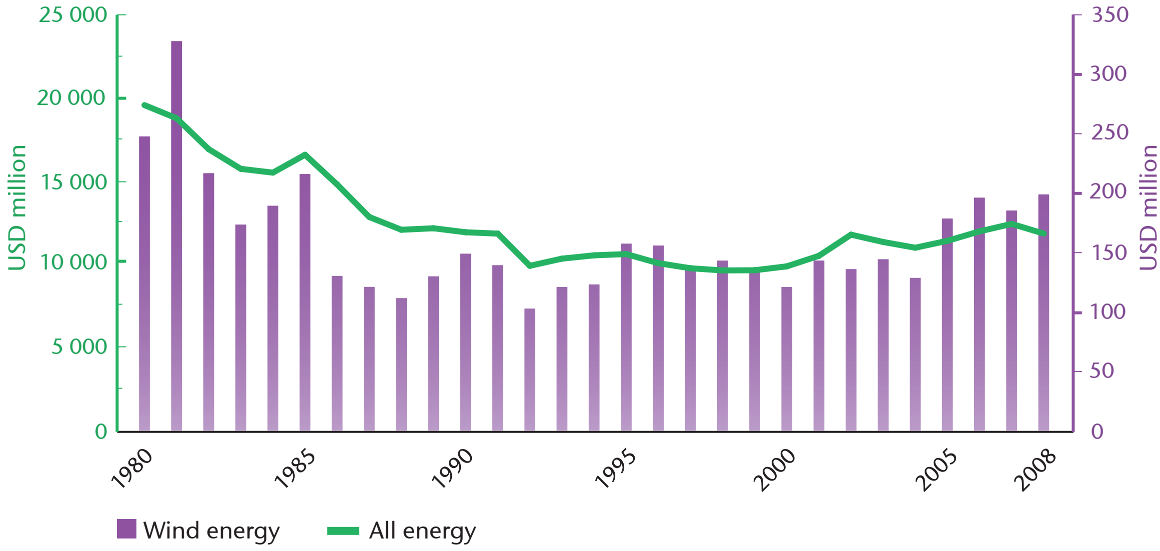
Increase wind energy research & development funding

Achieving the technology milestones listed above will require increased R&D funding. Private companies tend towards shorter-term R&D efforts where returns on investment are more certain. Long-term, fundamental research is usually the role of the public sector and primary focus of public R&D initiatives. Additional benefits can be realised from increased coordination among R&D and demonstration efforts, particularly in offshore wind.

Large test sites are needed to test and validate new components and turbines such as the new German offshore test field, Alpha Ventus, which includes a comprehensive, interdisciplinary research programme. The project started operation in 2009 at sea depths between 30 m to 40 m and distances of up to 40 km from the shore.[10]

10 Further information on Alpha Ventus can be found at http://www.alpha-ventus.de

Figure 12: OECD funding for wind energy (USD 2008, millions)



Source: IEA Data.

KEY POINT: Public finance of wind energy R&D peaked in 1981 in OECD countries.

For the last three decades, OECD research funding for wind power has fluctuated between 1% and 2% of all energy R&D funding. In 2008 the figure stood at 1.5%, USD 200 million (EUR 136 million), considerably less than in 1981 when funding rose briefly to USD 328 million in the wake of the oil crises (Figure 12).

Given the substantial role that wind power is expected to play in forwarding our 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.

The European Technology Platform for Wind Energy has attempted to identify research, development and demonstration financing needs in Europe. It takes as its basis that investment should be 3% of turnover at a minimum in accordance with the objectives of the Barcelona European Council (EC, 2002); although in other high tech industries the proportion can be higher. The platform also assumes a public/private share of investment of 1:2. In the period 2006 to 2020, the platform suggests a total R&D budget shortfall of some USD 1.45 bn (EUR 1 bn) in Europe (TPWind, 2008).

Delivery and System Integration: Actions and Milestones

In addition to wind technology, R&D and other activities are also needed to address two important transmission-related issues: system integration and grid reliability. While improvements in transmission technology are critical for the successful deployment of wind power (*e.g.,* underground cable technology for improved connection access, smart grids for improved system balancing and reliability), the scope of this section focuses primarily on the strategic planning, structural and operational requirements for successful integration of wind into major power systems.

Transmission deployment to connect wind resources

This roadmap recommends the following actions:	Milestones
1. Provide incentives for accelerated construction of transmission capacity to link wind energy resources to demand centres (using latest proven technology); establish mechanisms for cost recovery and allocation.	Complete by 2015.
2. Develop long-term interconnection-wide transmission infrastructure plans in concert with power plant deployment plans.	Complete by 2015.
3. Identify single agencies to lead large-scale, multi-jurisdictional transmission projects.	Complete by 2015.
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 existing transmission lines, offshore wind resources and bordering power markets.	Complete plans by 2015. Achieve deployment by 2030.

Set incentives for transmission capacity

To reduce the combined delay to the development of both transmission and new power plants, regulators should consider establishing incentives to encourage transmission companies to build out to areas of high resource and offering guarantees for cost recovery, possibly in the form of transmission rents from subsequent wind power plants. Cost allocation of new transmission is an important consideration. Broadly distributed, cost allocation will reduce the burden on any single consumer, and will depend to what extent additional transmission is judged to be a "common good", and therefore to be paid for by all consumers.

Plan transmission deployment up to the long term

While high quality wind resources can be close at hand, much of the best resource lies some distance from demand centres and existing transmission and distribution systems (grids). Such is the case, for example, in the central United States or outlying parts of China. Alternatively, the best wind speeds may be offshore – close to major (coastal) demand centres, but requiring greater technical know-how and higher costs per kilometre of cable to deliver wind energy to market.

The connection of wind resources is therefore a key challenge for achieving this roadmap's goals. The absence of transmission is a major obstacle among EU countries including Ireland, the United States and Germany. In the United States, some 300 GW of wind power projects are estimated to be waiting for transmission interconnection agreements (although not all of these projects will make it to actual construction). Therefore, governments and energy regulators should urgently accelerate the development of integrated, economically optimum plans for new transmission. Such plans should look several decades ahead as well as emphasise short-term milestones.

Much of the existing transmission infrastructure is at least 40 years old. Grid upgrades are in many cases necessary regardless of the specific needs of new wind power, but should additionally take into account new technologies that will help integrate wind energy. Emerging underground cable technology, for example, may help overcome local public opposition and ecological concerns. Thus, strong support for R&D initiatives towards new transmission technology will be a key enabler (see IEA, 2008c for more details).

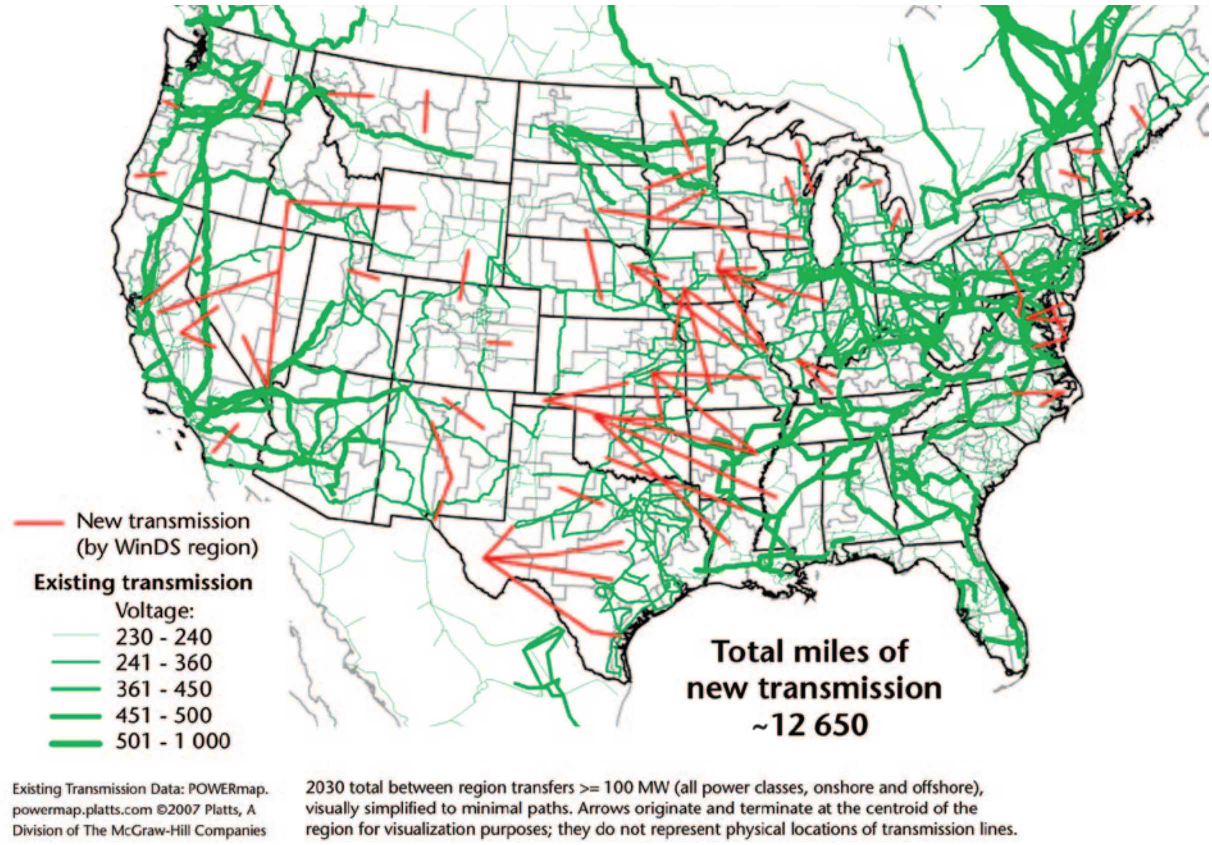
Coordinate transmission deployment at the regional level

Integrated planning of new grid development – across the whole of an interconnected power system – is a critical enabler for wind power deployment. Individual wind projects offer less returns for transmission companies than multiple or very large projects.

Efficient transmission deployment will serve multiple plants, and could potentially serve multiple technologies sharing transmission capacity according to their output schedules. Where there is strong complementarity between hydropower production (in summer) and wind (in winter), as in parts of China for example, transmission that serves both will be a more efficient use of resources than if it served only one or the other. If transmission planning is carried out hand-in-hand with deployment of the power plants themselves, greater returns for transmission companies can be identified.

For example, an approach to planning new transmission in the United States was developed through the US National Renewable Energy Laboratory (NREL) WinDS Model (Figure 13). In China, the government has proposed a "Green Silk Road" Project, which is a new transmission corridor that would integrate the output of seven planned 10 GW wind power plant clusters over six provinces as part of the national effort to reach a target of 100 GW of wind power by 2020.

Figure 13: US transmission scenario (new transmission in red)



Source: US DOE (2008).

KEY POINT: Strategic planning of new transmission should take wind energy resources into account.

Ensure clear leadership of transmission planning

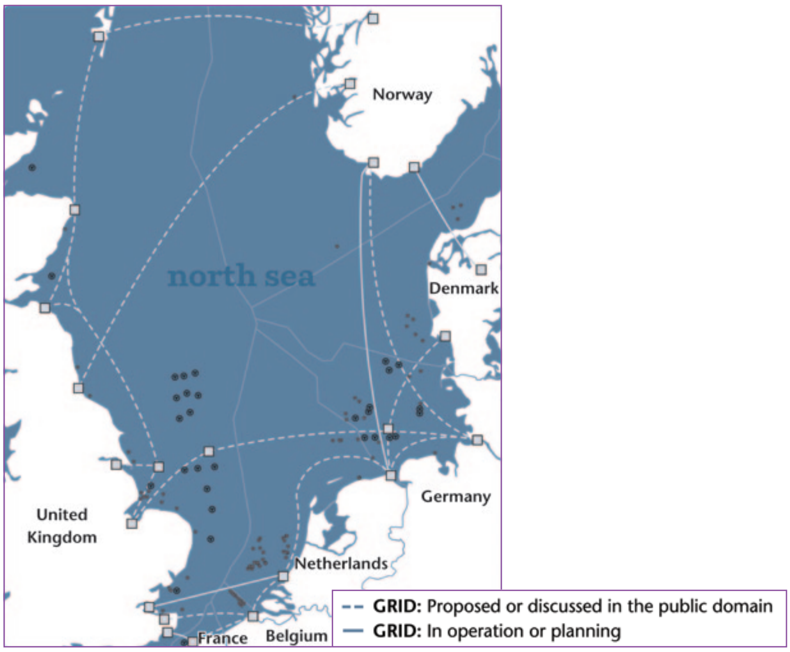
The siting and permitting of transmission expansion often involves multiple jurisdictions (local, state, federal), each with different regulations and methods of assessing cost, benefit and environmental impact. A stalemate commonly exists wherein neither wind plant developer nor transmission developer will invest without certainty that the other will also invest because of the risk of being left with a stranded asset should the other fail to materialise. In Europe and the United States, this issue has been made worse by the regulated separation of generation and transmission assets. This lack of integrated planning and investment constitutes one of the most important barriers to wind energy deployment. However, solutions exist.

Policy makers may consider the merits of mandating a single agency to lead the planning and permitting process when several jurisdictions are involved, or implementing a "one-stop shop" approach to regulatory approval of major transmission infrastructure projects. For example, following the development of four development scenarios provided by the Electric Reliability Council of Texas (ERCOT), the Public Utilities Commission (PUC) of Texas confirmed in 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. The project is expected to cost USD 4.9 bn (EUR 3.4 bn), equivalent to USD 4 (EUR 2.7) per month per residential rate payer. It is expected that the new lines will be in service within four to five years. Coherent planning of this type represents an important opportunity to develop deployment "best practice" guidelines.

Plan and deploy regional-scale and offshore grids

High voltage overlays connecting distinct, neighbouring power systems are a step further than interconnection-wide grid planning. The linking of markets, where possible, can provide an opportunity to integrate high resource areas and link neighbouring power systems. Figure 14 provides a concept of large-scale grid development offshore – in this case in the North Sea. The development and deployment of new types of high-voltage direct current (HVDC) cable will be important in this regard, so that pre-existing, individual transmission cables can be linked into an offshore grid once it becomes economically desirable.

Figure 14: "Super grid" concept in the North Sea



Source: Woyte et al., 2008.

KEY POINT: An offshore grid may be more efficient than a series of one-off transmission link-ups, while interconnecting larger markets.

Very large, interconnected power systems will need the greatest collaboration among neighbouring system operators and governments, requiring transparent, advanced information exchange and measures put in place to avoid the spread of a single fault throughout the entire area. An international offshore system operator, for example, may be needed to adequately coordinate grid operation. Recently, the new European Network of Transmission System Operators body (ENTSO-E) has dedicated a special regional group for studying the feasibility of a North Sea grid, and the European Commission appointed a European Coordinator to facilitate concerted offshore interconnection in 2007.

Reliable system operation with large shares of wind energy

This roadmap recommends the following actions:	Milestones
1. Develop methods to assess the need for additional power system flexibility to enable variable renewable energy deployment; carry out grid studies to examine the opportunities, costs and benefits of high shares of wind power integration.	Complete by 2015.
2. Accelerate development of larger-scale, faster and deeper trading of electricity through evolved power markets and advanced "smart grid" technology.	Continue over 2010-2050 period.
3. Incentivise timely development of additional flexible reserves, innovative demand-side response and storage; build demand for clean energy by labelling.	Continue over 2010-2050 period.
4. Assess grid codes and ensure open access to transmission networks for independent power producers, where not already available.	Ongoing. Complete by 2015.

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, it must be reliably integrated into the power system in a cost-effective manner.

Present day transmission and distribution networks and the physical power markets they support were designed around dispatchable, centralised power generation. Dispatchable plants, such as coal, gas or hydropower can typically be turned off and on according to demand. In contrast, the generation of electricity from wind energy depends on a continually fluctuating energy resource that can not be stored in its original form.

Variability is not a new characteristic in power systems. Demand also fluctuates, although in a more predictable manner than the wind resource.

In any power system, to maintain system security at accepted levels, reserves must be available to back-up conventional plants in case of failure, or to make up for errors in demand forecasts. Experiences in Western Europe and the United States suggest that at low variable renewable energy (varRE) shares (around 5%), the increase in variability "seen" by the system will be negligible, and the existing reserve margin is therefore sufficient to cover the needs of new varRE.

As varRE penetrations in the energy mix continue to grow, the effective size of the reserve margin will decrease. Eventually, the need will arise for new investments to ensure that combined (forecast/actual) production from varRE and dispatchable power plants can continue to be reliably balanced against (forecast/actual) demand.

This section provides recommendations as to how to modify power system operation to enable higher varRE shares.

For example, wind power today provides on average around 11% of Spanish and Portuguese electricity. At these significant levels, and with limited trade capacity with neighbours, system operators must take careful account of on-line wind generation, and of output forecasts. Predictability is a primary tool therefore in the management of variability. Increasingly accurate wind output forecasting on a three-day horizon is already an important tool for more cost-effective scheduling of dispatchable generation capacity.

Geographic "smoothing" of variable output

The output of wind power plants is generally less correlated as the distance among them increases. 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. At the same time, interconnected markets can share dispatchable reserve capacity (Enernex, 2006; UWIG, 2007), increasing the extent to which wind plants can displace conventional energy production. Larger, deeper, more liquid electricity markets can be achieved through merging "balancing-areas" and increasing trade among systems.

The Nordic power market, which covers the whole of Scandinavia, has facilitated the trade of Danish wind for Norwegian hydropower, helping wind energy to reach 20% of the Danish market. However, and particularly if trade is not an option, the question remains as to how best to cost-effectively accommodate high shares of wind energy while maintaining power system reliability, and simultaneously upgrading transmission and generation infrastructure. Analysis of power system "flexibility" can help shed light on solutions to this question.

The flexibility of a power system is its ability to rapidly and reliably balance large, sudden fluctuations in supply and/or demand. In most power systems today it is largely a function of the generation portfolio, but a wide range of other measures exist that offer potential to increase the flexibility of a power system and consequently its ability to incorporate larger shares of wind energy.

Carry out grid studies to identify challenges

Wind power should be seen as an integral part of power system evolution, rather than in isolation. System operators need as early as possible notice of targeted wind energy shares in order to plan accordingly, and should collaborate with wind power developers. Detailed grid studies are an important first step towards high renewable energy shares, such as the recent All Island Grid Study carried out in Ireland.[11]

Develop electricity markets and "smart grids" to enable flexibility

Improved electricity trading rules can be a powerful enabler of flexibility. Regulators tasked with market design may wish to consider a range of market characteristics in this regard. These include intra-hour to day-ahead trading, distinct markets for balancing and ancillary services, demand response, and the uptake of wind output forecast models.[12]

Importantly, markets need to be designed in such a way that price signals incentivise timely investment in flexible generation (*e.g.,* reservoir-based hydro, gas turbines, concentrating solar power (CSP) with integrated thermal storage), deeper trade among adjacent markets, the use of deferrable and responsive demand (DSM) through a "smart meter", and investment in electrical and other types of storage as well as electric and

11 For full details, see http://www.dcenr.gov.ie/Energy/North-South+Co-operation+in+the+Energy+Sector/All+Island+Electricity+Grid+Study.htm

12 IEA Wind Task 25 and recent IEA analyses examine these in some detail (IEA, 2008c; IEA Wind, 2009b).

hybrid vehicles. The development of smart grids that enable demand and supply agents to interact in real time is particularly important given the potential for an exponential increase in the number of market participants resulting from large-scale demand-side participation.

At the same time, customer demand for wind and other clean energies can be increased through voluntary labelling programmes that educate consumers about supplier sources. Consumers willing to pay a premium can stimulate further wind energy investment. In this way, a well-designed market can empower customers to increase investment in wind energy capacity.

Assess grid codes and ensure open access to transmission

Obstacles to grid access can be addressed by cooperative stakeholder efforts to standardise the content, definitions, terminology, and compliance-test methods of grid codes. These grid codes represent the requirements of system operators on power producers, and include voltage and frequency stability specifications. However, without careful calibration, codes may also prevent access to transmission. Most modern wind turbines have the required capabilities to answer to these codes, although these may not be necessary at low energy penetrations. Regulators should ensure that grid codes are equitable and provide a level playing field for all entrants.

Policy Frameworks: Actions and Milestones

Technology research, design and demonstration make up just half of the wind energy equation. To complement the technology push, there must be a strong market pull. This chapter identifies key tasks in the creation of a deployment framework for wind power and other technologies. Barriers to deployment vary by region. They range from inaccurate perceptions of the value of wind power to constraints on planning and permitting to the design of physical electricity markets that have evolved as part of the conventional electricity generating paradigm.

Incentivising investment

This roadmap recommends the following actions:	Milestones
1. Where not already in place, establish long-term targets for renewable energy deployment, including short-term milestones.	Complete by 2015.
2. Implement support mechanisms that provide sufficient incentive to investors; develop effective systems to internalise the external costs of all forms of electricity production into market prices for electricity.	Complete by 2015.

A principal role of government is to attract investment in clean energy technologies by facilitating a transparent and stable deployment environment. Without government incentives or equivalent support, rates of return would be too low in most cases and markets would stagnate.

Set deployment targets

Binding deployment targets with near-term milestones provide a clear pathway for technology development and indicate government support for such technologies, further encouraging 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 its member states. It is important to note here that wind (as well as other resources) varies geographically and the unevenness of this resource should be taken into account when developing targets.

Attracting private finance

To attract lenders and investors, a project must be transparent, and its risk and return profiles dependable. If they are not, commercial investors will pursue projects they perceive to be more reliable, including more conventional technologies. Secondly, project risk must be reduced so that the returns offered to investors are attractive. Sufficiently confident lenders will provide finance at a more affordable rate. Therefore reducing the risk of a project reduces its cost.

Confidence can be strengthened in a number of ways. Solid understanding is required of the full range of both perceived and real risks represented by a wind power investment. Risk types can include wind resource uncertainty, technology risk (including unforeseen O&M costs and down-time), longevity of government incentives, instability in the carbon price, and uncertainty regarding the reliability and credit worthiness of other parties.

Public-private partnerships (PPP) can reduce the risk, perceived or real, to private investors. PPPs may be effective mechanisms, 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, guaranteeing a return on the investment.

Establish support mechanisms and internalise external costs

Government support and incentives for renewable energy producers varies from country to country. Common types of mechanisms are the fixed feed-in tariff (FIT), feed-in premium (FIP), production tax credit, renewable portfolio standards (RPS) or quotas (with or without tradable green certificates), capital grants and loan guarantees. Mechanisms seek to establish a return per megawatt of electricity that is competitive with other energy sources and sufficient to attract private investment in new deployment of renewable energy.

Subsidies offer a degree of protection to promising new technologies as they approach market competitiveness while balancing subsidies to the conventional electricity sector. Secondly, they serve to reflect the value of clean energy production – including reduced emissions of GHGs and pollutants – that is not yet effectively internalised in electricity prices. Another method of internalising the cost of GHG emissions in the price of electricity – and more importantly in investment decisions – is by putting a price on emissions through an emissions trading system, such as the European Emissions Trading Scheme. Careful design of such systems is paramount, however, to ensure the emissions price is meaningful (fully cost-reflective) and stable.

Support mechanisms, regardless of type, should satisfy certain design principles (IEA, 2008b). Above all, their objective should be to reduce project risk and stimulate deployment, while encouraging the technology to reduce cost towards market competitiveness.

1. A policy must be transparent, stable and predictable in the long-term to enable developers to plan and to minimise investor uncertainty.
2. The level of support should decrease over time to encourage the technology towards competitiveness. This is the primary objective of such support. It should distinguish among varying degrees of technology maturity, for example the relative youth of offshore wind technology relative to onshore.
3. Due consideration must be given to the impacts of policy support for any one technology or group of technologies on the integrated power system. Policy should encourage both the development of transmission and the geographic dispersion of wind plants as this has a beneficial effect of smoothing variability.
4. Incentives should be part of a coherent framework and be consistent with measures that target the removal of administrative barriers (*e.g.,* unnecessarily long permitting processes), as well as with other initiatives to support R&D. International, national and regional mechanisms should be complementary to the extent that investors are encouraged to invest where the resource is best, rather than simply being attracted by the highest level of government support.
5. Support should relate to energy produced, rather than capacity installed, to encourage investors to maintain high energy production over the lifetime of the project.
6. A policy must be easy to implement and enforceable. For example, in a quota based support mechanism the onus may be on suppliers to provide customers with a certain percentage of "green" electricity, but unless this can be easily monitored and penalties are sufficiently high to induce compliance, the mechanism may fail in its objective.

Public engagement and the environment

This roadmap recommends the following actions:	Milestones
1. Improve techniques for assessing, minimising and mitigating social and environmental impacts and risks.	Complete by 2020.
2. Conduct new outreach on the value of wind energy as part of a portfolio of GHG emissions and pollution-abatement technologies; promote the role of new transmission in achieving these goals.	Ongoing over 2010-2050 period.

International, national and regional policies targeting GHG emission reductions have wide public support. The most important environmental groups are squarely behind the large scale deployment of wind power. But as a relative newcomer on the energy scene, and despite its rapid growth, wind power is still perceived by many to have limited importance.

At the same time, continuing uncertainty about impacts on the natural environment jeopardise the deployment of wind plants, and of related infrastructure, especially new transmission lines and pylons. Local concerns mainly relate to visual impacts, the effect on property values, and health concerns, as well as avian, bat, and offshore ecology. In some European cases, local opposition has delayed key transmission interconnector projects by as much as 15 years.

Improve environmental impact assessment techniques

In response to the sometimes polarised public debate, there needs to be a rigorous assessment of the real extent of environmental and ecological concerns. Local environmental impact assessment is an important tool to identify and allay real public concerns, as well as to 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. Support can be built via the provision of reliable and balanced information, and with community participation, including open public hearings. In cases where negative environmental effects from wind are likely, means for minimising and mitigating these effects need to be identified and developed.[13]

Educate the public about the role of wind energy

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 characteristic of wind power is taken by some as a measure of unreliability so that its role in strategic socio-environmental strategy to abate CO_2 emissions is often underestimated. This needs to be addressed with effective public information campaigns that highlight quantifiable benefits of the technology.

13 Work to establish best practice, and tools for policy makers and planners, is underway in the IEA Wind Task 28 on social acceptance of wind energy projects. The group's work targets 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.

Planning and permitting

This roadmap recommends the following actions:	Milestones
1. Develop long-term plans for deployment of new wind power plants, taking into account other likely power plant developments and transmission deployment.	Complete by 2015.
2. Harmonise, accelerate, and streamline permitting practices.	Complete by 2020.

Develop integrated, long-term plans for wind power deployment

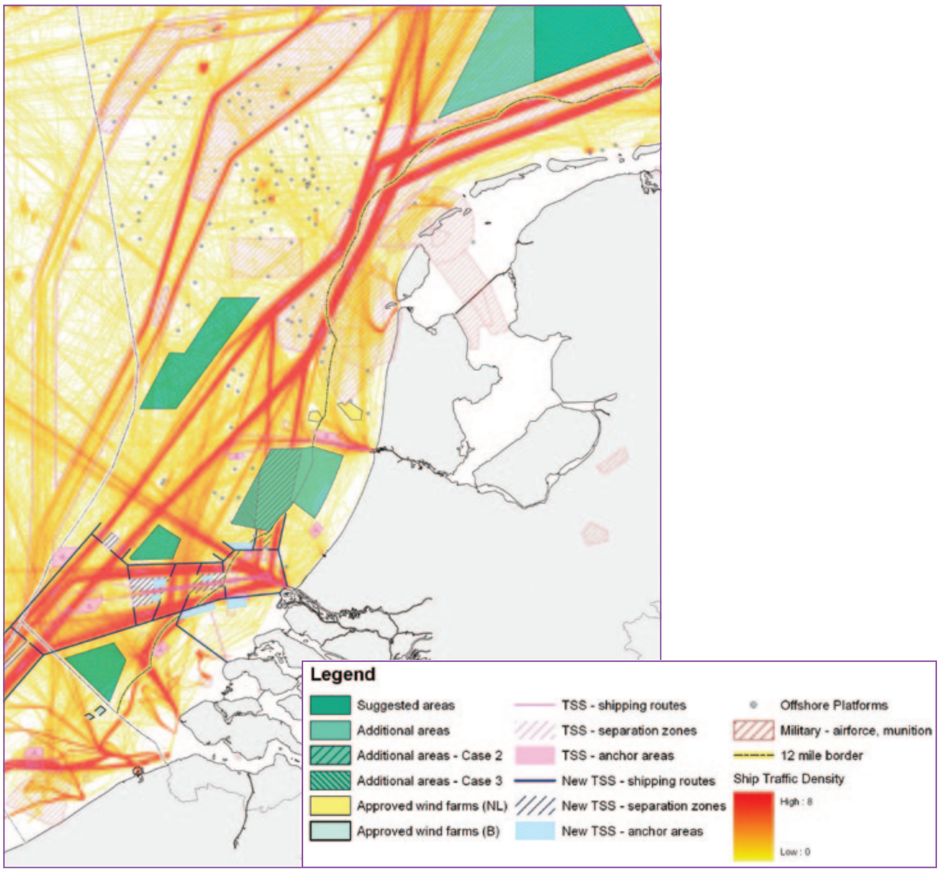
Early, integrated, long-term planning of deployment of wind power and associated infrastructure is vital to ensure balanced development and to minimise subsequent delays. The identification of pre-screened zones for fast-tracked renewables deployment will lighten the burden on developers by enabling them to take pre-emptive action to avoid likely obstacles.

To be effective, large-scale development zones should take into account resource distribution, evolving demand patterns, deployment targets, and grid infrastructure (both existing and development potential), particularly where a large wind resource is located in an area served by insufficient or non-existent transmission to bring it to market. Development zones must also be allocated on an equitable basis with socio-environmental requirements, as well as defence (radar), and other industrial interests. Such a wide range of potentially conflicting attributes and interests requires very careful planning.

Additional planning barriers may result from apparently unconnected government departments or agencies. For example, in 2007, Japan's new planning regulations reclassified turbines over 60 m in height (ground to blade tip) as buildings, and as a consequence both national as well as local government approval is now required for new turbines. Fortunately, deployment in 2008 remained in line with past growth in Japanese wind power.

One example of a national strategic planning effort is the Dutch government's 2008 draft National Water Plan, which includes wind power development potential in Dutch waters in the North Sea alongside the fisheries, shipping, sand extraction, oil and gas extraction, nature conservation, and coastal defences. Figure 15 shows part of the Dutch coastline with a range of potential wind development areas marked in green.

Figure 15: Example of strategic planning in Dutch waters in the North Sea



Source: NL MEA (2009).

KEYPOINT: Spatial planning should take into account physical factors and the full range of stakeholders.

The National Water Plan proposes two areas for wind energy deployment: Borssele (344 km²), which could theoretically accommodate over 2 000 MW of wind power,[14] and Ijmuiden (1 170 km²), which might accommodate over 7 000 MW. The plan assesses four scenarios of connecting wind plants in these zones to the existing onshore grid, as well as outlining the cost of such transmission. The final plan (due in late 2009) will designate the areas in which sufficient permits for wind energy parks can be granted to achieve the Dutch wind power deployment target of 6 000 MW in 2020.

Streamline permitting procedures

Permitting procedures are critical to ensure that deployment takes into account 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 investors. A more holistic approach is needed, identifying the various approvals that are required and integrating them in an effective way. In this way, public safety and other concerns can be effectively addressed during wind project development. For example, the US Department of the Interior and the Federal Energy regulatory Commission ended a two-year debate regarding jurisdiction over offshore renewable energy development on the outer continental shelf, and are now undertaking deployment of wind, wave and tidal power in partnership.

Standardised, more transparent permitting procedures reduce project uncertainty. In Denmark, offshore permitting procedures have been streamlined into a one-stop-shop system wherein the Danish Energy Agency serves as the coordinating authority. However, such a centralised approach may not be appropriate for all countries, particularly in federal countries such as the United States.

14 The National Water Plan assumes a capacity of wind plants of 6 MW per km².

International Collaboration: Actions and Milestones

Clean energy deployment will have a global benefit in terms of GHG emissions abatement. Efforts to spread deployment of wind and other clean energy technologies worldwide will contribute to the effective use of the best resources.

This roadmap recommends the following actions:	Milestones
1. Increase international RD&D collaboration, making best use of national competencies.	Continue over 2010-2050 period.
2. Develop new mechanisms to encourage exchange of technology and deployment best practice with developing economies.	Continue over 2010-2050 period.
3. Assess and express the value of wind energy in economic development, poverty alleviation, and efficient use of fresh water resources.	Continue over 2010-2050 period.
4. Encourage multilateral development banks (MDBs) to target clean energy deployment.	Continue over 2010-2050 period.
5. Further develop mechanisms such as the CDM to attract investment in wind deployment.	Continue over 2010-2050 period.

Expand international RD&D collaboration

Greater coordination is needed between national approaches to wind energy RD&D. Increased collaboration among nations would 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 is also needed. Of particular importance is the establishment of international testing facilities for components and turbines. The location of turbine and component-testing facilities will have important implications for domestic and international manufacturing.

One example of international wind energy technology collaboration is the IEA Wind Energy Systems Implementing Agreement. This Implementing Agreement is one of 42 such agreements covering the complete spectrum of technology development. IEA Wind includes national technology experts from over 20 countries, who together have developed a coherent research programme in a number of important areas up to 2013.[15] 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, and is also one of a range of different technology platforms established in partnership with the European Commission with cross-cutting activities. TPWind has developed a research agenda and market deployment strategy up to 2030, which provides a focus for EU and national financing initiatives. In the offshore sector, a German-Danish-Swedish Cooperation Agreement exists with specific focus on offshore wind energy RD&D.

Build capacity in emerging economies

Strong wind resources exist in many countries where deployment has yet to begin to approach its potential (see, *e.g.*, Figure 3 and Figure 6). By 2050, according to the BLUE Map scenario, more than half of cumulative global investment in new capacity will have taken place in non-OECD countries (Figure 9). In China alone, to build the 630 GW of installed capacity envisaged in the scenario would at today's prices cost around USD 380 bn (EUR 260 bn) by 2030, and in total USD 1.1 trillion (EUR 750 bn) by 2050.

15 See www.ieawind.org

Fast economic growth, limited energy supply, and abundant conventional resources are encouraging key countries to look first to conventional energy supply. Without sufficient incentive to do otherwise, such countries as India and China are likely to follow a carbon-intensive development path (UNEP, 2009). Efforts are being made bilaterally and multilaterally to address this problem.

Table 3: Cumulative investment needs to reach BLUE Map scenario (USD billions)[16]

	2030	2050
China	379	1 116
India	53	152
Other developing Asia	35	114
Africa	16	78
Latin America	37	291

Multilateral development banks (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, and will be worth approximately USD 5.2 bn (EUR 3.5 bn). The CTF was established in the first half of 2009 to provide support for the low carbon objectives in Turkey's Ninth Development Plan (2007 to 2013). Via joint efforts with the private sector, the CTF targets 19 GW of wind power in its Accelerated Emission Reduction Case (World Bank, 2009).

Bilateral development banks are also an important source of development finance. The German state-owned Kreditanstalt fuer Wiederaufbau Bank (KfW), for example, invested USD 230 million (EUR 340 million) in renewable energy projects in developing economies in 2008.

16 At USD 1.77 bn (EUR 1.2 bn) per GW.

Carefully designed support policy, following the design principles discussed above, is essential if asset finance is to be used efficiently. For example, in some countries, state support for wind energy is based on capacity installed rather than electricity produced. As a result, it is reported that many turbines, though built, are not yet operational or even in some cases connected to the grid (UNEP, 2009).

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, for example. Before signature of a power purchase agreement (PPA), a project's risk profile is considerably higher than afterwards, when an off-taker has been securely identified to buy the electricity to be produced by the project. In India, China and elsewhere PPAs are habitually signed at project completion, long after financing will need to have been secured, thereby reducing the attractiveness of the project to investors. Additionally, the financial reliability of potential off-takers may be in question. In this example, 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 development of a mechanism to shield investors from subsequent failure to secure a PPA.

The United Nations Framework Convention on Climate Change (UNFCCC) is pursuing global agreements to cap GHG emissions. Its Clean Development Mechanism (CDM) has shown some success in building clean energy capacity in developing economies, although CDM alone is not enough. Countries also need to have significant government support for wind as well as a well functioning Designated National Authority who actively provides information and helps facilitate the development of projects, as is the case in China.[17]

Wind development has been seen as one of the biggest success stories of the CDM with a significant amount of projects being deployed. As of August 2009, there were 740 wind projects in the CDM pipeline, amounting to 16% of all projects within the mechanism, second only to hydropower projects (27%). Wind power projects are expected to yield 11% of total certified emissions reductions (CERs) issued per year (UNEP, 2009b).

17 Correspondence with International Emissions Trading Association, US.

CDM experiences in China and India

China and India dominate among wind CDM projects. Although they have similar numbers of projects in the pipeline (371 and 301 respectively), in terms of installed capacity Chinese projects account for 21 GW of capacity, more than three and a half times the expected amount in India (5.7 GW). Mexico and South Korea have the next highest numbers of projects in the pipeline, with 12 projects (1.5%) each.

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 in turn led to the development of domestic wind manufacturing bases, particularly in China, and although this growth is not attributed entirely to CDM, the CDM has been a major contributing factor as supported by the fact that today virtually all new wind in China is going through the CDM process.[18]

OECD governments 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 (UNEP, 2009), and in such cases specific, tailored actions will be necessary.[18]

The strong expression by developed economies of the value of wind energy, in terms additional to climate protection, is important. Benefits in terms of innovation, employment, fresh water stress and environmental protection should be accurately quantified and expressed to developing economy partners, particularly in terms of its ability to contribute towards the fundamental questions of energy provision and poverty alleviation.

18 Correspondence with Environmental Resources Management, the Netherlands.

Roadmap Action Plan and Next Steps

This chapter summarises actions highlighted in this roadmap, and sorts them into three categories to indicate the stakeholder with the lead responsibility. The three stakeholder groups are the wind industry, government, and power system actors. Each comprises a range of sub-groups, which are listed in each section. The milestone dates will be refined over time. It is important to note that collaboration among categories will be important.

Actions led by the wind industry

The wind industry category includes the fundamental research community of universities, government research centres and other institutions; turbine and component manufacturers; and developers of wind plants and associated infrastructure. The underlying objective of the actions listed is to reduce the lifecycle cost of energy production.

Resource	Milestones and actors
1. Refine and set standards for wind resource modelling techniques, and site-based data measurement with remote sensing technology; improve understanding of complex terrain, offshore conditions and icy climates.	Ongoing. Complete by 2015. Wind industry and research institutions, climate and meteorological institutions.
2. Develop publicly accessible database of onshore and offshore wind resources and conditions, with the greatest possible coverage taking into account commercial sensitivities.	Complete by 2015. Industry and research institutions.
3. Develop more accurate, longer-horizon forecast models, for use in power system operation.	Ongoing. Complete by 2015. Industry, research institutions and system operators.
Technology	
4. Develop stronger, lighter materials to enable larger rotors, lighter nacelles, and to reduce dependence on steel for towers; develop super-conductor technology for lighter, more electrically efficient generators; deepen understanding of behaviour of very large, more flexible rotors.	Ongoing. Continue over 2010-2050 period. Industry and research institutions.
5. Build shared database of offshore operating experiences, taking into account commercial sensitivity issues; target increase of availability of offshore turbines to current best-in-class of 95%.	Complete by 2015. Wind power plant developers, owners and operators, industry associations.
6. Develop competitive, alternative foundation-types for use in water depths up to 40 m.	Ongoing. Complete by 2015. Industry and research institutions.
7. Fundamentally design new generation of turbines for offshore application, with minimum O&M requirement.	Commercial scale prototypes by 2020. Industry and research institutions.

Technology	Milestones and actors
8. Develop deep-water foundations/sub-surface structures for use in depths up to 200 m.	Ongoing. Complete by 2025. Industry and research institutions.

Supply chains	
9. Accelerate automated, localised, large-scale manufacturing for economies of scale, with an increased number of recyclable components.	Ongoing. Continue over 2010-2050 period. Industry.
10. For offshore deployment, make available sufficient purpose-designed vessels; improve installation strategies to minimise work at sea; make available sufficient and suitably equipped large harbour space.	Sufficient capacity by 2015. Wind industry, shipping industry, and local governments.
Environment	
11. Improve techniques for assessing, minimising and mitigating social and environmental impacts and risks.	Complete by 2015. Industry, research institutions, governments, and NGOs.

Actions led by governments

The government category includes international, national, regional and local levels of government. The underlying role of government actors is to remove deployment barriers; ensure the wind industry and the wider electricity sector work together effectively; and to encourage private sector investment alongside increased public investment.

R&D Finance	Milestones and actors
1. Identify and provide a suitable level of public funding for wind energy R&D, proportionate to the potential of the technology in terms of electricity production and CO_2 abatement.	From 2010. Iterate over 2010-2050 period. Governments, research institutions and industry.
Education and employment	
2. Develop internationally standard education and training strategies for the complete range of skills needed, from design to deployment.	Complete by 2015. Governments, universities, and industry.
Deployment incentives	
3. Where not already in place, establish long-term targets for renewable energy deployment, including short-term milestones.	Complete by 2015. Governments with input from industry.
4. Implement support mechanisms that provide sufficient incentive to investors; develop effective systems to internalise the external costs of all forms of electricity production into market prices for electricity.	Complete by 2015. Governments with input from investors and financiers, research institutions and regulators.
Transmission development	**Milestones and actors**
5. Provide incentives for accelerated construction of transmission capacity to link wind energy resources to demand centres (using new latest proven technology); establish mechanisms for cost recovery and allocation.	Complete by 2015. Governments, wind developers, transmission companies and system operators; regulators.

6. Identify single agencies to lead large-scale, multi-jurisdictional transmission projects.	Complete by 2015. Government agencies, regional and local government.
Public engagement	
7. Conduct new outreach on the value of wind energy as part of a portfolio of GHG emissions and pollution-abatement technologies; promote the role of new transmission in achieving these goals.	Continue over 2010-2050 period. National, regional and local government, transmission companies, environmental NGOs (national and local), industry associations, and consumer groups.
Planning and permitting of wind projects	
8. Develop long-term plans for deployment of new wind power plants, taking into account other likely power plant developments and transmission deployment.	Complete by 2015. Government (national, regional and local), wind developers, other power developers, national and local NGOs, system operators and transmission companies.
9. Harmonise, accelerate, and streamline permitting practices.	Complete by 2015. National, regional and local government.
International collaboration	
10. Increase international R&D collaboration, making best use of national competencies.	Continue over 2010-2050 period Governments, governmental organisations, research networks, and international technology platforms.
11. Develop new mechanisms to encourage exchange of technology and deployment best practice with developing economies.	Continue over 2010-2050 period. Governments and governmental organisations, NGOs.
12. Assess and express the value of wind energy in economic development, poverty alleviation, and efficient use of fresh water resources.	Continue over 2010-2050 period. OECD and developing country governments, governmental organisations, international development and environmental organisations.
13. Encourage MDBs to target clean energy deployment.	Continue over 2010-2050 period. Governments, international development organisations and NGOs.
14. Further develop mechanisms such as the CDM to attract investment in deployment.	Continue over 2010-2050 period. Governments and governmental organisations, project developers active in development countries.

Actions led by power system actors

This category includes transmission companies, system operators and independent electricity sector regulators as established by governments. The key role of power system actors is to enable physical power markets and the infrastructure underpinning them to evolve in a manner that cost-effectively reduces the impact of variability and increases the value of wind power.

Transmission development	Milestones and actors
1. Develop interconnection-wide transmission infrastructure plans in concert with power plant deployment plans.	Complete by 2015. Transmission companies, system operators, government, regulators and industry.
2. Develop and implement plans for continental-scale transmission overlays to link regional power markets.	Complete plans by 2015. Achieve deployment by 2030. Transmission companies, system operators, government, regulators and industry.
3. Develop and implement plans for offshore grids, linking existing transmission lines, offshore wind resources and bordering power markets.	Complete plans by 2015. Achieve deployment by 2030. Transmission companies, system operators, government, regulators and industry.
Power systems and markets	
4. Develop methods to assess the need for additional power system flexibility to enable variable renewable energy deployment; carry out grid studies to examine the opportunities, costs and benefits of high shares of wind power integration.	Complete by 2015. System operators and research institutions.
5. Accelerate development of larger-scale, faster and deeper trading of electricity through evolved power markets and advanced "smart grid" technology.	Continue over 2010-2050 period. Regulators and system operators.
6. Incentivise timely development of additional flexible reserves, innovative demand-side response and storage; build demand for clean energy by labelling.	Continue over 2010-2050 period. Regulators and system operators; regulators, environmental NGOs and consumer groups.
7. Assess grid codes and ensure open access to transmission networks for independent power producers, where not already available.	Complete by 2015. Regulators, system operators and wind industry.

Next steps

This roadmap has responded to the G8 and other government leaders' requests for more detailed analysis regarding the growth pathway for wind energy, a key GHG mitigation strategy. It has described approaches and specific tasks regarding wind energy RDD&D, financing, planning, grid integration, legal and regulatory framework development, public engagement, and international collaboration. It also provided regional projections for wind energy deployment from 2010 to 2050 based on *Energy Technology Perspectives 2008*, in an effort to indicate wind energy deployment potential. Finally, this roadmap detailed 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 that are required by 2050. As such, the IEA, together with government, industry and 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, including additional analyses that informed the conclusions in this document, visit www.iea.org/roadmaps.

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