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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation dedicated to renewable energy.

In accordance with its Statute, IRENA's objective is to "promote the widespread and increased adoption and the sustainable use of all forms of renewable energy". This concerns all forms of energy produced from renewable sources in a sustainable manner and includes bioenergy, geothermal energy, hydropower, ocean, solar and wind energy.

As of May 2012, the membership of IRENA comprised 158 States and the European Union (EU), out of which 94 States and the EU have ratified the Statute.

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This working paper is available for download from www.irena.org/Publications

Disclaimer

Preface

Renewable power generation can help countries meet their sustainable development goals through provision of access to clean, secure, reliable and affordable energy.

Renewable energy has gone mainstream, accounting for the majority of capacity additions in power generation today. Tens of gigawatts of wind, hydropower and solar photovoltaic capacity are installed worldwide every year in a renewable energy market that is worth more than a hundred billion USD annually. Other renewable power technology markets are also emerging. Recent years have seen dramatic reductions in renewable energy technologies' costs as a result of R&D and accelerated deployment. Yet policy-makers are often not aware of the latest cost data.

International Renewable Energy Agency (IRENA) Member Countries have asked for better, objective cost data for renewable energy technologies. This working paper aims to serve that need and is part of a set of five reports on wind, biomass, hydropower, concentrating solar power and solar pholtovoltaics that address the current costs of these key renewable power technology options. The reports provide valuable insights into the current state of deployment, types of technologies available and their costs and performance. The analysis is based on a range of data sources with the objective of developing a uniform dataset that supports comparison across technologies of different cost indicators - equipment, project and levelised cost of electricity – and allows for technology and cost trends, as well as their variability to be assessed.

The papers are not a detailed financial analysis of project economics. However, they do provide simple, clear metrics based on up-to-date and reliable information which can be used to evaluate the costs and performance of different renewable power generation technologies. These reports help to inform the current debate about renewable power generation and assist governments and key decision makers to make informed decisions on policy and investment.

The dataset used in these papers will be augmented over time with new project cost data collected from IRENA Member Countries. The combined data will be the basis for forthcoming IRENA publications and toolkits to assist countries with renewable energy policy development and planning. Therefore, we welcome your feedback on the data and analysis presented in these papers, and we hope that they help you in your policy, planning and investment decisions.

Dolf Gielen

Director, Innovation and Technology

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Key findings

1. **Installed costs in 2010** for onshore wind farms were as low as USD 1 300 to USD 1 400/kW in China and Denmark, but typically ranged between USD 1 800/kW and USD 2 200/kW in most other major markets. Preliminary data for the United States in 2011 suggests that wind turbine costs have peaked and that total costs could have declined to USD 2 000/kW for the full year (i.e. a reduction of USD 150/kW compared to 2010). Wind turbines account for 64% to 84% of total installed costs onshore, with grid connection costs, construction costs, and other costs making up the balance. Offshore wind farms are more expensive and cost USD 4 000 to USD 4 500/kW, with the wind turbines accounting for 44% to 50% of the total cost.

Table 1: Typical new wind farm costs and performance in 2010

	Installed cost (2010 USD/kW)	Capacity factor (%)	Operations and maintenance (USD/kWh)	LCOE* (USD/kWh)
Onshore				
China/India	1 300 to 1 450	20 to 30	n.a.	0.06 to 0.11
Europe	1 850 to 2 100	25 to 35	0.013 to 0.025	0.08 to 0.14
North America	2 000 to 2 200	30 to 45	0.005 to 0.015	0.07 to 0.11
Offshore				
Europe	4 000 to 4 500	40 to 50	0.027 to 0.048	0.14 to 0.19

** Assumes a 10% cost of capital*

2. **Operations and maintenance costs (O&M)** can account for between 11% and 30% of an onshore wind projects levelised cost of electricity (LCOE). O&M costs for onshore wind farms in major wind markets averages between USD 0.01/kWh and USD 0.025/kWh. The O&M costs of offshore wind farms are higher due to the difficulties posed by the offshore environment and can be between USD 0.027 and USD 0.048/kWh. Cost reduction opportunities towards best practice levels exist for onshore wind farms, while experience offshore should help to reduce costs over time, but they will always be higher than onshore.

3. **The levelised cost of electricity** from wind varies depending on the wind resource and project costs, but at good wind sites can be very competitive. The LCOE of typical new onshore wind farms in 2010 assuming a cost of capital of 10% was between USD 0.06 to USD 0.14/kWh. The higher capital costs offshore are somewhat offset by the higher capacity factors achieved, resulting in the LCOE of an offshore wind farm being between USD 0.13 and USD 0.19/kWh assuming a 10% cost of capital.

4. **The potential for renewed cost reductions is good,** as supply bottlenecks have been removed and increased competition among suppliers will put downward pressure on prices in the next few years. Assuming that capital costs onshore decline by 7% to 10% by 2015, and O&M costs trend towards best practice, the LCOE of onshore wind could decline by 6% to 9%. The short-term cost reduction potential for wind is more uncertain, but the LCOE of offshore wind could decline by between 8% and 10% by 2015.

5. **In the medium-to long-term,** reductions in capital costs in the order of 10% to 30% could be achievable from learning-by-doing, improvements in the supply chain, increased manufacturing economies of scale, competition and more investment in R&D.

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1. Introduction

Renewable energy technologies can help countries meet their policy goals for secure, reliable and affordable energy to expand electricity access and promote development. This paper is part of a series on the cost and performance of renewable energy technologies produced by IRENA. The goal of these papers is to assist government decision-making and ensure that governments have access to up-to-date and reliable information on the costs and performance of renewable energy technologies.

Without access to reliable information on the relative costs and benefits of renewable energy technologies, it is difficult, if not impossible, for governments to arrive at an accurate assessment of which renewable energy technologies are the most appropriate for their particular circumstances. These papers fill a significant gap in information availability, because there is a lack of accurate, comparable, reliable and up-to-date data on the costs and performance of renewable energy technologies. The rapid growth in installed capacity of renewable energy technologies and the associated cost reductions mean that even data one or two years old can significantly overestimate the cost of electricity from renewable energy technologies. There is also a significant amount of perceived knowledge about the cost and performance of renewable power generation technologies that is not accurate or is misleading. Conventions on how to calculate cost can influence the outcome significantly and it is imperative that these are clearly documented.

The absence of accurate and reliable data on the cost and performance of renewable power generation technologies is a significant barrier to the uptake of these technologies. Providing this information will help governments, policy-makers, investors and utilities make informed decisions about the role renewable energy can play in their power generation mix. This paper examines the fixed and variable cost components of wind power, by country and region and provides estimates of the levelised cost of electricity from wind power given a number of key assumptions. This up-to-date analysis of the costs of generating electricity from wind will allow a fair comparison with other generating technologies.[1]

1.1 DIFFERENT MEASURES OF COST AND DATA LIMITATIONS

Cost can be measured in a number of different ways, and each way of accounting for the cost of power generation brings its own insights. The costs that can be examined include equipment costs (e.g. wind turbines, PV modules, solar reflectors, etc.), financing costs, total installed cost, fixed and variable operating and maintenance costs (O&M), fuel costs, and the levelised cost of energy (LCOE).

The analysis of costs can be very detailed, but for comparison purposes and transparency, the approach used here is a simplified version. This allows greater scrutiny of the underlying data and assumptions, improving transparency and the confidence in the analysis, as well as facilitating the comparison of costs by country or region for the same technologies in order to identify what are the key drivers in any differences.

The three indicators that have been selected are:

- Equipment cost (factory gate FOB and delivered at site CIF);
- Total installed project cost, including fixed financing costs[2]; and
- The levelised cost of electricity LCOE.

The analysis in this paper focuses on estimating the cost of wind energy from the perspective of a private investor, whether they are a state-owned electricity generation utility, an independent power producer, or

[1] IRENA, through its other work programmes, is also looking at the costs and benefits, as well as the macroeconomic impacts, of renewable power generation technologies. See WWW.IRENA.ORG for further details.

[2] Banks or other financial institutions will often charge a fee, usually a percentage of the total funds sought, to arrange the debt financing of a project. These costs are often reported separately under project development costs.

an individual or community looking to invest in small-scale renewables (Figure 1.1). The analysis is a pure cost analysis, not a financial one, and excludes the impact of government incentives or subsidies, taxation, system-balancing costs associated with variable renewables, and any system-wide cost savings from the merit order effect.[3] Similarly, the analysis doesn't take into account any CO^2 pricing, nor the benefits of renewables in reducing other externalities (e.g. reduced local air pollution, contamination of natural environments, etc.). Similarly, the benefits of renewables being insulated from volatile fossil fuel prices have not been quantified. These issues and others are important, but are covered by other programmes of work at IRENA.

It is important to include clear definitions of the technology categories, where this is relevant, to ensure that cost comparisons are robust and provide useful insights (e.g. off-shore wind vs. onshore wind PV). Similarly, it is important to differentiate between the functionality and/or qualities of the renewable power generation technologies being investigated. It is important to ensure that system boundaries for costs are clearly set and that the available data are directly comparable. Other issues can also be important, such as cost allocation rules for combined heat and power plants, and grid connection costs and rules.

The data used for the comparisons in this paper come from a variety of sources, such as business journals, industry associations, consultancies, governments, auctions and tenders. Every effort has been made to ensure that these data are directly comparable and are for the same system boundaries. Where this is not the case, the data have been corrected to a common basis using the best available data or assumptions. It is planned that this data will be complemented by detailed surveys of real world project data in forthcoming work by the agency.

An important point is that, although this paper tries to examine costs, strictly speaking, the data available are actually prices, and not even true market average prices, but price indicators. The difference between costs and prices is determined by the amount above, or below, the normal profit that would be seen in a competitive market. The rapid growth of renewables markets from a small base means that the market for renewable power generation technologies is rarely well-balanced. As a result, prices can rise significantly above costs in the short-term if supply is not expanding as fast as demand, while in times of excess supply, losses can occur and prices may be below production costs. This makes analysing the cost of renewable power generation technologies challenging and every effort is made to indicate whether current equipment costs are above or below their long-term trend.

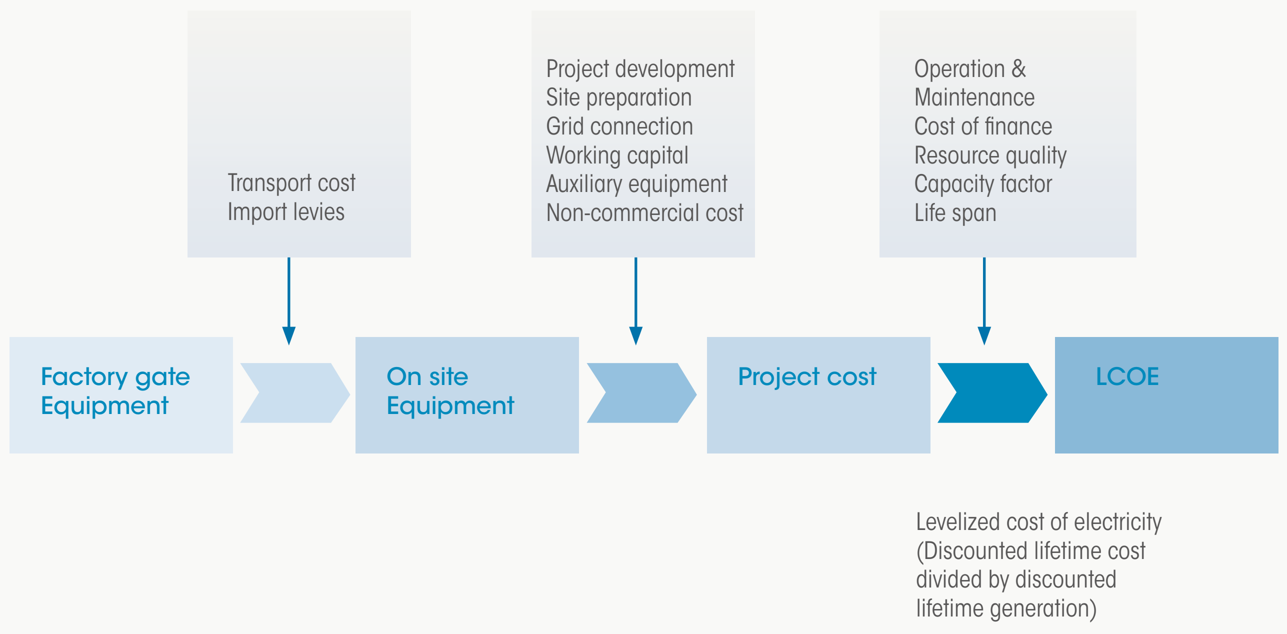


Figure 1.1: Renewable power generation cost indicators and boundaries

[3] *See EWEA, Wind Energy and Electricity Prices, April 2010 for a discussion.*

The cost of equipment at the factory gate is often available from market surveys or from other sources. A key difficulty is often reconciling different sources of data to identify why data for the same period differ. The balance of capital costs in total project costs tends to vary even more widely than power generation equipment costs, as it is often based on significant local content, which depends on the cost structure where the project is being developed. Total installed costs can therefore vary significantly by project, country and region, depending on a wide range of factors.

1.2 LEVELISED COST OF ELECTRICITY GENERATION

The LCOE is the price of electricity required for a project where revenues would equal costs, including making a return on the capital invested equal to the discount rate. An electricity price above this would yield a greater return on capital, while a price below it would yielder a lower return on capital, or even a loss.

The LCOE of renewable energy technologies varies by technology, country and project, based on the renewable energy resource, capital and operating costs, and the efficiency/performance of the technology. The approach used in the analysis presented here is based on a simple discounted cash flow (DCF) analysis.[4] This method of calculating the cost of renewable energy technologies is based on discounting financial flows (annual, quarterly or monthly) to a common basis, taking into consideration the time value of money. Given the capital intensive nature of most renewable power generation technologies and the fact that fuel costs are low, or often zero, the weighted average cost of capital (WACC), also referred to as the discount rate in this report, used to evaluate the project has a critical impact on the LCOE.

There are many potential trade-offs to be considered when developing an LCOE modelling approach. The approach taken here is relatively simple, given the fact that the model needs to be applied to a wide range of technologies in different countries and regions. However, this has the additional advantage of making the analysis transparent, easy to understand and allows clear comparisons of the LCOE of individual technologies across countries and regions, and between technologies. The differences in LCOE can be attributed to project and technology performance, not differing methodologies. More detailed LCOE analysis may result in more "accurate" absolute values, but results in a significantly higher overhead in terms of the granularity of assumptions required and risks reducing transparency. More detailed methodologies can often give the impression of greater accuracy, but when it is not possible to robustly populate the model with assumptions, or to differentiate assumptions based on real world data, then the supposed "accuracy" of the approach can be misleading.

The formula used for calculating the LCOE of renewable energy technologies is:

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where:

LCOE = the average lifetime levelised cost of electricity generation;

$\mathbf{I_t}$ **=** investment expenditures in the year **t**;

$\mathbf{M_t}$ **=** operations and maintenance expenditures in the year **t**;

$\mathbf{F_t}$ **=** fuel expenditures in the year **t**;

$\mathbf{E_t}$ **=** electricity generation in the year **t**;

r = discount rate; and

n = economic life of the system.

All costs presented in this paper are real 2010 USD unless otherwise stated;[5] that is to say, after inflation has been taken into account.[6] The discount rate used in the analysis, unless otherwise stated, is 10% for all projects and technologies.

As already mentioned, although different cost measures are useful in different situations, the LCOE of renewable energy technologies is a widely used measure by which renewable energy technologies can be evaluated for modelling or policy development. Similarly, more detailed DCF approaches taking into account taxation, subsidies and other incentives are used by renewable energy project developers to assess the profitability of real world projects.

[4] Including the impacts of subsidies, taxation and other factors that impact the financial viability of an individual project would lead to different results.

[5] Exchange rate fluctuations can have a significant impact on project costs depending on the level of local content. In an ideal world the local and imported cost components could be tracked separately and trends in each followed without the "noise" created by exchange rate fluctuations.

[6] An analysis based on nominal values with specific inflation assumptions for each of the cost components is beyond the scope of this analysis. Project developers will develop their own specific cash-flow models to identify the profitability of a project from their perspective.

2. Wind power technologies and resources

Wind power technologies transform the kinetic energy of the wind into useful mechanical power. The kinetic energy of the air flow provides the motive force that turns the wind turbine blades that, via a drive shaft, provide the mechanical energy to power the generator in the wind turbine.[7]

Wind and hydro power have been used by man since antiquity and they are the oldest large-scale source of power that has been used by mankind. However, the invention of the steam engine and its wide spread deployment in the nineteenth century allowed the industrial revolution to occur by providing cheap, on-demand mechanical and then electrical energy, with the possibility of taking advantage of the waste heat produced as well. Their low cost and the fact they did not depend on fickle winds or need to be located next to a convenient water source allowed the great leap in productivity and incomes that stemmed from the Industrial Revolution. Their success saw the importance of wind energy decline dramatically, particularly in the twentieth century.

The modern era of wind power began in 1979 with the mass production of wind turbines by Danish manufacturers Kuriant, Vestas, Nordtank and Bonus. These early wind turbines typically had small capacities (10 kW to 30 kW) by today's standards, but pioneered the development of the modern wind power industry that we see today.

The current average size of grid-connected wind turbines is around 1.16 MW (BTM Consult, 2011), while most new projects use wind turbines between 2 MW and 3 MW. Even larger models are available, for instance REPower's 5 MW wind turbine has been on the market for seven years. When wind turbines are grouped together, they are referred to as "wind farms". Wind farms comprise the turbines themselves, plus roads for site access, buildings (if any) and the grid connection point.

Wind power technologies come in a variety of sizes and styles and can generally be categorised by whether they are horizontal axis or vertical axis wind turbines (HAWT and VAWT), and by whether they are located onshore or offshore. The power generation of wind turbines is determined by the capacity of the turbine (in kW or MW), the wind speed, the height of the turbine and the diameter of the rotors.

Most modern large-scale wind turbines have three blades rotating around the horizontal axis (the axis of the drive shaft). These wind turbines account for almost all utility-scale wind turbines installed. Vertical-axis wind turbines exist, but they are theoretically less aerodynamically efficient than horizontal-axis turbines and don't have a significant market share.[8] In addition to large-scale designs, there has been renewed interest in small-scale wind turbines, with some innovative design options developed in recent years for small-scale vertical-axis turbines.

Horizontal-axis wind turbines can be classified by their technical characteristics, including:

- » rotor placement (upwind or downwind);
- » the number of blades;
- » the output regulation system for the generator;
- » the hub connection to the rotor (rigid or hinged; the so-called "teetering hub");
- » gearbox design (multi-stage gearbox with high speed generator; single stage gearbox with medium speed generator or direct drive with synchronous generator);

[7] *Wind turbine refers to the tower, blades, rotor hub, nacelle and the components housed in the nacelle.*

[8] *There are three vertical-axis wind turbine design concepts: the Gyro-turbine, the Savonius turbine and the Darrieus turbine. Only the Darrieus turbine has been deployed at any scale (in Denmark in the 1970s). Today, they are used for small scale applications in turbulent environments, like cities. Some prototypes have been proposed for large-scale offshore applications in order to reduce installation and maintenance costs.*

» the rotational speed of the rotor to maintain a constant frequency (fixed or controlled by power electronics); and

» wind turbine capacity.

The turbine size and the type of wind power system are usually related. Today's utility-scale wind turbine generally has three blades, sweeps a diameter of about 80 to 100 metres, has a capacity from 0.5 MW to 3 MW and is part of a wind farm of between 15 and as many as 150 turbines that are connected to the grid.

Small wind turbines are generally considered to be those with generation capacities of less than 100 kW. These smaller turbines can be used to power remote or off-grid applications such as homes, farms, refuges or beacons. Intermediate-sized wind power systems (100 kW to 250 kW) can power a village or a cluster of small enterprises and can be grid-connected or off-grid. These turbines can be coupled with diesel generators, batteries and other distributed energy sources for remote use where there is no access to the grid. Small-scale wind systems remain a niche application, but it is a market segment that is growing quickly.[9] They are emerging as an important component of renewable electrification schemes for rural communities in hybrid off-grid and mini-grid systems.

The wind speed and electricity production

As wind speed increases, the amount of available energy increases, following a cubic function. Therefore, capacity factors rise rapidly as the average mean wind speed increases. A doubling of wind speed increases power output of wind turbine by a factor of eight (EWEA, 2009). There is, therefore, a significant incentive to site wind farms in areas with high average wind speeds. In addition, the wind generally blows more consistently at higher speeds at greater heights. For instance, a five-fold increase in the height of a wind turbine above the prevailing terrain can result in twice as much wind power. Air temperature also has an effect, as denser (colder) air provides more energy. The "smoothness" of the air is also important. Turbulent air reduces output and can increase the loads on the structure and equipment, increasing materials fatigue, and hence O&M costs for turbines.

The maximum energy than can be harnessed by a wind turbine is roughly proportionally to the swept area of the rotor. Blade design and technology developments are one of the keys to increasing wind turbine capacity and output. By doubling the rotor diameter, the swept area and therefore power output is increased by a factor of four. Table 2.1 presents an example for Denmark of the impact of different design choices for turbine sizes, rotor diameters and hub heights.

The advantage of shifting offshore brings not only higher average mean wind speeds, but also the ability to build very large turbines with large rotor diameters. Although this trend is not confined to offshore, the size of wind turbines installed onshore has also continued to grow. The average wind turbine size is currently between 2 MW and 3 MW. Larger turbines provide greater efficiency and economy of scale, but they are also more complex to build, transport and deploy.[10] An additional consideration is the cost, as wind towers are usually made of rolled steel plate. Rising commodity prices during the period 2006-2008 drove increased wind power costs, with the price of steel tripling between 2005 and its peak in mid-2008.

Table 2.1: Impact of turbine sizes, rotor diameters and hub heights on annual production

Generator size, MW	Rotor, m	Hub Height, m	Annual production, MWh
3.0	90	80	7 089
3.0	90	90	7 497
3.0	112	94	10 384
1.8	80	80	6 047

Source: Nielsen, et al., 2010

[9] The World Wind Energy Association estimates that the number of installed small wind turbines by end of 2010 was around 665 000 units.

[10] As tower height increases, so does the diameter at the base. Once the diameter of the tower exceeds about 4 metres, transportation by road can became problematic.

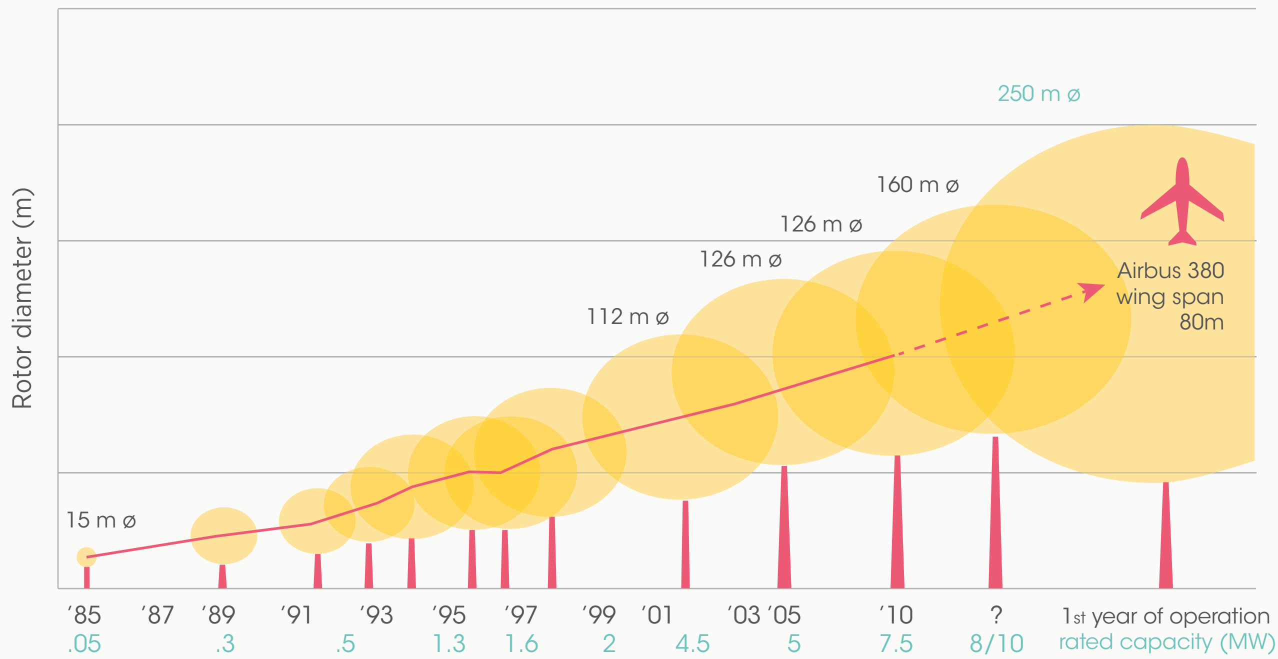


FIGURE 2.1: GROWTH IN THE SIZE OF WIND TURBINES SINCE 1985

Source: UpWind, 2011.

2.1. WIND TURBINE AND WIND FARM DESIGNS

2.1.1 Onshore wind power technologies

Many different design concepts of the horizontal-axis wind turbine are in use. The most common is a three-bladed, stall- or pitch-regulated, horizontal axis machine operating at near-fixed rotational speed. However, other concepts for generation are available, notably gearless "direct drive" turbines with variable speed generator designs have a significant market share. Wind turbines will typically start generating electricity at a wind speed of 3 to 5 metres per second (m/s), reach maximum power at 15 m/s and generally cut-out at a wind speed of around 25 m/s.

There are two main methods of controlling the power output from the rotor blades. The first, and most common method, is "pitch control", where the angle of the rotor blades is actively adjusted by the control system. This system has built-in braking, as the blades become stationary when they are fully 'feathered'. The other method is known as "stall control" and, in this case, it is the inherent aerodynamic properties of the blade which determine power output. The twist and thickness of the rotor blade varies along the length of the blade and is designed in such a way that turbulence occurs behind the blade whenever the wind speed becomes too high. This turbulence means that blade becomes less efficient and as a result minimises the power output at higher speeds. Stall control machines also have brakes at the blade base to bring the rotor to a standstill, if the turbine needs to be stopped for any reason.

In addition to how the output is controlled, the wind turbine generator can be "fixed speed" or "variable speed". The advantages of variable-speed turbines using direct-drive systems are that the rotors will operate more efficiently[11], loads on the drive train can be reduced and pitch adjustments minimised. At rated power, the turbine essentially becomes a constant speed turbine. However, these advantages have to be balanced by the additional cost of the necessary power electronics to enable variable speed operation.[12]

[11] A fixed rpm wind turbine will have only one wind speed at which the rotors are operating at their optimum efficiency.
[12] Variable speed operation requires a doubly fed induction generator or the use of direct drive with asynchronous generator.

A typical modern wind turbine can be broken down into its major parts, which are the:

Blades: Modern turbines typically use three blades, although other configurations are possible. Turbine blades are typically manufactured from fibreglass-reinforced polyester or epoxy resin. However, new materials, such as carbon fibre, are being introduced to provide the high strength-to-weight ratio needed for the ever larger wind turbine blades being developed. It is also possible to manufacture the blades from laminated wood, although this will restrict the size.

Nacelle: This is the main structure of the turbine and the main turbine components are housed in this fibreglass structure.

Rotor Hub: The turbine rotor and hub assembly spins at a rate of 10 to 25 revolutions per minute (rpm) depending on turbine size and design (constant or variable speed). The hub is usually attached to a low-speed shaft connected to the turbine gearbox. Modern turbines feature a pitch system to best adjust the angle of the blades, achieved by the rotation of a bearing at the base of each blade. This allows rotor rpm to be controlled and spend more time in the optimal design range. It also allows the blades to be feathered in high wind conditions to avoid damage.

Gearbox: This is housed in the nacelle although "direct drive" designs which do not require one are available. The gearbox converts the low-speed, high-torque rotation of the rotor to high-speed rotation (approximately 1 500 rpm) with low-torque for input to the generator.

Generator: The generator is housed in the nacelle and converts the mechanical energy from the rotor to electrical energy. Typically, generators operate at 690 volt (V) and provide three-phase alternating current (AC). Doubly-fed induction generators are standard, although permanent magnet and asynchronous generators are also used for direct-drive designs.

Controller: The turbine's electronic controller monitors and controls the turbine and collects operational data. A yaw mechanism ensures that the turbine constantly faces the wind, Effective implementation of control systems can have a significant impact on energy output and loading on a turbine and they are, therefore, becoming increasingly advanced. The controllers monitor, control or record a vast number of parameters from rotational speeds and temperatures of hydraulics, through blade pitch and nacelle yaw angles to wind speed. The wind farm operator is therefore able to have full information and control of the turbines from a remote location.

Tower: These are most commonly tapered, tubular steel towers. However, concrete towers, concrete bases with steel upper sections and lattice towers are also used. Tower heights tend to be very site-specific and depend on rotor diameter and the wind speed conditions of the site. Ladders, and frequently elevators in today's larger turbines, inside the towers allow access for service personnel to the nacelle. As tower height increases, diameter at the base also increases.

Transformer: The transformer is often housed inside the tower of the turbine. The medium-voltage output from the generator is stepped up by the transformer to between 10 kV to 35 kV; depending on the requirements of the local grid.

2.1.2 Offshore wind power technologies

Offshore wind farms are at the beginning of their commercial deployment stage. They have higher capital costs than onshore wind farms, but this is offset to some extent by higher capacity factors.[13] Ultimately, offshore wind farms will allow a much greater deployment of wind in the longer-term. The reasons for the higher capacity factors and greater potential deployment are that offshore turbines can be:

- Taller and have longer blades, which results in a larger swept area and therefore higher electricity output.
- Sited in locations that have higher average wind speeds and have low turbulence.
- Very large wind farms are possible.
- Less constrained by many of the siting issues on land. However, other constraints exist, may be just as problematic and need to be adequately considered (e.g. shipping lanes, visual impact, adequate onshore infrastructure, etc.).

[13] *Offshore, average mean wind speeds tend to be higher than onshore, and can increase electricity output by as much as 50% compared to onshore wind farms (Li, et al., 2010).*

A key long-term constraint on wind in many countries is that gaining approval for wind farms with high average wind speeds close to demand will become more difficult over time. With the right regulatory environment, offshore wind farms could help offset this challenge by allowing large wind turbines to be placed in high average wind speed areas. Thus, although offshore wind remains nearly twice as expensive to install as onshore wind, its longer term prospects are good. As an example, it is expected that offshore wind installations could have electricity outputs 50% larger than equivalent onshore wind farms because of the higher, sustained wind speeds which exist at sea (IEA, 2010).

Offshore wind turbines for installation in marine environments were initially based on existing land-based machines, but dedicated offshore designs are emerging. The developers and manufacturers of turbines have now accumulated more than ten years' experience in offshore wind power development. Turbines and parts used for offshore turbines have constantly improved, and knowledge about the special operating conditions at sea has steadily expanded. However, reducing the development cost of offshore wind power is a major challenge.

Offshore turbines are designed to resist the more challenging wind regime offshore, and require additional corrosion protection and other measures to resist the harsh marine environment. The increased capital costs are the result of higher installation costs for the foundations, towers and turbines, as well as the additional requirements to protect the installation from the offshore environment.

The most obvious difference between onshore and offshore wind farms is the foundations required for offshore wind turbines. These are more complex structures, involving greater technical challenges, and must be designed to survive the harsh marine environment and the impact of large waves. All these factors and especially the additional costs of installation mean they cost significantly more than land-based systems.

Offshore wind farm systems today use three types of foundation: single-pile structures, gravity structures or multi-pile structures. The choice of which foundation type to use depends on the local sea-bed conditions, water depth and estimated costs. In addition to these techniques, floating support structures are also being investigated, but these are only at the R&D and pilot project phase.

Table 2.2: Offshore wind turbine foundation options

FoundationType/ Concept	Aplication	Advantages	Disadvantages
Mono-piles	Most conditions, preferably shallow water and not deep soft material. Up to 4 m diameter. Diameters of 5-6 m are the next step.	Simple, light and versatile. Of lengths up to 35 m.	Expensive installation due to large size. May require pre-drilling a socket. Difficult to remove.
Multiple-piles (tripod)	Most conditions, preferably not deep soft material. Suits water depth above 30 m.	Very rigid and versatile.	Very expensive construction and installation. Difficult to remove.
Concrete gravity base	Virtually all soil conditions.	Float-out installation	Expensive due to large weight
Steel gravity base	Virtually all soil conditions. Deeper water than concrete.	Lighter than concrete. Easier transportation and installation. Lower expense since the same crane can be used as for erection of turbine.	Costly in areas with significant erosion. Requires a cathodic protection system. Costly compared with concrete in shallow waters.
Mono-suction caisson	Sands, soft clays.	Inexpensive installation. Easy removal.	Installation proven in limited range of materials.
Multiple-suction caisson (tripod)	Sands and soft clays. Deeper water.	Inexpensive installation. Easy removal.	Installation proven in limited range of materials. More expensive construction
Floating	Deep waters	Inexpensive foundation construction. Less sensitive to water depth than other types. Non-rigid, so lower wave loads	High mooring and platform costs. Excludes fishing and navigation from areas of farm.

Source: EWEA, 2004

At present, most of the offshore wind turbines installed around the world have used a mono-pile structure and are in shallow water, usually not exceeding 30 m (IEA, 2009). The most widely used type of mono-pile structure involves inserting steel tubes with a diameter of 3-5 into the seabed to a depth of 15-30 using drilling bores. The merit of this foundation is that a seabed base is not required and its manufacturing is relatively simple, but the installation can be relatively difficult and the load from waves and currents in deeper water means flexing and fatigue are an issue to be considered. The key challenge in the longer-term will be to develop lower cost foundations, particularly for deep-water offshore where floating platforms will be required.

The future of offshore wind is likely to be based on the development of larger scale projects, located in deeper waters in order to increase capacity factor and to have sufficient space for the large wind turbines to operate effectively. However, the distance to shore, increased cable size, deep water foundations and installation challenges will increase the cost of the wind farm. There is an economic trade-off that can be very site-specific

The current average capacity of wind turbines installed at offshore wind farms is 3.4 MW (EWEA, 2011a), up from 2.9 MW in 2010. Recently installed wind farms have typically used a 3.6 MW turbine, but 5 MW or larger turbines are available or under development. The trend towards larger wind turbines is therefore likely to continue in the near future; and 5 MW turbines and larger are likely to dominate offshore installations in the future.[14]

2.1.3 Small wind turbines

Although there is no official definition of what constitutes a small wind turbine, it is generally defined as a turbine with a capacity of 100 kW or less. Compared with utility-scale wind systems, small wind turbines generally have higher capital costs and achieve lower capacity factors, but they can meet important unmet electricity demands and can offer local economic and social benefits, particularly when used for off-grid electrification. Small wind turbines share of the total global wind power market was estimated at around 0.14% in 2010 and is expected to increase to 0.48% by the year 2020 (GlobalData, 2011).

Small wind turbines can meet the electricity needs of individual homes, farms, small businesses and villages or small communities and can be as small as 0.2 kW. They can play a very important role in rural electrification schemes in off-grid and mini-grid applications. They can be a competitive solution for off-grid electrification and can complement solar photovoltaic systems in off-grid systems or mini-grids.

Although small wind turbines are a proven technology, further advances in small wind turbine technology and manufacturing are required in order to improve performance and reduce costs. More efficient installation and maintenance techniques will also help improve the economics and attractiveness of small wind turbines.

Small wind turbine technologies have steadily improved since the 1970s, but further work is needed to improve operating reliability and reduce noise concerns to acceptable levels. Advanced airfoils, super-magnet generators, smart power electronics, very tall towers and low-noise features will not only help improve performance, but reduce the cost of electricity generated from small wind turbines.

The deployment of small wind turbines is expanding rapidly as the technology finally appears to be coming of age. The development of small wind turbine technology has mirrored that of large turbines, with a variety of sizes and styles having been developed, although horizontal axis wind turbines dominate (95% to 98% of the market).

Currently, some 250 companies in 26 countries are involved in supplying small wind turbines (AWEA, 2011). The vast majority of these companies are in the start-up phase. Less than ten manufacturers in the United States account for around half the world market for small wind turbines. After the United States, the United Kingdom and Canada are the largest markets for small wind. At the end of 2010, the total installed capacity of small wind turbines reached 440 MW from 656 000 turbines (WWEA, 2012)

Almost all current small wind turbines use permanent magnet generators, direct drive, passive yaw control and two to three blades. Some turbines use 4-5 blades to reduce the rotational speed and increase the torque

[14] Even larger designs are being developed, but it is unlikely that larger turbines will be installed offshore in any significant numbers in the short- to medium-term, because the capacity to install even larger turbines is unlikely to be available for some time.

available. Siting is a critical issue for small wind turbines, as collecting accurate wind measurements is not economic due the cost and time required relative to the investment. Siting must therefore be based on experience and expert judgement, leaving significant room for error. As a result, many systems perform poorly and can even suffer accelerated wear and tear from bad siting.

The height of the tower is another key factor for small wind turbines. Low towers will have low capacity factors and often expose the turbines to excessive turbulence. Tall towers help avoid these issues, but increase the cost significantly compared to the turbine cost. An important consideration for small wind turbines is their robustness and maintenance requirements. Reliability needs to be high, as high operations and maintenance costs can make small wind turbines uneconomic, while in rural electrification schemes qualified maintenance personnel may not be available.

A key challenge for small wind turbines is that they are generally located close to settlements where wind speeds are often low and turbulent as a result of surrounding trees, buildings and other infrastructure. Designing reliable small wind turbines to perform in these conditions where noise levels must be very low is a challenge. As a result, there is increased interest in vertical-axis technologies given that:

» They are less affected by turbulent air than standard horizontal-axis wind turbines.

» Have lower installation costs for the same height as horizontal-axis wind turbines.

» They require lower wind speeds to generate, which increases their capacity to serve areas with lower than average wind speeds.

» They rotate at one-third to one-quarter the speed of horizontal-axis turbines, reducing noise and vibration levels, but at the expense of lower efficiency.

These advantages mean that small vertical-axis wind turbines can play a very important role in rural electrification schemes in off-grid and mini-grid applications, as and in other niche applications. As a result of this potential, a range of companies are either manufacturing or plan to manufacture small-scale, building-mounted vertical-axis wind turbines.

2.2 THE GLOBAL WIND ENERGY RESOURCE

The overall potential for wind depends heavily on accurately mapping the wind resource. Efforts to improve the mapping of the global wind resource are ongoing and further work will be required to refine estimates of the wind resource. There is currently a lack of data, particularly for developing countries and at heights greater than 80 m (IEA, 2009)

The wind resource is very large, with many parts of the world having areas with high average wind speeds onshore and offshore. Virtually all regions have a strong wind resource, although this is usually not evenly distributed and is not always located close to demand centres.

Work is ongoing, by the private and public sector, to identify the total wind resource in ever more detail in order to assist policy-makers and project promoters to identify promising opportunities that can then be explored in more detail with onsite measurements.

The total wind resource potential depends on a number of critical assumptions in addition to the average wind speed, including: turbine size, rotor diameter, density of turbine placement, portion of land “free” for wind farms, etc. This is before consideration of whether the wind resource is located next to demand centres, transmission bottlenecks, economics of projects in different areas, etc. Despite these uncertainties, it is clear that the onshore wind resource is huge and could meet global electricity demand many times over (Archer and Jacobson, 2005) and combining the onshore and close-in offshore potential results in estimates as high as 39 000 TWh (WBGU, 2003) of sustainable technical potential.

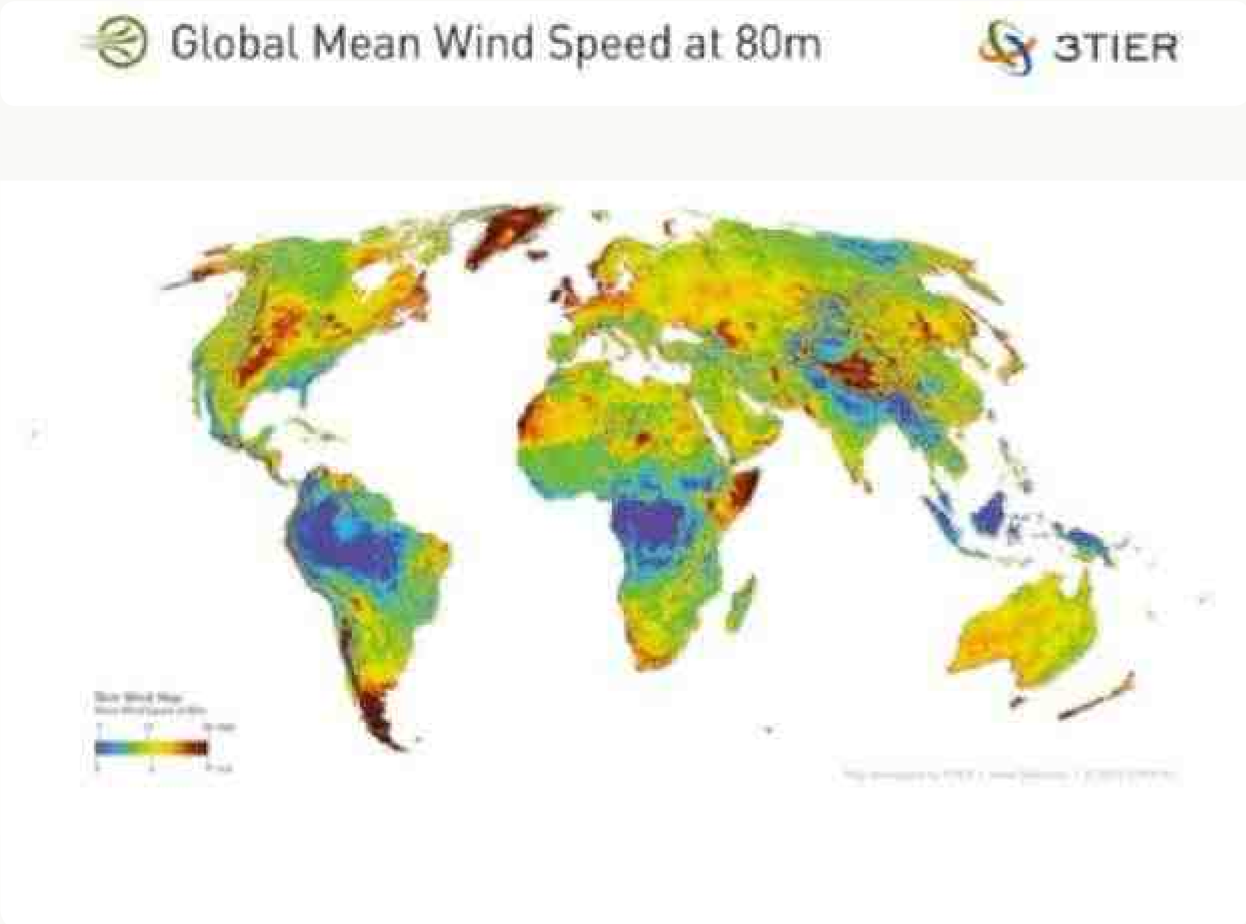


FIGURE 2.2: WORLD WIND RESOURCE MAP

Source: 3TIER, 2012

3. Global wind power market trends

The growth in the wind market was driven by Europe until 2008, as Denmark, and later Germany and Spain, drove increases in installed capacity. More recently, Italy, France and Portugal have also added significant new capacity. However, since 2008, new capacity additions have been large in North America and China. In 2011, China added 17.6 GW of wind capacity, 43% of the global total for 2011 and 70% more than Europe added (GWEC, 2012).

3.1 TOTAL INSTALLED CAPACITY

The wind power industry has experienced an average growth rate of 27% per year between 2000 and 2011, and wind power capacity has doubled on average every three years. A total of 83 countries now use wind power on a commercial basis and 52 countries increased their total wind power capacity in 2010 (REN21, 2011). The new capacity added in 2011 totalled 41 GW, more than any other renewable technology (GWEC, 2012). This meant total wind power capacity at the end of 2011 was 20% higher than at the end of 2010 and reached 238 GW by the end of 2011 (Figure 3.1).

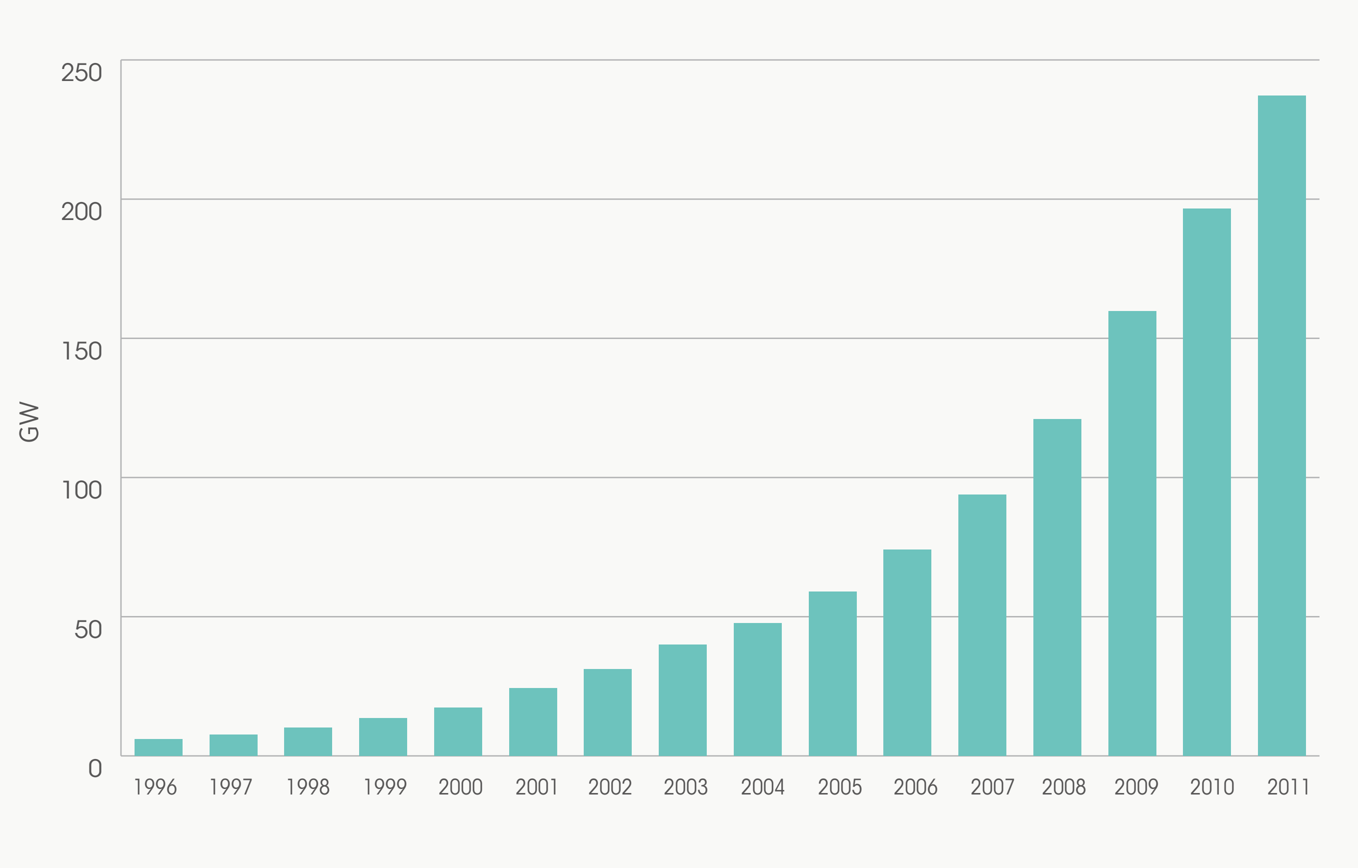
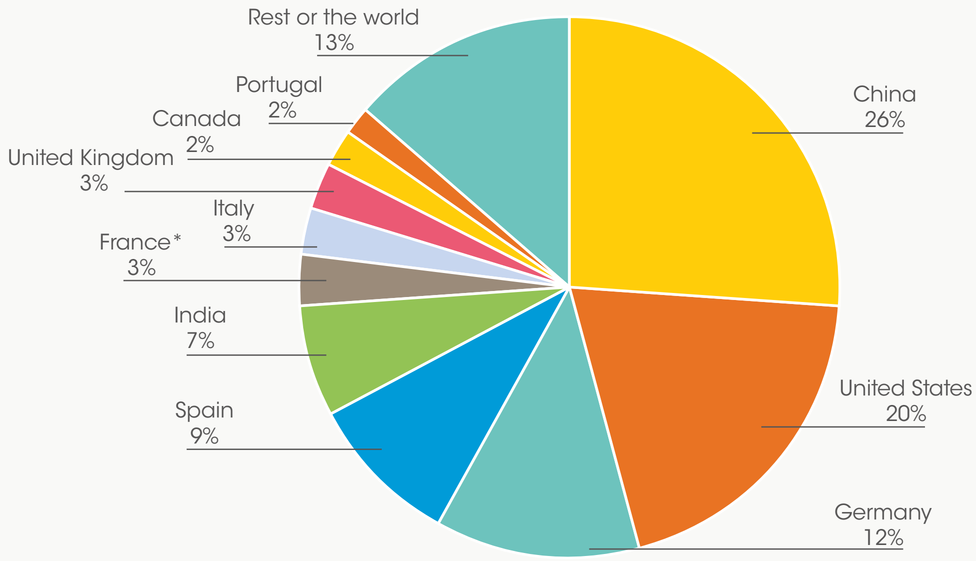


Figure 3.1: Global installed wind power capacity, 1996 to 2011

Source: GWEC, 2012

Europe accounted for 41% of the global installed wind power capacity at the end of 2011, Asia for 35% and North America for 22%. The top ten countries by installed capacity accounted for 86% of total installed wind power capacity worldwide at the end of 2011 (Figure 3.2). China now has an installed capacity of 62 GW, 24 times the capacity they had in 2006. China now accounts for 26% of global installed capacity, up from just 3% in 2006. Total installed capacity at the end of 2011 in the United States was 47 GW (20% of the global total), in Germany it was 29 GW (12%), in Spain it was 22 GW (9%) and in India it was 16 GW (7%).

COUNTRY	MW	%
China	62 364	26.2
United States	46 919	19.7
Germany	29 060	12.2
Spain	21 674	9.1
India	16 084	6.8
France*	6 800	2.9
Italy	6 737	2.8
UK	6 540	2.7
Canada	5 265	2.2
Portugal	4 083	1.7
Rest of the world	32 143	13.5



* Provisional figure

Figure 3.2: The top ten countries by installed wind capacity, end-2011

Source: GWEC, 2012.

3.2 ANNUAL CAPACITY ADDITIONS

The global wind power market was essentially flat in 2009 and 2010, but in 2011 capacity added was 40.6 GW up from 38.8 in 2010 (Figure 3.3). This represents an investment in new capacity in 2011 of USD 68 billion (EUR 50 billion) (GWEC, 2012). Onshore wind accounted for 97% of all new capacity additions in 2010.

In 2011, the European market added around 10 GW of new capacity, while in the United States new capacity additions have rebounded from their lower levels in 2010 to reach 8.1 GW in 2011. If it had not been for the growth in the Chinese market, global new capacity additions in 2010 would have been significantly lower than in 2009.

Asia, Europe and North America dominated new wind power capacity additions with the additions of 20.9 GW, 10.2 GW and 8.1 GW respectively in 2011. For the second year running, more than half of all new wind power was added outside of the traditional markets of Europe and North America. This was mainly driven by the continuing rapid growth in China, which accounted for 43% the new global wind power installations (17.6 GW). The top ten countries by capacity additions in 2010 accounted for 88% of the growth in global capacity (Figure 3.4).

However, emerging wind power markets in Latin America are beginning to take off. Capacity additions in Latin America and the Caribbean were 120% higher in 2011 than in 2010.

The market is still dominated by onshore wind and there remain significant onshore wind resources yet to be exploited. However, the offshore wind market is growing rapidly, and reached a total installed capacity of 3 118 MW at the end of 2010. Worldwide, 1 162 MW was added in the year 2010, a 59.4 % increase over 2009 (WWEA, 2011a).

In Europe, in 2010, 883 MW of new offshore wind power capacity was added, a 51% increase on 2009 additions. This is at the same time as onshore new capacity additions declined by 13%. Total offshore wind capacity in Europe reached 2.9 GW at the end of 2010. The size of offshore wind farms is also increasing. In 2010, the average size of offshore wind farms was 155 MW, more than double the 2009 average of 72 MW (EWEA, 2011b). Preliminary data for 2011 suggests offshore wind power capacity in Europe increased by 866 MW (EWEA, 2011a).

Other countries are also looking at offshore wind, and significant new offshore capacity should be added in the coming years in the United States, China and other emerging markets.

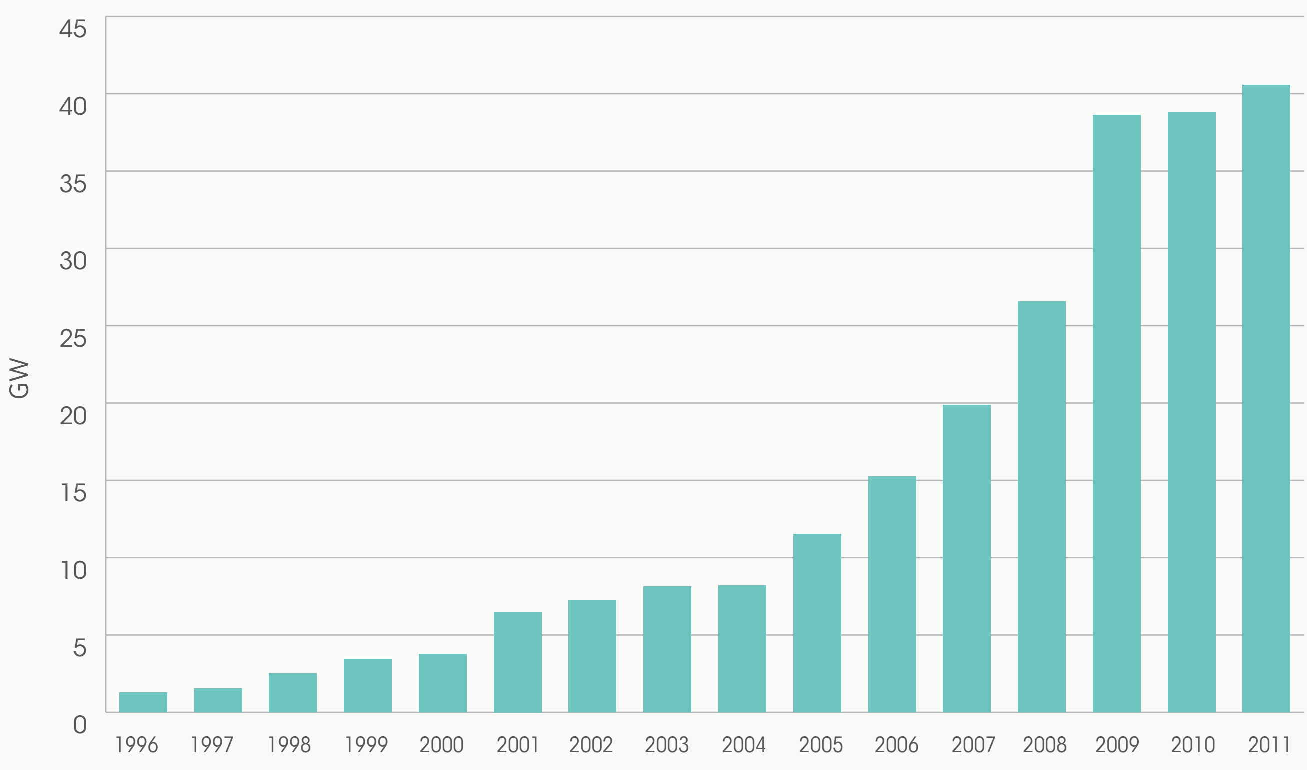
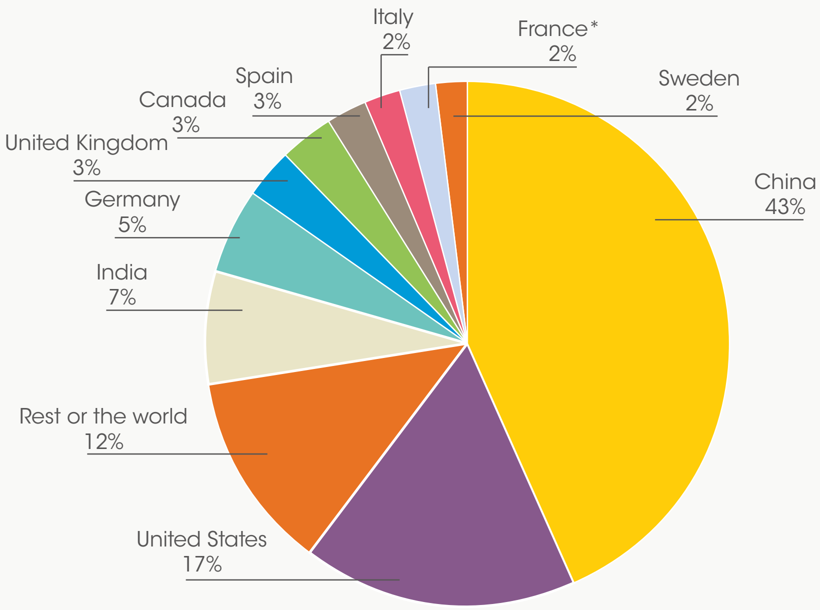


Figure 3.3: Global new wind power capacity additions, 1996 to 2011

Source: GWEC, 2011 ; and WWEA, 2012.



COUNTRY	MW	%
China	17 631	43
USA	6 810	17
India	3 019	7
Germany	2 086	5
UK	1 293	3.2
Canada	1 267	3.1
Spain	1 050	2.6
Italy	950	2.3
France*	830	2
Sweden	763	1.9
Rest of the world	4 865	12

** Provisional figure*

Figure 3.4: Top ten countries by new wind power capacity additions in 2011

Source: GWEC and WWEA, 2012.

3.3 FUTURE PROJECTIONS OF CAPACITY GROWTH

The wind industry has faced a difficult period, as low order levels during the financial crisis translated into lower capacity additions in 2010 compared with 2009, in the key markets of Europe and North America. However, global capacity still increased by one-quarter in 2010 and the outlook for the coming years is cautiously optimistic.

The world market for wind energy experienced solid growth in the first half of 2011, recovering from a weak year in 2010. Total installed capacity worldwide reached 215 GW by the end of June 2011, and 239 GW by the end of 2011.

The current analysis of the market suggests that as much as 85 GW of new capacity could come online in the next one to two years based on the project pipeline for wind power projects already in the process of being commissioned, constructed or which have secured financing (Figure 3.5). The United Kingdom could become a significant player in the European market in the coming years.

The offshore market is likely to be driven by the United Kingdom and Germany, while France and Sweden also have significant projects in the pipeline. The interest in offshore wind is also increasing in China which already has around 150 MW in the water and has plans to deploy 5 GW by 2015 and 30 GW by 2020, while the United States has also discussed significant deployment.

In 2011, offshore wind power capacity in Europe grew by 866 MW, with 348 MW installed in the first half of the year. In 2011 there were 11 offshore wind farms under development in Europe, which, when all completed, will have a capacity of nearly 2.8 GW (EWEA, 2011a). This is likely to be just the beginning of the offshore expansion in Europe, as a total of 19 GW of offshore wind power projects have received planning approval, although it remains to be seen how much of this capacity will actually be constructed (EWEA, 2011b). The United Kingdom has a significant number of offshore projects in the pipeline and could become the largest offshore market.

The Global Wind Energy Council (GWEC) is projecting that new capacity additions will increase out to 2015. New capacity additions are projected to grow from 41 GW in 2011 to 62.5 GW in 2015 (Figure 3.6). If these projections come to pass, global installed wind capacity will reach 460 GW by 2015, 2.3 times the total installed capacity in 2010. Other projections are even higher, the World Wind Energy Association projects a global capacity of 600 GW by 2015 (WWEA, 2011a).

Asia, Europe and North America will continue to drive new capacity additions in the foreseeable future. China is likely to continue to dominate new capacity additions, as ambitious plans and supportive policies align. Although new capacity additions may not grow as rapidly as they have in recent years, even so China has plans to reach 200 GW of installed capacity by 2020. India is likely to emerge as an important new market, with capacity additions of 2 GW to 3 GW per year. Overall, new capacity additions in Asia could increase from 21.5 GW in

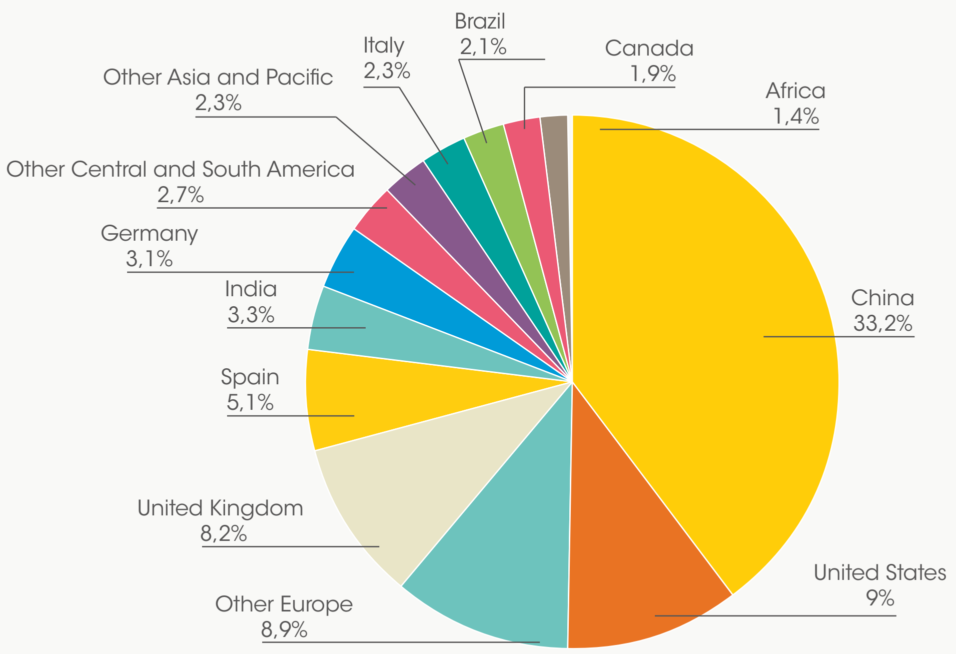


Figure 3.5: Wind power projects partially commissioned, under construction or with financing secured (84.8 GW).

Source: BNEF, 2011a.

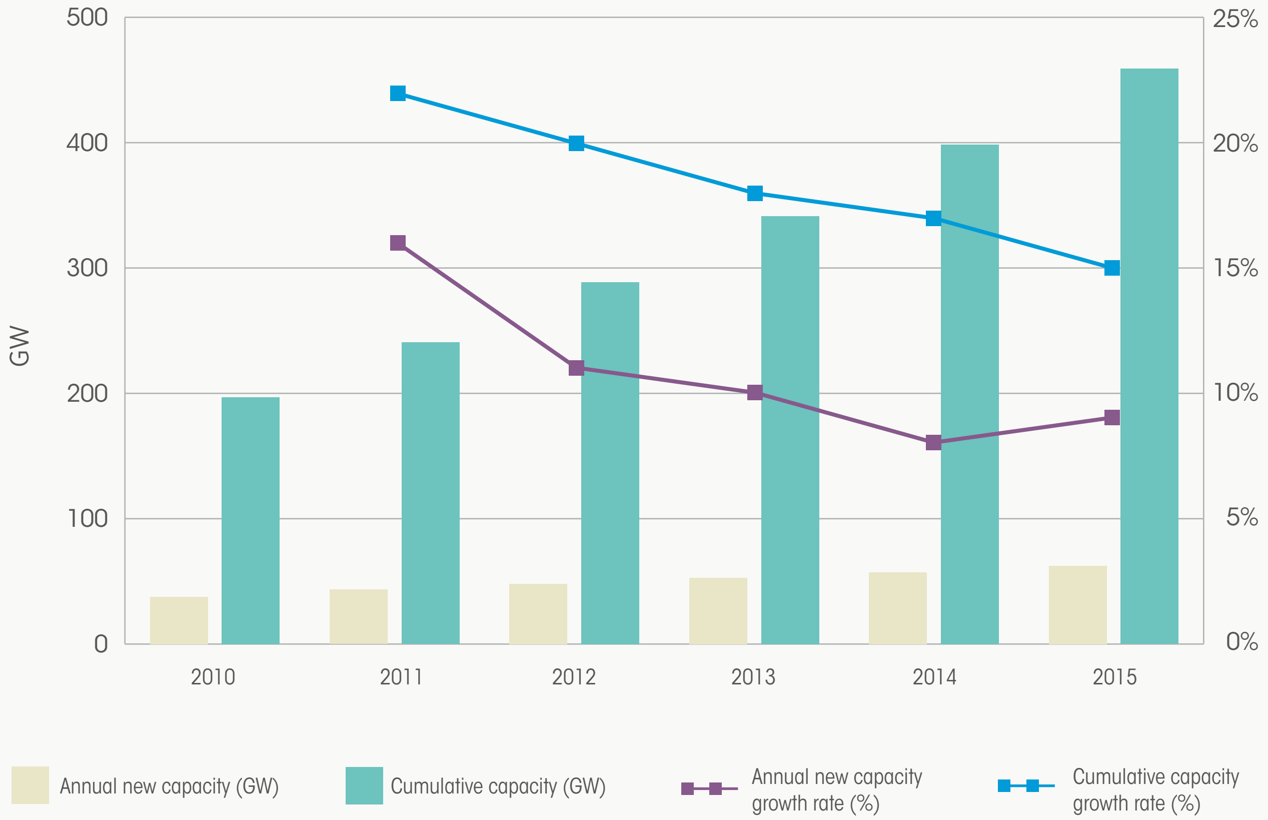


FIGURE 3.6: PROJECTED GROWTH IN GLOBAL WIND POWER ANNUAL CAPACITY ADDITIONS AND CUMULATIVE INSTALLED CAPACITY, 2010 TO 2015

Source: GWEC, 2011.

2010 to 28 GW in 2015 (GWEC, 2011). This implies that by 2015 Asia could have a total of 185 GW of installed wind capacity, displacing Europe as the region with the highest installed capacity.

The outlook in North America is considerably more uncertain, due to legislative uncertainties and the ongoing impact of weak economic fundamentals, but new capacity additions could increase to 12 GW in 2015. In Europe new capacity additions should increase to 14 GW by 2015 and total installed capacity to 146 GW by the end of that year.

In Latin America new capacity additions are projected to grow strongly from 0.7 GW in 2010 to 5 GW in 2015, increasing cumulative installed capacity from 2 GW to 19 GW. This rate of growth is less than the excellent wind resource could support, but encouraging developments in Brazil, Mexico and Chile are offset by a lack of political commitment and supportive policy frameworks elsewhere.

The outlook for Africa and the Middle East is particularly uncertain, but new capacity additions could increase ten-fold from 0.2 GW in 2010 to 2 GW in 2015. Africa has an excellent wind resource, although it is not evenly distributed, and there is potential for Africa to see much stronger growth rates in the future.

4. Current cost of wind power

Like other renewable energy technologies, wind is capital intensive, but has no fuel costs. The key parameters governing wind power economics are the:

- Investment costs (including those associated with project financing);
- Operation and maintenance costs (fixed and variable);
- Capacity factor (based on wind speeds and turbine availability factor);
- Economic lifetime; and
- Cost of capital.

Although capital intensive, wind energy is one of the most cost-effective renewable technologies in terms of the cost per kWh of electricity generated.

4.1. A BREAKDOWN OF THE INSTALLED CAPITAL COST FOR WIND

The installed cost of a wind power project is dominated by the upfront capital cost (often referred to as CAPEX) for the wind turbines (including towers and installation) and this can be as much as 84% of the total installed cost. Similarly to other renewable technologies, the high upfront costs of wind power can be a barrier to their uptake, despite the fact there is no fuel price risk once the wind farm is built. The capital costs of a wind power project can be broken down into the following major categories:

» **The turbine cost:** including blades, tower and transformer;

» **Civil works:** including construction costs for site preparation and the foundations for the towers;

» **Grid connection costs:** This can include transformers and subs-stations, as well as the connection to the local distribution or transmission network; and

» **Other capital costs:** these can include the construction of buildings, control systems, project consultancy costs, etc.

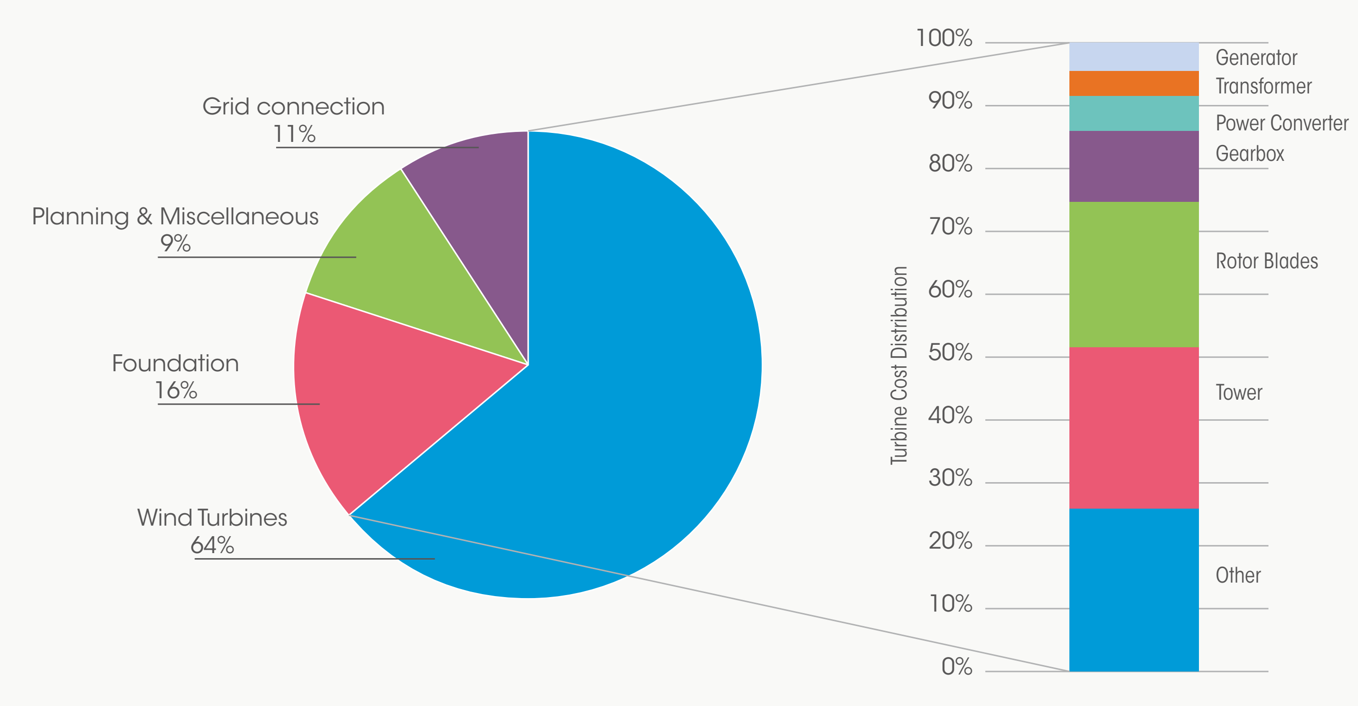


FIGURE 4.1: CAPITAL COST BREAKDOWN FOR A TYPICAL ONSHORE WIND POWER SYSTEM AND TURBINE

Source: Blanco, 2009.

Table 4.1: Comparison of capital cost breakdown for typical onshore and offshore wind power systems in developed countries, 2011

	Onshore	Offshore
Capital investment costs (USD/kW)	1 700-2 450	3 300-5 000
Wind turbine cost share (%)[1]	65-84	30-50
Grid connection cost share (%) [2]	9-14	15-30
Construction cost share (%) [3]	4-16	15-25
Other capital cost share (%) [4]	4-10	8-30

[1] Wind turbine costs includes the turbine production, transportation and installation of the turbine.
[2] Grid connection costs include cabling, substations and buildings.
[3] The construction costs include transportation and installation of wind turbine and tower, construction wind turbine foundation (tower), and building roads and other related infrastructure required for installation of wind turbines.
[4] Other capital cost here include development and engineering costs, licensing procedures, consultancy and permits, SCADA (Supervisory, Control and Data Acquisition) and monitoring systems.

Source: Blanco, 2009; EWEA, 2009; Douglas-Westwood, 2010; and Make Consulting, 2011c.

For the turbine, the largest costs components are the rotor blades, the tower and the gearbox. Together, these three items account for around 50% to 60% of the turbine cost. The generator, transformer and power converter account for about 13% of the turbine costs, with the balance of "other" costs being made up miscellaneous costs associated with the tower, such as the rotor hub, cabling and rotor shaft. Overall, the turbine accounts for between 64% to as much as 84% of the total installed costs, with the grid connection, civil works and other costs accounting for the rest (Blanco, 2009 and EWEA, 2009).

The reality is that the share of different cost components varies by country and project, depending on turbine costs, site requirements, the competitiveness of the local wind industry and the cost structure of the country where the project is being developed. Table 4.2 shows typical ranges for onshore and offshore wind farms.

4.2. TOTAL INSTALLED CAPITAL COSTS OF WIND POWER SYSTEMS, 1980 TO 2010

The installed cost of wind power projects is currently in the range of USD 1 700/kW to USD 2 150/kW for onshore wind farms in developed countries (Wiser and Bolinger, 2011 and IEA Wind, 2011a). However, in China, where around half of recent new wind was added, installed costs are just USD 1 300/kW.

Although global time series data are not readily available, data for the United States show that installed costs declined significantly between the early 1980s and 2001. Between 2001 and 2004, the average installed cost of projects in the United States was around USD 1 300/kW (Wiser and Bolinger, 2011). However, after 2004 the installed cost of wind increased steadily to around USD 2 000/kW; with data for 2010 and 2011 suggesting a plateau in prices may have been reached.

The reasons for these price increases are several, and include:

- The rapidly rising cost of commodities in general, and steel and copper prices in particular. In offshore projects, copper and steel alone can account for as much as 20% to 40% of the total project cost.
- The shift to offshore developments may be raising average installed costs in Europe. This is being accelerated by the shift from a shallow water market driven by Denmark to deeper water projects in the United Kingdom and Germany.
- Growing pains and more sophisticated systems. Market demand grew so rapidly that the supply chain and human capacity required had difficulty keeping up[15] with demand and shortages in

[15] This was compounded by policy uncertainty, which left some companies hesitant to invest in new capacity.

certain components – notably, wind turbines, gear boxes, blades, bearings and towers – and led to higher costs. The increasing sophistication of turbine design, component integration and grid interaction also pushed up prices.

The plateau in data for the United States suggests that for onshore wind installations, the supply chain has progressively caught up with demand, aided by more stable (but still volatile) commodity prices. Increased competition at a global level is also helping, especially the emergence of manufacturers with significant local content in countries with low-cost manufacturing bases.

For offshore wind, the market is still quite immature and mainly located in Europe. Costs for offshore wind projects vary, but are in the range USD 3 300 to USD 5 000/kW. This market was shared by Vestas and Siemens in 2010 and by Siemens and Bard in the first half of 2011. However, the Chinese market is growing and new markets are ready to start, notably in the United States and Korea, while several manufacturers – including Spanish, Chinese, Japanese and Koreans – are positioning themselves for growth in the offshore market.

4.2.1 Wind turbine costs

The wind turbine is the largest single cost component of the total installed cost of a wind farm. Wind turbine prices increased steadily in recent years, but appear to have peaked in 2009. Between 2000 and 2002 turbine prices averaged USD 700/kW, but this had risen to USD 1 500/kW in the United States and USD 1 800/kW in Europe in 2009. Since the peak of USD 1 800/kW for contracts with a 2009 delivery, wind turbine prices in Europe have declined by 18% for contracts with delivery scheduled in the first half of 2010 (Figure 4.2). Global turbine contracts for delivery in the second half of 2010 and the first half of 2011 have averaged USD 1 470/kW, down by 15% from peak values of USD 1 730/kW (BNEF, 2011b).

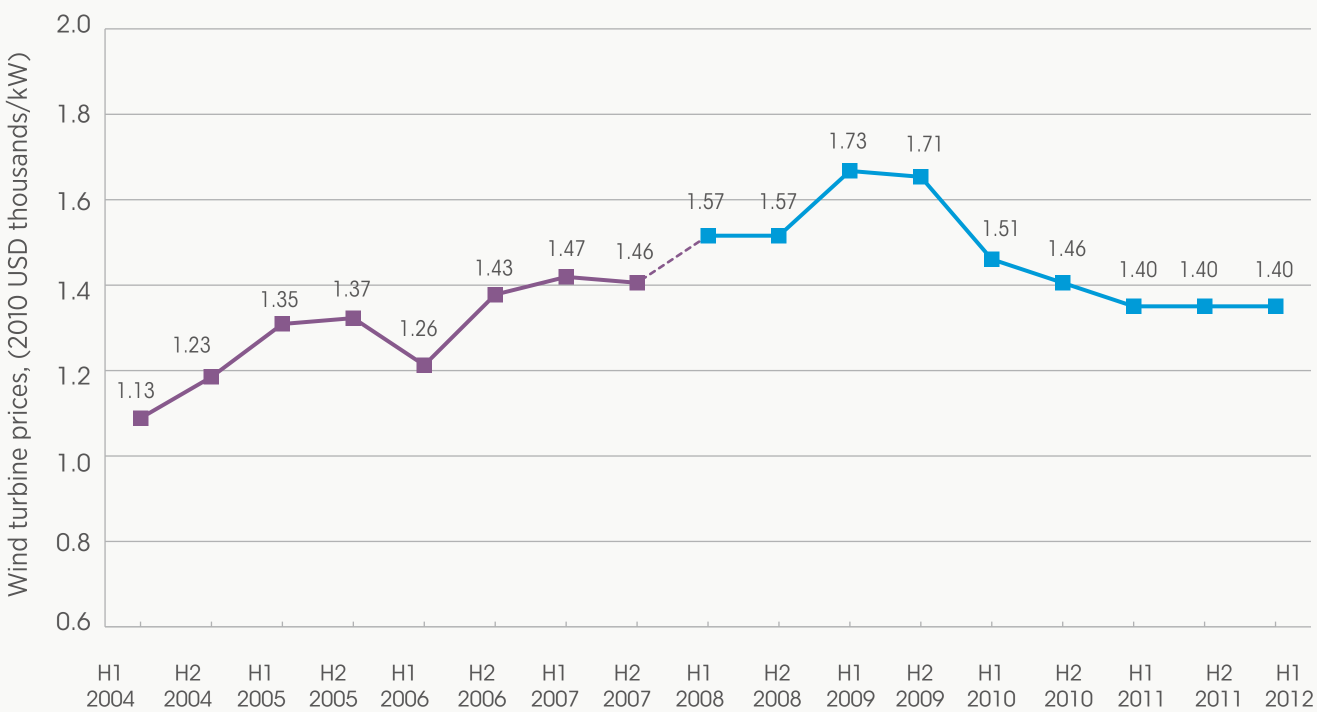


Figure 4.2: Wind turbine price index by delivery date, 2004 to 2012

Source: BNEF, 2011b.

The wind turbine prices quoted for recent transactions in developed countries are in the range of USD 1 100 to USD 1 400/kW (Bloomberg NEF, 2011b). The recent decline in wind turbine prices reflects increased competition among wind turbine manufacturers, as well as lower commodity prices for steel, copper and cement.

Data for the United States market has followed a similar trend. Average wind turbine prices more than doubled from a low of around USD 700/kW between 2000 and 2002 to USD 1 500/kW in 2008 and 2009 (Figure 4.3).[16]

In the United States market, this increase in wind turbine prices accounted for 95% of the increase in total installed wind costs over the same period.

Analysis of different markets suggests that there is quite a wide variation in wind turbine prices, depending on the cost structure of the local market. China appears to have the lowest prices, with a turbine price of just USD 644/kW in 2010 (WWEA, 2011). In contrast, Japan and Austria appear to have the highest costs, with turbine prices of around USD 2 000/kW and USD 2 100/kW in 2010 respectively (IEA Wind, 2011a). Of the developed countries, the United States and Portugal appear to have the lowest prices for wind turbines. The reasons for this wide variation include the impact of lower labour costs in some countries, local low-cost manufacturers, the degree of competition in a specific market, the bargaining power of market actors, the nature and structure of support policies for wind, as well as site specific factors.

Wind turbine prices have declined significantly since their peak in 2007/2008 in most countries (the notable exception being Japan). Prices were between 11% and 29% lower than their values in 2008 in the countries for which a consistent set of data is available (Figure 4.5). China, which is now the most important wind market, experienced the highest percentage decline and had the lowest absolute wind turbine prices in 2010.

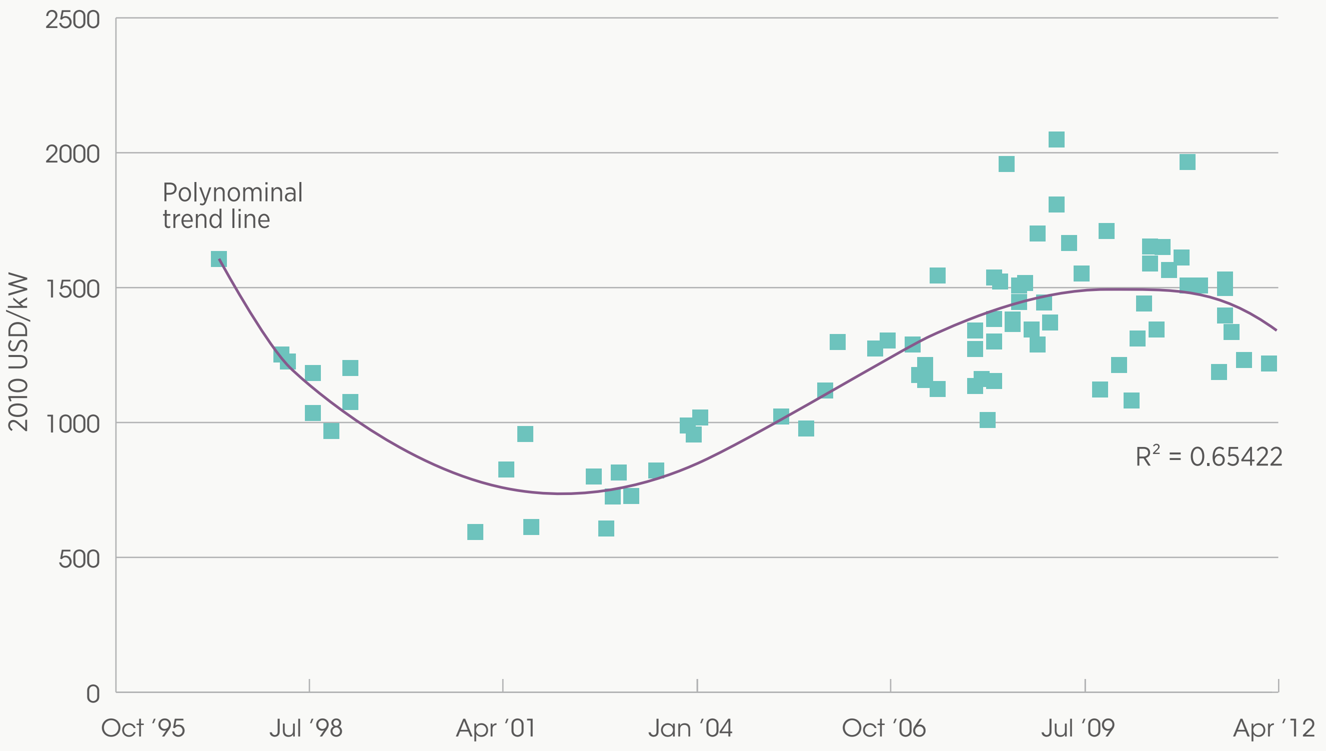


Figure 4.3: Reported wind turbine transaction prices in the United States, 1997 to 2012

Source: Wiser and Bolinger, 2011.

[16] *This is based on a dataset of 471 completed wind power projects in the continental United States, which represent 33 517 MW, or roughly 83% of all wind power capacity installed at the end of 2010. The dataset also includes a small sample of projects installed in 2011.*

Table 4.2: Average wind turbine prices (real) by country, 2006 to 2010

	Wind Turbine Price				
	2006	2007	2008	2009	2010
	2010 USD/kW				
Australia	–	–	–	1 635	1 725
Austria	–	–	2 384	2 053	2 123
Canada	–	–	–	1 685	–
China	885	928	911	864	644
Denmark	1 147	–	–	–	–
Germany	1 333	–	1 699	–	–
Greece	–	–	–	–	–
India	–	–	–	–	–
Ireland	–	1 730	1 639	1 380	1 460
Italy	1 290	1 874	1 892	1 798	1 592
Japan	865	1 652	1 713	2 123	1 991
Mexico	–	–	–	1 557	1 526
Netherlands	–	–	–		–
Norway	1 238	–	–		–
Portugal	1 086	1 478	1 581	1 593	1 261
Spain	–	–	–	1 317	–
Sweden	–	–	–	1 607	1 858
Switzerland	–	–	2 160	2 053	1 924
United Kingdom	–	–	–		–
United States	1 183	1 224	1 456	1 339	1 234

Note: Data were converted to USD using the following USD/euro exchange rates: 1.256 in 2006, 1.371 in 2007, 1.472 in 2008, 1.393 in 2009 and 1.327 in 2010 (IMF, 2011).

Sources: IEA Wind 2007, 2008, 2009, 2010 and 2011a and 2011b; and WWEA/CWEA, 2011.

Box 1

A BREAKDOWN OF WIND TURBINE COSTS

The wind turbine is the most expensive component of most wind farms. Figure 4.4 presents an example of the indicative cost breakdown for a large offshore wind turbine. The reality is that a range of costs exists, depending on the country, maturity of the wind industry in that country and project specifics. The two most expensive components are the towers and rotor blades, with these contributing around half of the total cost. After these two components, the next largest cost component is the gearbox. But this underestimates the importance of gearboxes, as these generally are an important part of the O&M costs, as they can require extensive maintenance. Onshore wind turbines, with their smaller sizes, will tend to have slightly lower shares for the tower and blades.

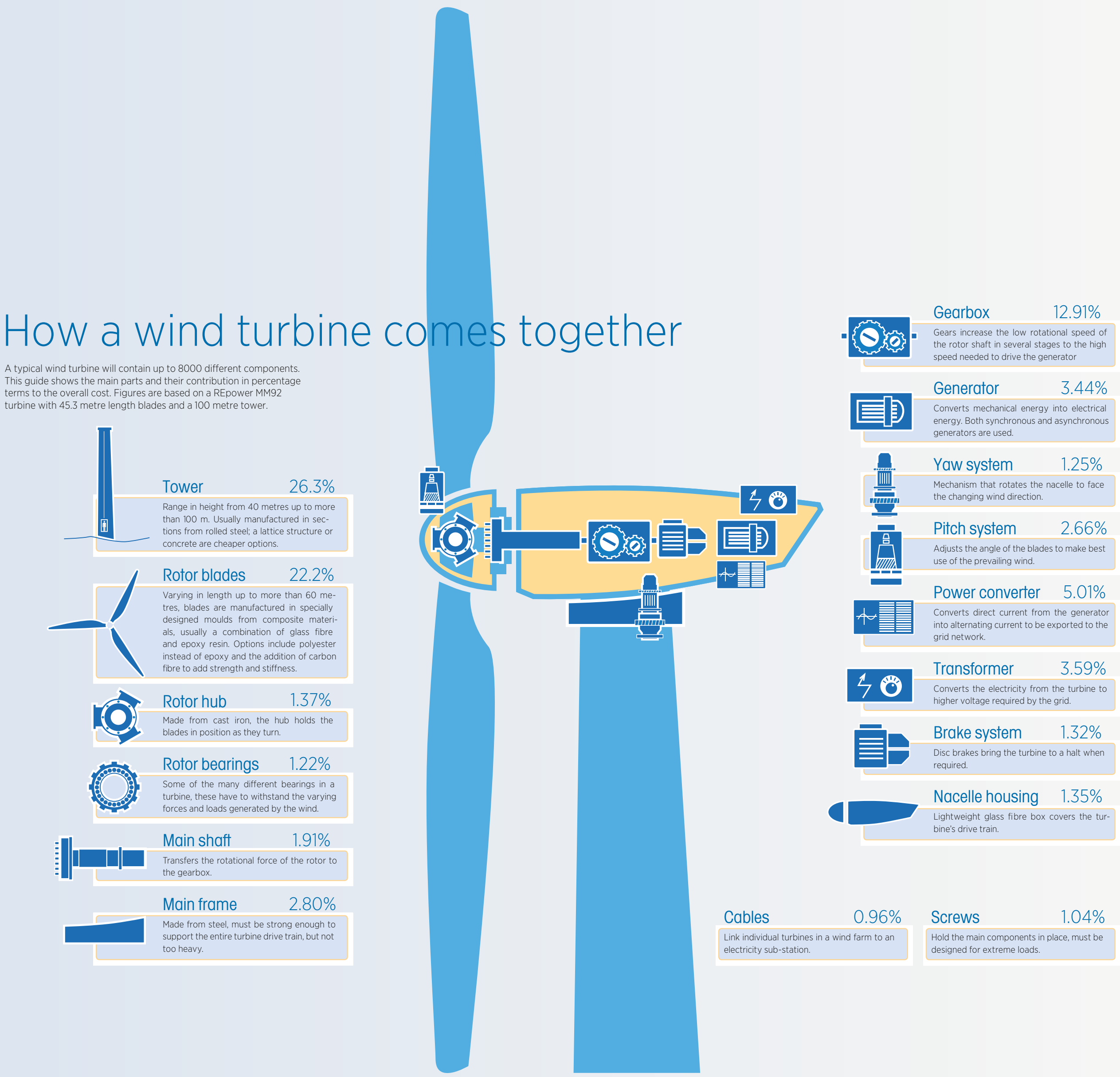


Figure 4.4: Wind turbine cost breakdown (5 MW offshore wind turbine)

Source: EWEA, 2007

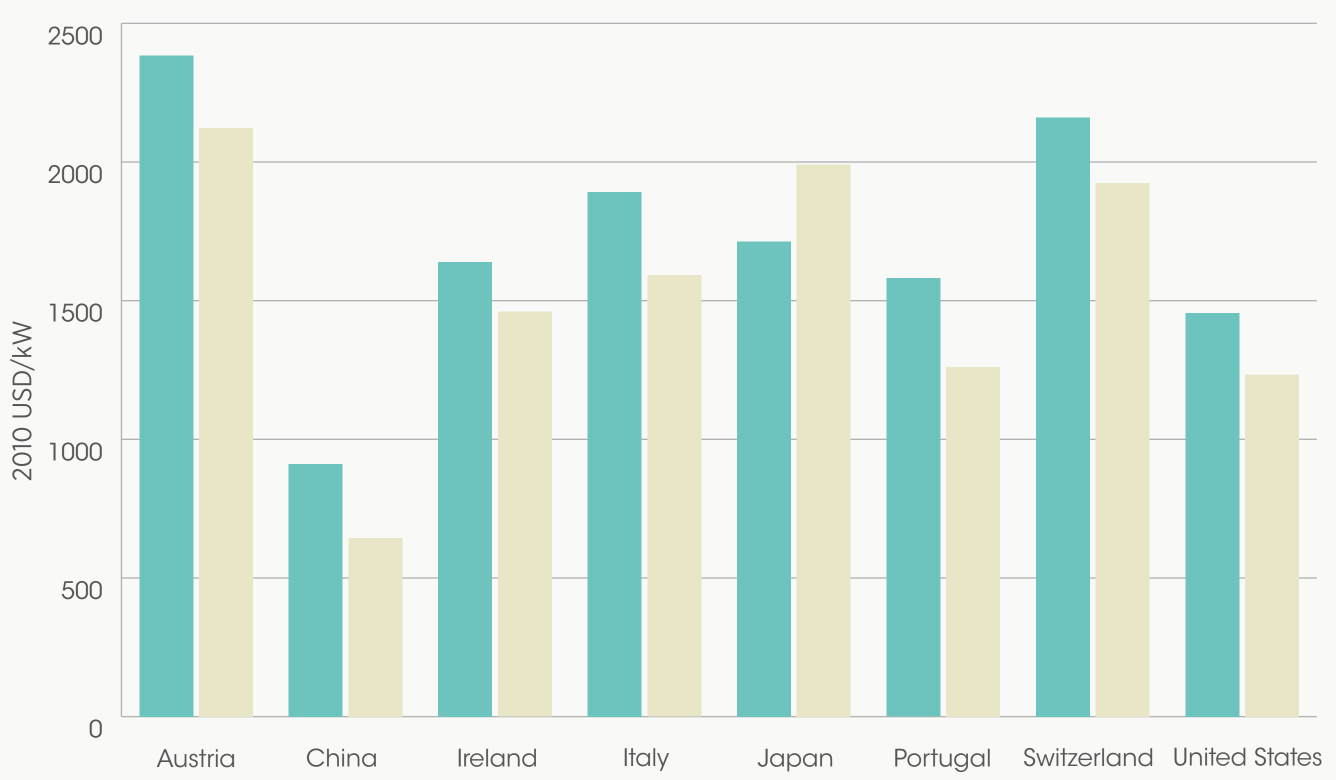


Figure 4.5: Wind turbine cost in selected countries, 2008 and 2010

Sources: IEA Wind 2009 and 2011a; and WWEA/CWEA, 2011.

In the United States wind turbine costs declined by 15% between 2008 and 2010, and data for February 2011 suggests a decline of 17%, which could translate into a full year reduction for 2001 of 20% to 25% compared to the 2008 peak.

4.2.2 Grid connection costs

Wind farms can be connected to electricity grids via the transmission network or distribution network. In the former case, transformers will be required to step-up to higher voltages than if the wind farm is feeding into the distribution network. This will tend to increase costs. If the grid connection point is not far from the wind farm, the connection is typically a high voltage alternating current (HVAC) connection. Over longer distances it may make sense to use a high voltage direct current (HVDC) link, as the reduced losses over this link will more than offset the losses in converting to direct current and back again to alternating current. It has been estimated that HVDC connections will be attractive for distances over 50 km in the future (Douglas-Westwood, 2010).

Grid connection costs can also vary significantly by country depending on who bears what costs for grid connection cost. For example, in some regimes, it is the transmission system operator that bears the cost of any transmission system upgrade required by the connection of a wind farm, in other regimes, the wind farm owner will be required to pay for these costs. Grid connection costs (including the electrical work, electricity lines and the connection point) are typically 11% to 14% of the total capital cost of onshore wind farms and 15% to 30% of offshore wind farms (Douglas-Westwood, 2010).

4.2.3 Civil works and construction costs

The construction costs include transportation and installation of wind turbine and tower, the construction of the wind turbine foundation (tower), and the construction of access roads and other related infrastructure required for the wind farm.

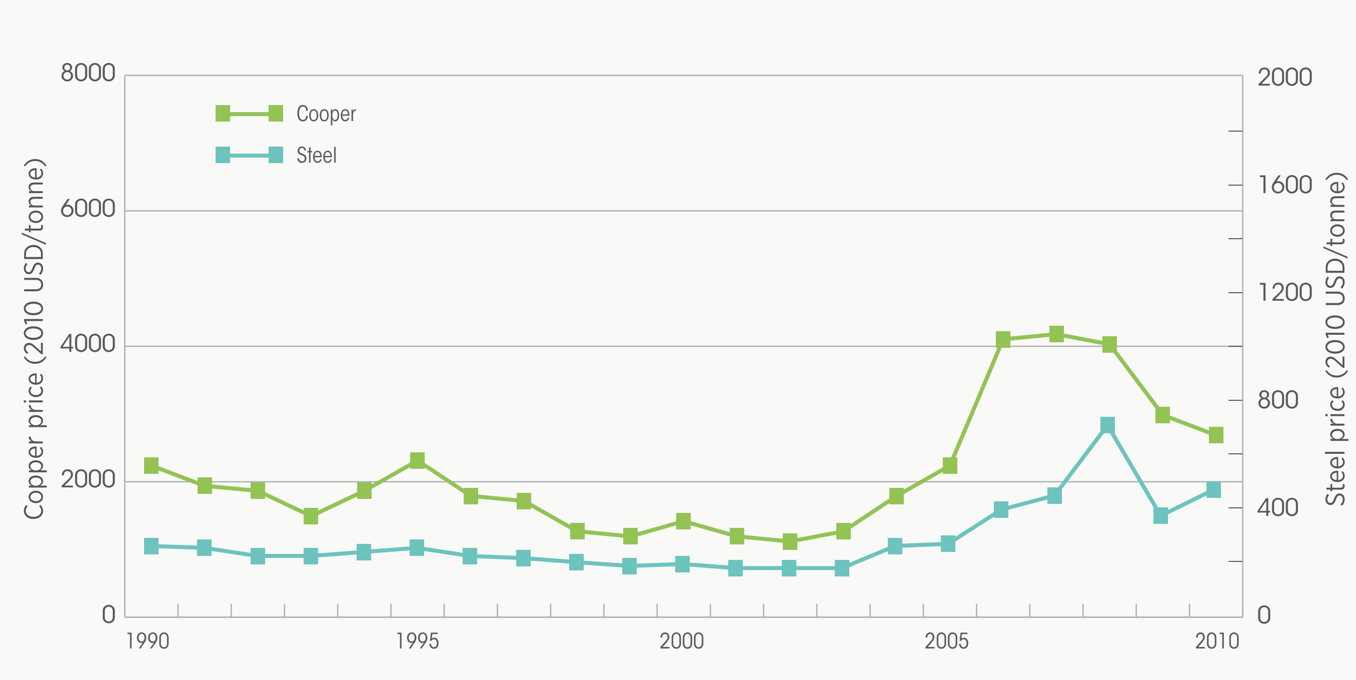


FIGURE 4.6: COPPER AND STEEL PRICES, 1990 TO 2010

Source: Based on data from World Bank, 2008; US Steel 2009; and UNCTAD, 2010.

The main foundation type onshore are a poured concrete foundation, while offshore it is currently driven/drilled steel monopiles. However, other types of foundations are possible (e.g. suction, caisson, guyed towers, floating foundations and self-installing concepts using telescopic towers) and will be required for offshore developments in deep water. Foundations are material-intensive, with 45% to 50% of the cost of monopile foundations being attributable to the steel required (Junginger, 2004). Cost reductions for foundations can be made through economies of scale, reduced material consumption and reduced material cost.

Figure 4.6 shows the commodity price development between 1990 and 2010 for copper and (structural) steel, both essential metals for wind power deployment. The market price of these commodities has undergone a substantial increase since 2005, with a peak (reached around 2007/2008) about three times its average pre-2005 level. While prices of both metals subsequently declined, in 2010 they were still approximately twice as high as they were throughout the 1990s.

The transportation and installation of the wind turbines and towers are also a major cost component. The increase in the average size of wind turbines has increased the absolute cost per wind turbine, but transport and installation costs have not grown proportionately to turbine size, helping to reduce the relative importance of these costs in onshore wind farms. Offshore, these costs are much higher than onshore and a shortage of purpose-built vessels and cranes means that these costs are unlikely to decline rapidly in the near future until this constraint eases.

The construction of vessels and cranes specifically designed to install wind turbines therefore offers an opportunity to reduce installation time and costs. An idea of the potential is that purpose-built installation ships in Denmark have reduced the average installation time per wind turbine from 3 days to 1.4 days (Junginger, 2004).

4.3 OPERATIONS AND MAINTENANCE COSTS

The fixed and variable operations and maintenance (O&M) costs are a significant part of the overall LCOE of wind power. O&M costs typically account for 20% to 25% of the total LCOE of current wind power systems (EWEA, 2009).

Actual O&M costs from commissioned projects are not widely available. Even where data are available, care must be taken in extrapolating historical O&M costs given the dramatic changes in wind turbine technology that have occurred over the last two decades. However, it is clear that annual average O&M costs of wind power systems have declined substantially since 1980. In the United States, data for completed projects suggest that total O&M costs (fixed and variable) have declined from around USD 33/MWh for 24 projects that were completed in the 1980s to USD 22/MWh for 27 projects installed in the 1990s and to USD 10/MWh for the 65 projects installed in the 2000s.[17]

The data are widely distributed, suggesting that O&M costs, or at least their reporting, are far from uniform across projects. However, since the year 2000 O&M costs appear to be lower and to be more uniform across projects than was the case prior to 2000. This decline in O&M costs may be due to the fact more recent projects use larger, more sophisticated turbines and have higher capacity factors (reducing the fixed O&M costs per unit of energy produced).

Another important consideration for wind energy is the fact that O&M costs are not evenly distributed over time. They tend to increase as the length of time from commissioning increases. This is due to an increasing probability of component failures and that when a failure does occur it will tend to be outside the manufacturer's warranty period. Although the data to support this hypothesis are not widely available, data for a limited number of projects in the United States suggest that this could be correct (Figure 4.8).[18]

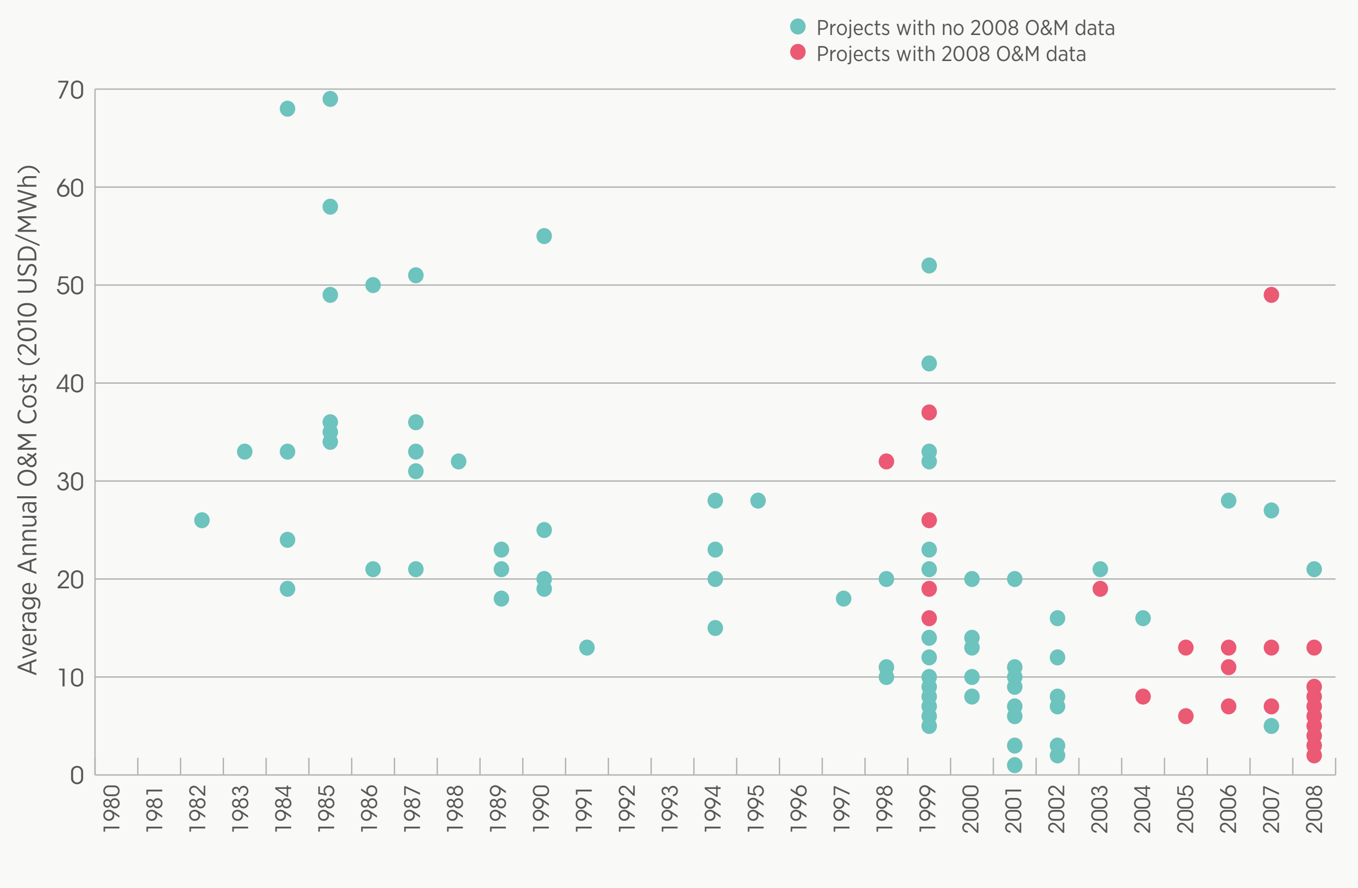


FIGURE 4.7: O&M COSTS FOR WIND POWER PROJECTS IN THE UNITED STATES, 1980 TO 2008

Note: The data are for the year a wind power system started commercial operation.

Source: Wiser and Bolinger, 2011.

[17] *Although what is included in the O&M costs is not clearly defined, in most cases the reported values appear to include the costs of wages and materials associated with operating and maintaining the facility, as well as rent (i.e. land lease payments). Other expenses, including taxes, property insurance, and workers' compensation insurance, are generally not included.*

[18] *Assumptions for Italy assume that O&M costs rise from 1% of installed capacity in year 1 to 4% in year 20 (IEA Wind, 2011b).*

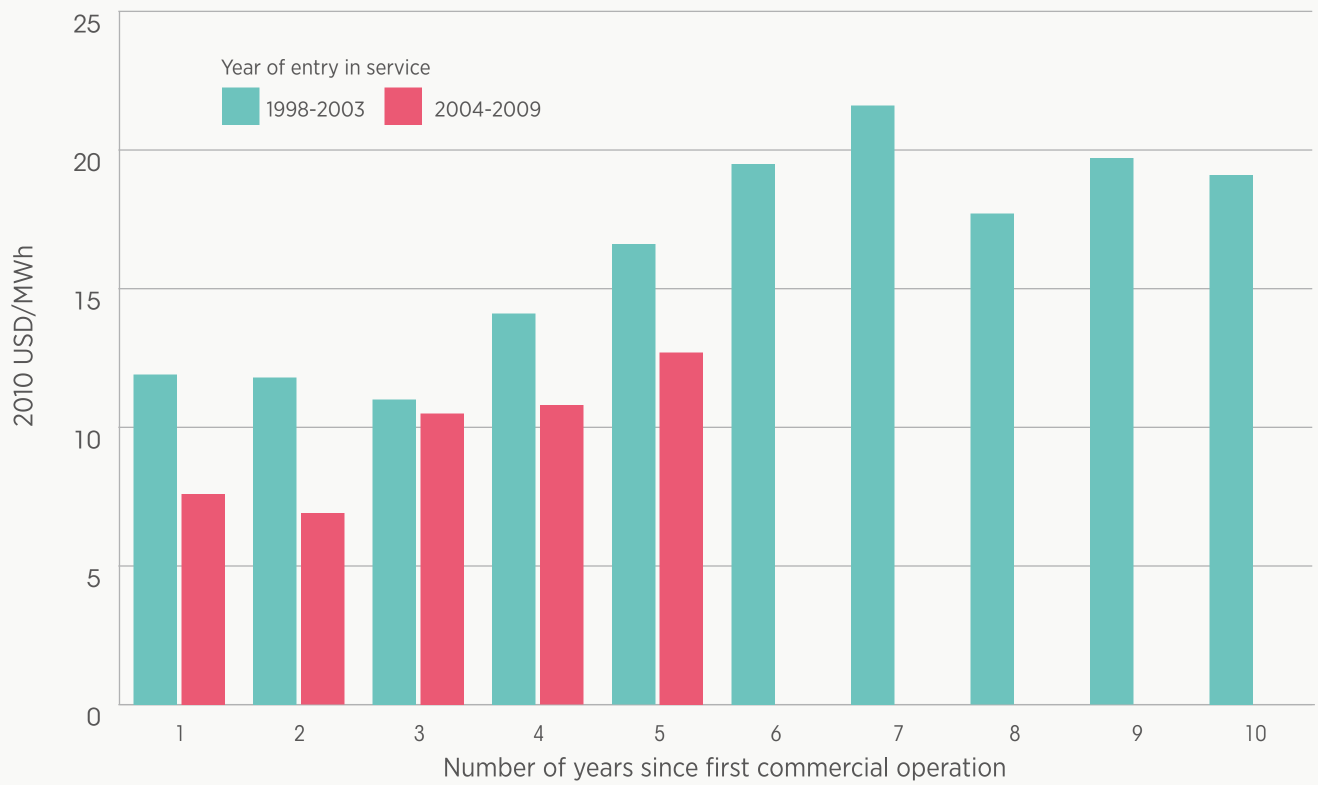


Figure 4.8: O&M costs in the United States by number of years since start of commercial operation

Source: Wiser and Bolinger, 2011.

Unfortunately, not all sources separate out fixed and variable O&M costs, and it is not uncommon for O&M costs to be quoted as a total of USD/kW/year. This section will thus present the two together to comparability of different sources. Fixed O&M costs typically include insurance, administration, fixed grid access fees and service contracts for scheduled maintenance. Variable O&M costs typically include scheduled and unscheduled maintenance not covered by fixed contracts, as well as replacement parts and materials, and other labour costs.[19] Maintenance measures may be small and frequent (replacement of small parts, periodic verification procedures, etc.), or large and infrequent (unscheduled repair of significant damage or the replacement of principal components).

O&M costs appear to be the lowest in the United States at around USD 0.01/kWh (USD 10/MWh), perhaps due to the scale of the market and the long experience with wind power. European countries tend to have higher cost structures for O&M for onshore wind projects.

O&M costs for offshore wind farms are significantly higher than for onshore wind farms due to the higher costs involved in accessing and conducting maintenance on the wind turbines, cabling and towers. Maintenance costs are also higher as a result of the harsh marine environment and the higher expected failure rate for some components. Overall, O&M costs are expected to be in the range of USD 0.027 to USD 0.054/kWh (USD 27 to USD 54/MWh) (ECN, 2011).

Given that offshore wind farms are at the beginning of their deployment phase, O&M costs remain highly project-specific and it will take time for learning to reduce costs and for a clear trend to emerge. However, it is clear that reducing O&M costs for offshore wind farms remains a key challenge and one that will help improve the economics of offshore wind.

[19] It is worth noting that in some electricity markets, depending on their rules for wind projects, there will be some variable costs associated with power system services, such as reactive power compensation.

Table 4.3: O&M costs for onshore wind projects

	Variable, USD/kWh	Fixed, USD/kW/year
Austria	0.038	
Denmark	0.0144 - 0.018	
Finland		35 - 38
Germany		64
Italy		47
Japan		71
The Netherlands	0.013 – 0.017	35
Norway	0.020 – 0.037	
Spain	0.027	
Sweden	0.010 – 0.033	
Switzerland	0.043	
United States	0.010	

Source: IEA Wind, 2011

4.4 TOTAL INSTALLED COST OF WIND POWER SYSTEMS

Onshore wind

The installed capital costs for wind power systems vary significantly depending on the maturity of the market and the local cost structure. China and Denmark have the lowest installed capital costs for new onshore projects of between USD 1 300/kW and USD 1 384/kW in 2010. Other low cost countries include Greece, India, and Portugal (see Table 4.4 and Figure 4.9).

A detailed analysis of the United States market shows that the installed cost of wind power projects decreased steadily from the early 1980s to 2001, before rising as increased costs for raw materials and other commodities, coupled with more sophisticated wind power systems and supply chain constraints pushed up wind turbine costs (Figure 4.10). However, installed costs appear to have peaked. The capacity-weighted average installed cost of wind projects built in 2010 in the United States was USD 2 155/kW virtually unchanged from the 2009 figure of USD 2 144/kW in 2009. The initial data for 2011 suggest a slight decline in installed costs, driven by lower turbine costs.

The full year outlook for 2011 is therefore that installed costs should be slightly lower than 2010 in the United States and this trend should continue into 2012, as most developers are expecting further decreases in turbine prices for delivery in 2012. This trend is unlikely to be reversed in the short- to medium-term and will be replicated globally, as low-cost manufacturers (notably in China) start to enter the global market for turbines.

There are considerable economies of scale in wind power developments, as projects under 5 MW have significantly higher total installed costs than larger systems (Figure 4.11). However, there do not appear to be significant economies of scale beyond shifting into the 5 MW to 20 MW range or higher. In 2009 and 2010, the 6.8 GW (53 projects) installed at 100 MW to 200 MW capacity wind farms, had around the same total installed costs as the 257 MW (21 projects) installed in the 5 MW to 20 MW range. Without data from other regions to verify this trend in the United States, it is difficult to identify why this might be.

Table 4.4: Onshore wind power system installed costs for selected countries, 2003 to 2010

	Onshore wind power system installed cost 2010 USD/kW							
	2003	2004	2005	2006	2007	2008	2009	2010
Australia							2 566	1 991 - 3 318
Austria							2 477	2 256 - 2 654
Canada	865	785	1 367	1 855	2 268	1 749	2 336	1 975 - 2 468
China	0	0	0	0	1 472	1 463	1 392	1 287 - 1354
Denmark	790	725	886	1 331	1 503	1 759	1 840	1 367
Finland	922	836	924	0	1 893	2 126	2 134	2 100
Germany	1 044	956	1 084	1 750	1 979	2 174	2 122	1 773 - 2 330
Greece	959	862	952	1426	1 586	1 639	2 265	1 460 - 1 858
India	0	0	0	0	1 075	1 152	1 194	1 460
Ireland	1 034	973	0	0	2 883	2 533	2 268	2 419
Italy	846	853	943	1 629	2 595	2 682	2 463	2 339
Japan	818	734	943	1 643	1 856	2 980	3 185	3 024
Mexico				1 477		1 466	1 982	2 016
Netherlands	1 044	956	1 037	1 494	1 637	1 788	1 876	1 781
Norway	1 175	853	971	1 652	1 977	2 227	2 196	1 830
Portugal	1 063	939	1 094	1 589	1 874	1 932	1 982	1 327 - 1 858
Spain	903	802	896	1 657	1 802	2 086	1 770	1 882
Sweden	969	853	0	0	1 893	2 239	2 598	2 123
Switzerland				1 688		2 808	2 669	2 533
United Kingdom	0	879	1 433	1 714	1 981	1 955	1 858	1 734
United States	752	683	849	1 522	1 840	2 124	2 144	2 154

Sources: IEA Wind, 2007, 2008, 2009, 2010 and 2011; and WWEA/CWEC, 2011.

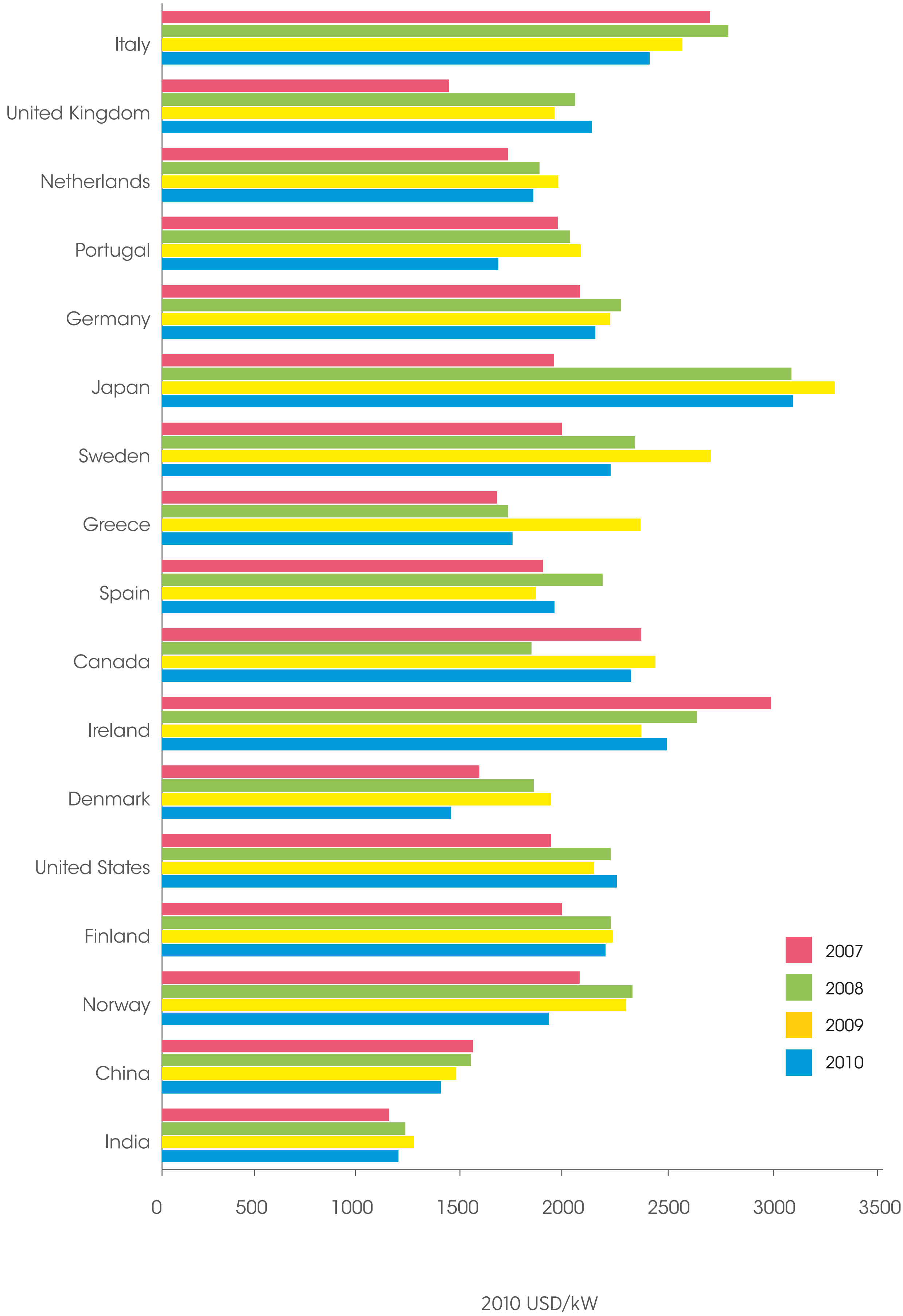


FIGURE 4.9: ONSHORE WIND POWER SYSTEM INSTALLED COST FOR SELECTED COUNTRIES, 2007 TO 2010

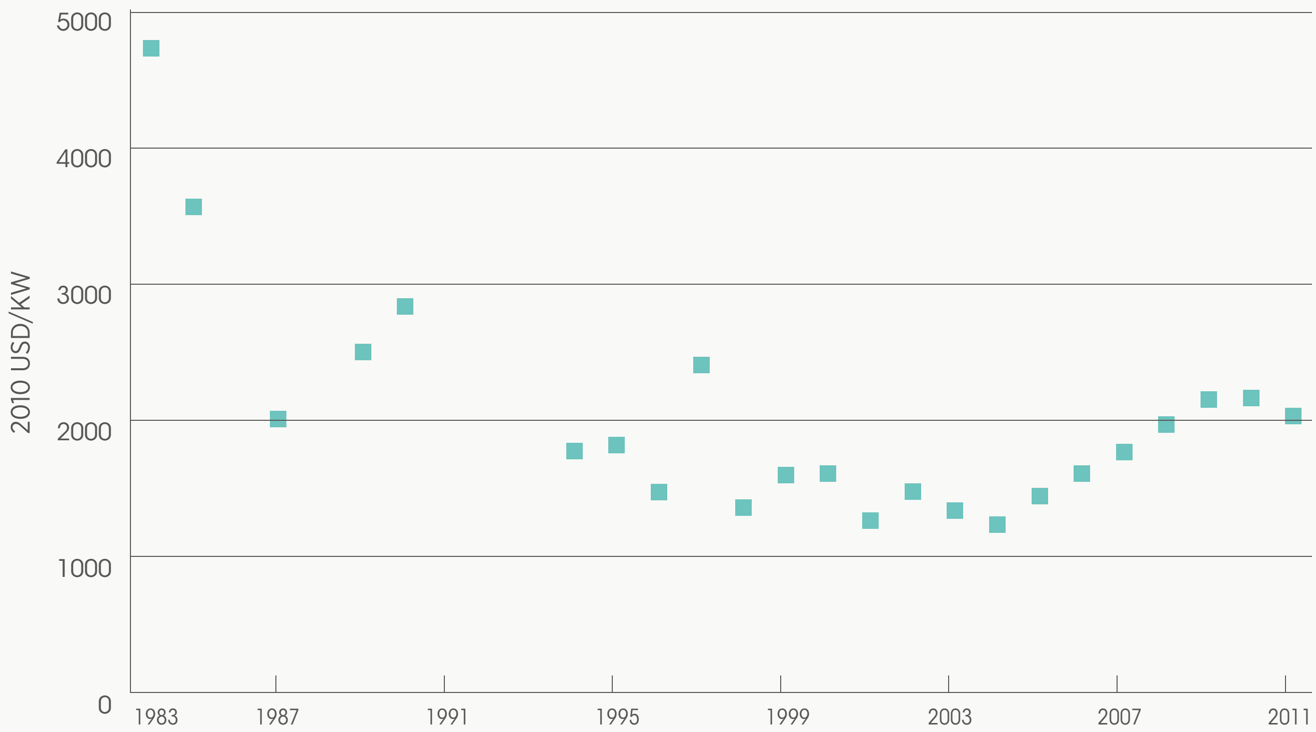


Figure 4.10: Installed cost of wind power projects in the United States, 1982 to 2011

Source: Wiser and Bolinger, 2011.

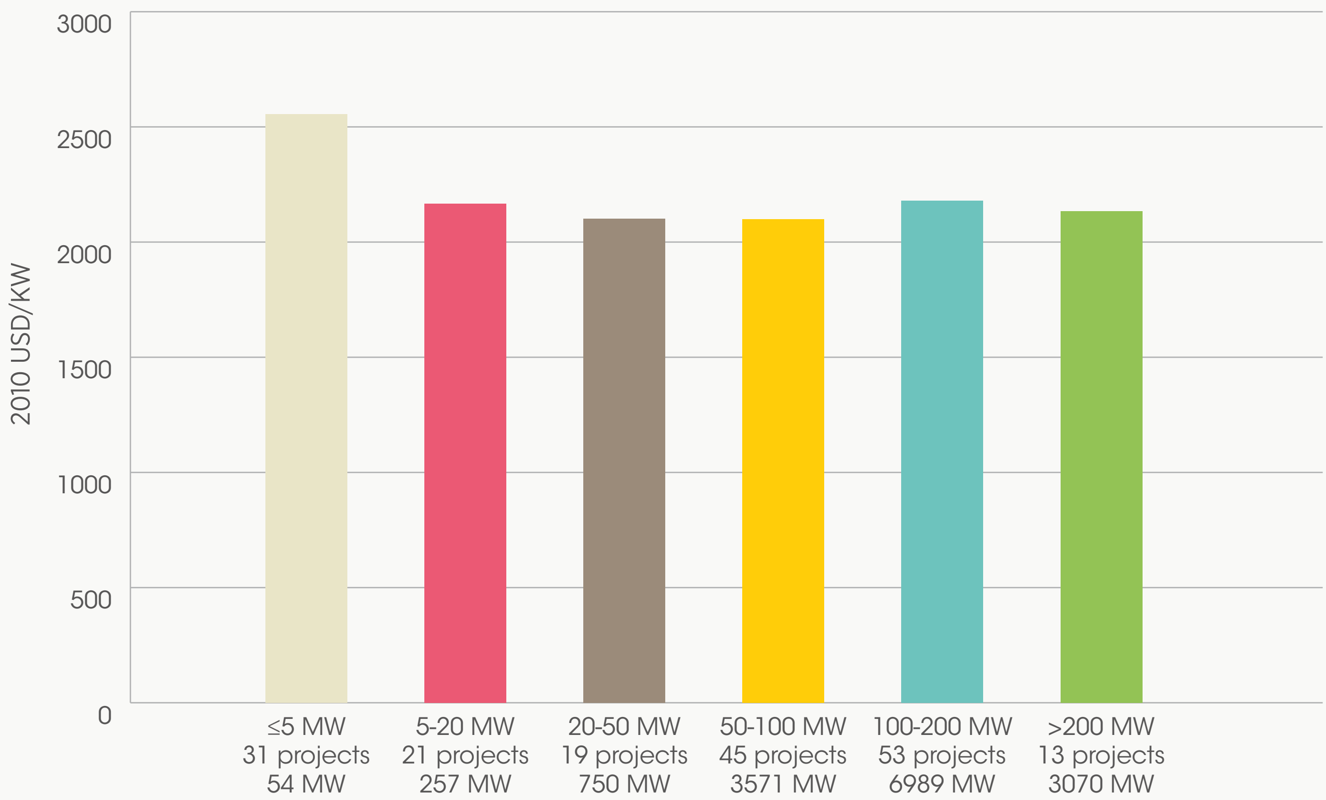


Figure 4.11: Average installed cost of wind power projects in the United States by project size, 2009 and 2010

Source: Wiser and Bolinger, 2011.

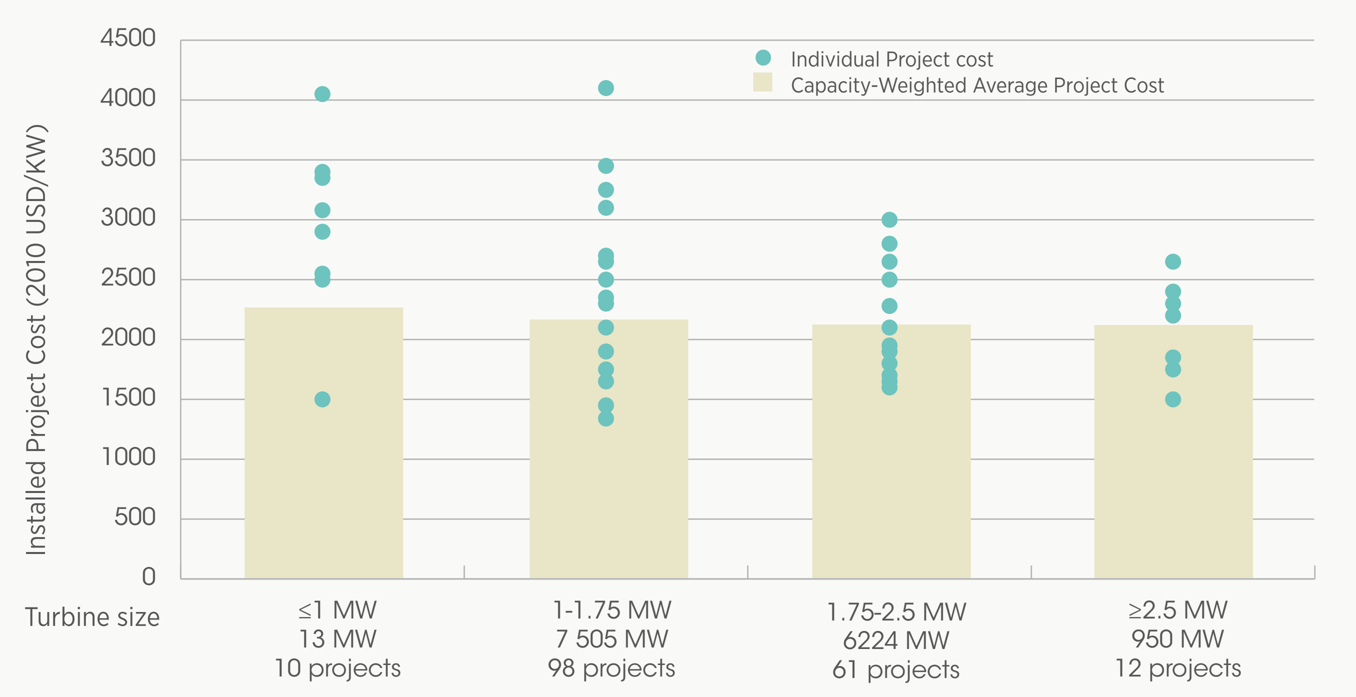


Figure 4.12: Installed cost of wind power projects in the United States by turbine size: 2009 and 2010

Source: Wiser and Bolinger, 2011.

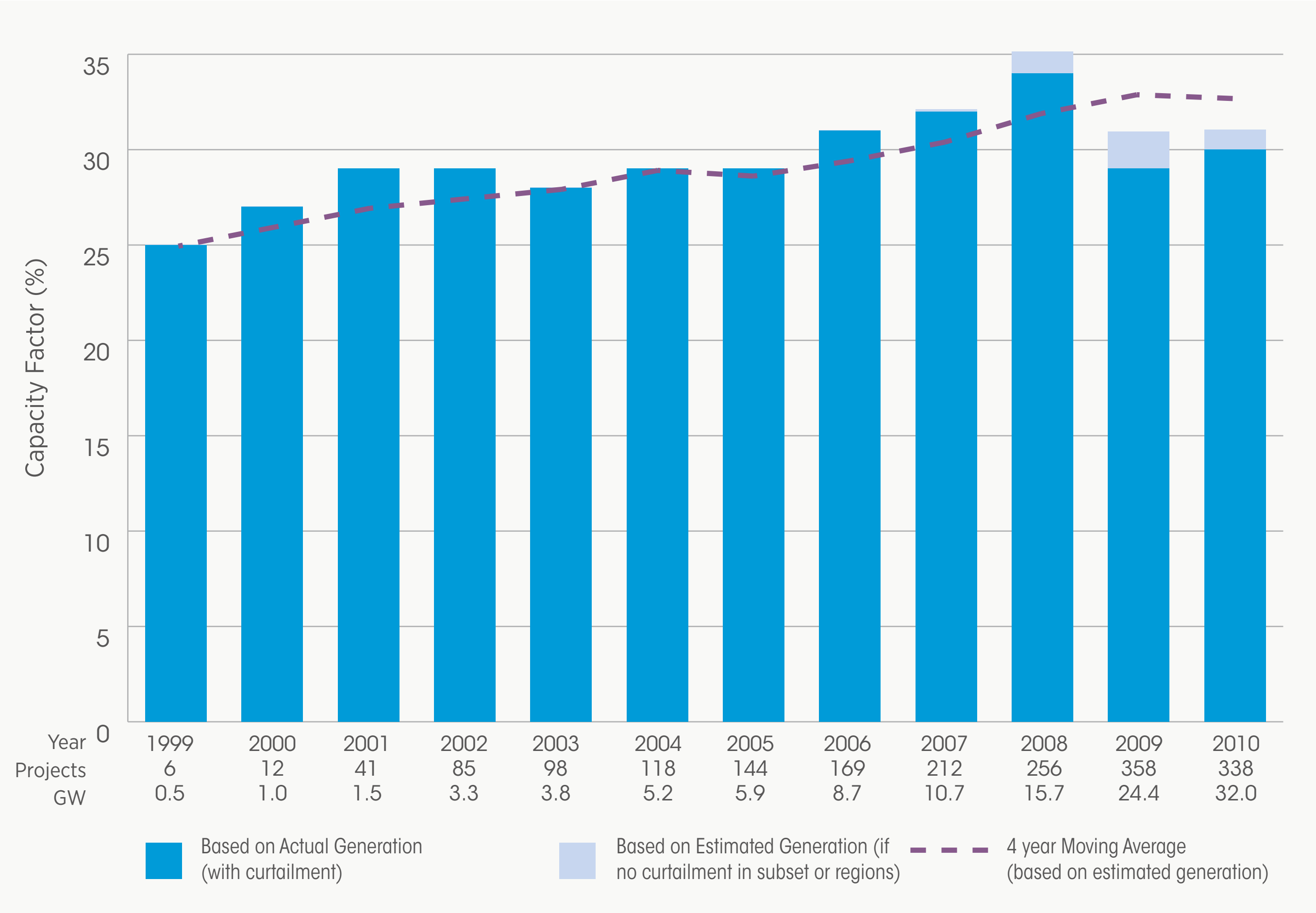


Figure 4.13: The capacity-weighted average capacity factors for projects in the United States, 1999 to 2010

Source: Wiser and Bolinger, 2011.

Shifting to larger turbine sizes with taller towers and larger rotor blades has contributed to increased output and to a lower LCOE for wind. However, looking at just one year, shifting to larger turbine sizes appears to significantly reduce the range of installed costs for projects, but the actual average cost reduction is small (weighted by capacity), at least in the United States (Figure 4.12).

The main benefit of larger turbines and hub heights therefore appears to be in[20] allowing turbines to access higher average wind speeds, have larger swept areas for the rotors and therefore achieve higher capacity factors. In the United States, the capacity-weighted average capacity factors for projects peaked in 2008 (for projects installed in 2007) at around 35%, but have since settled at around 31% to 32%.[21] (Figure 4.13)

Offshore wind

The capital cost of offshore wind power is around twice that of onshore wind energy projects. The higher cost is due to increased investments in laying cables offshore, constructing expensive foundations at sea, transporting materials and turbines to the wind farm, and installing foundations, equipment and the turbines themselves. The turbines, although based on onshore designs, are also more expensive. They need to be designed with additional protection against corrosion and the harsh marine environment to help reduce maintenance costs, which are also higher offshore (Douglas-Westwood, 2010).

A recent Douglas-Westwood study initiated by The Research Council of Norway (RCN) provides a detailed analysis of offshore wind power (Douglas-Westwood, 2010). The study describes recent trends in installed offshore wind power project costs, wind turbine transaction prices, project performance and O&M costs.

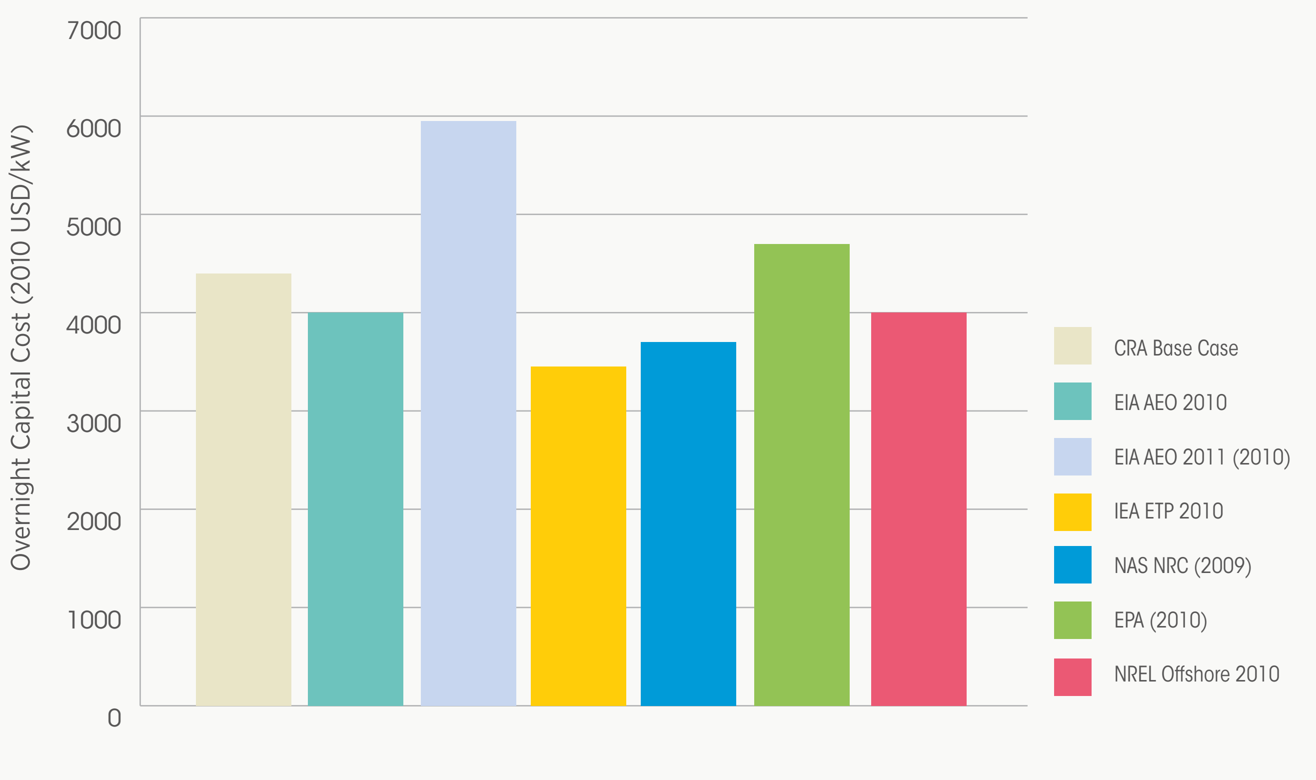


Figure 4.14 Estimates of offshore wind power capital costs

Source: Douglas-Westwood, 2010.

[20] *The data also suggest that wind farms with larger turbines also have a narrower range of costs. However, this is likely to be driven by the fact that larger turbines are chosen for larger wind farms which will result in more competitive prices.*

[21] *This includes an estimated allowance added back in for curtailment of wind generation for grid or system stability/capability reasons. This compensation for curtailment is, however, based on calculations with data for only a subset of regions. As a result, the true capacity factor is likely to have been somewhat higher. The data are also not corrected for the natural variations in the wind resource to any long term average; therefore, the four year moving average is a better indicator of the real trend in capacity factors.*

Table 4.5: Capital cost structure of offshore wind power systems, 2010

	Share of total cost (%)	Cost (USD/kW)	Sub- Components	Cost share of sub-components (%)
Wind turbine	44	1 970	Nacelle Blades Gearbox Generator Controller Rotor hub Transformer Tower Other	2 20 15 4 10 5 4 25 15
Foundations	16	712	-	-
Electrical infrastructure	17	762	Small array cable Large array cable Substation Export cable	4 11 50 36
Installation	13	580	Turbine installation Foundation installation Electrical installation	20 50 30
Planning and development	10	447	-	-
Total	100%	4 471		

Source: Douglas-Westwood, 2010.

The largest cost component for offshore wind farms is still the wind turbine, but it accounts for less than half (44%) of the total capital costs. Based on a price assessment of wind turbines of the major manufacturers, and other research into the component costs, it was estimated that the average price of an offshore wind turbine was around USD 1 970/kW (Douglas-Westwood, 2010). The foundations, electrical infrastructure, installation and project planning account 16%, 17%, 13% and 10% of the total costs, respectively.

According to the estimates of Douglas-Westwood, the current capital cost of the offshore wind power system for typical shallow water and semi-near shore conditions in the UK is USD 4 471/kW which is almost 2.5 times higher than onshore wind case (Douglas-Westwood, 2010). The cost of offshore wind electricity is estimated at USD 0.162/kWh. This is calculated using current capital and operational costs, a 20 year lifespan, 38% capacity factor and a 7% discount rate. The additional costs due to variability are modest and could add an additional USD 0.003/kWh to the LCOE (Douglas-Westwood, 2010).

Small wind turbines

The capital costs and the cost of the energy produced by small wind turbines are still higher than large-scale wind turbines (AWEA, 2011 and IEA Wind, 2010). The cost of small wind turbines varies widely depending on the competitiveness of the market and factors affecting installation, but costs for a well-sited turbine tend to range between USD 3 000 to USD 6 000/kW. The average installed price of a small wind turbine system in the United States is USD 4 400/kW and USD 5 430/kW in Canada (AWEA, 2011 and CanWEA, 2010). Costs are significantly lower in China, and range between USD 1 500 to USD 3 000/kW depending upon the quality and reliability. The LCOE of small wind is in range of USD 0.15 to USD 0.35/kWh (IEA Wind, 2010), estimated operations and maintenance (O&M) costs range between USD 0.01 to USD 0.05/kWh (AWEA, 2011).

5. Wind power cost reduction potentials

The recent increases in wind turbine prices makes projecting cost reductions for wind power projects in the short-term challenging. However, estimating cost reductions is important if policy makers, energy companies and project developers are to have robust information in order to compare between renewable power generation projects and conventional power generation technologies.

Numerous studies have looked at where cost reductions could be achieved and how large these savings might be. Most analysis has looked at quantitative estimates of cost reduction possibilities for onshore wind, but there is an increasing number of studies that have done this for offshore wind. Most of these studies focus on cost reductions caused by improved designs of wind farms. However, other factors (e.g. learning-by-doing, standardization and economies of scale) may also contribute significantly to cost reductions. The improved performance of wind turbines and their location in higher average wind speed locations will also help to reduce the LCOE of wind by improving the average capacity factor.

For offshore wind, cost reductions in other industries, such as the offshore oil and gas sector and offshore cable laying, will also have benefits for wind. At the same time, developments in commodity prices, particularly steel, copper and cement, will also influence wind power cost reduction potentials depending on how they evolve over time.

For onshore and offshore wind power projects the key cost components, and hence areas for cost reduction, are:

- Wind turbines;
- Foundations;
- Grid connection/cabling;
- Installation; and
- Project planning and development.

To achieve significant reductions in the LCOE of wind will require efforts to reduce the costs of each of these components of a wind power project. At the same time, efforts to improve the yield of wind farms (i.e. the capacity factor) will also need to be pursued.

Historical learning rates for wind power were around 10% prior to 2004, when wind turbine prices grew strongly. Solar photovoltaic experienced a similar divergence from its historical learning curve due to supply chain bottlenecks, but once these were overcome, prices returned to their historical trend. It is not yet clear whether or not the installed cost of wind power will return to the trend seen between the 1980s and 2004. Current projections by the IEA and GWEC are based on a learning rate of 7%, but lower values may also be possible. Increased competition, particularly from emerging market manufacturers will help keep costs down and will likely lead to a consolidation among wind manufacturers, helping to increase economies of scale.

An alternative approach is to look at the cost reduction potential from a bottom-up perspective, although these are often informed by learning rates as well. Recent analysis for the United Kingdom suggests that onshore wind farm costs could be 12% lower by 2020 than they are in 2011 and 23% lower by 2040. The largest percentage and absolute cost reductions come from the wind turbines. Wind turbines are projected to be 15% cheaper in 2020 than in 2011 and 28% cheaper in 2040. The sections that follow discuss these cost reduction potentials in more detail.

5.1 COST REDUCTION POTENTIAL BY SOURCE

Wind turbine cost reductions in the last two decades, for both onshore and offshore wind turbines, have been achieved by economies of scale and learning effects as installed capacity has grown. The LCOE of wind has been further reduced as the result of higher capacity factors that have come from increasing turbine height and rotor diameter. Onshore, wind turbines are typically in the 2

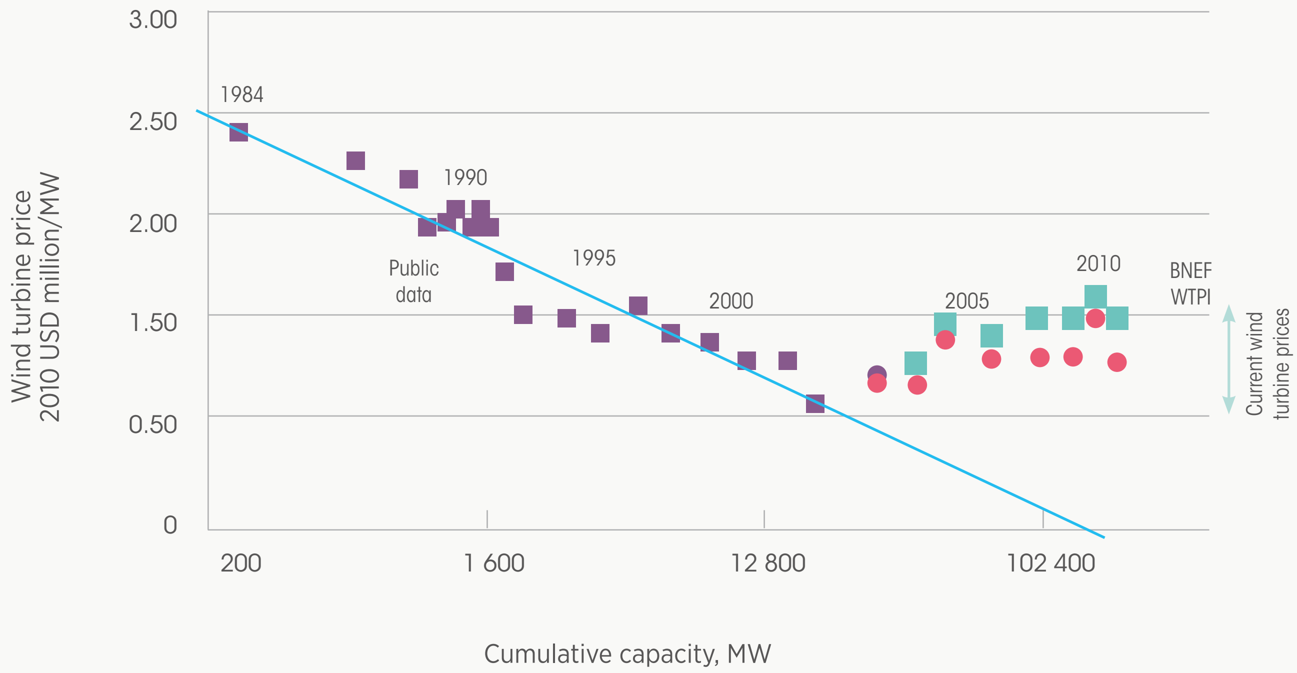


Figure 5.1: Historical learning rate for wind turbines, 1984 to 2010

Note: WTPI = Wind turbine price index

Source: BNEF, 2011b.

Table 5.1: Projected capital costs for small-scale wind farms (16 MW) with 2 MW turbines in the United Kingdom, 2011 to 2040

	2011	2020	2040	% of 2011 cost in 2020	% of 2011 cost in 2040
Development	100	98	93	98%	93%
Turbine	870	737	630	85%	72%
Foundation	170	159	144	93%	84%
Electrical	100	91	83	91%	83%
Insurance	40	37	34	93%	84%
Contingencies	70	65	59	93%	84%
Total	1 350	1 187	1 042	88%	77%

Source: Mott MacDonald, 2011.

MW to 3 MW size range, while offshore the average is higher at around 3.4 MW per turbine for projects in 2011 (EWEA, 2011b). This compares to less than one megawatt in 2000 (EWEA, 2011b). The growth in the average size of onshore turbines will slow as increasing wind farm heights on land will become increasingly difficult. The increase in the average size of offshore wind turbines will continue as increased rotor height and diameter allow greater energy yields.

The reason for this growth is simple; the LCOE of wind energy can be reduced significantly by having larger rotors and higher hub heights. This is because, all other things being equal, the energy yield of a turbine is roughly proportional to the swept area of the rotors. Similarly, all other things being equal, the energy yield is roughly proportional to the square root of the hub height due to higher wind speeds at greater heights (although surrounding terrain can affect this).

However, the increase in the size of turbines and blades also increases their weight, increasing the cost of towers and the foundations. Historically the increase in the weight of turbines has been limited by the utilisation of lighter materials and the optimisation of design, although it is not clear if this trend can continue. As a result, there appears to be relatively small economies of scale from larger turbines, their main benefit being the increased energy yield and scale given to wind farms.

Recent trends in wind turbine prices suggest that wind turbine prices have peaked. It is difficult to predict the evolution of wind turbine prices, but increasing competition among manufacturers and the emergence of large-scale wind turbine manufacturing bases in China and other emerging economies is likely to put continued downward pressure on wind turbine prices in the short- to medium-term. The current global manufacturing surplus in all major components of wind turbines also suggests that there are no major supply chain bottlenecks that could disrupt this trend in the next few years (MAKE Consulting, 2011a).

The largest cost reductions will therefore come from learning effects in wind turbine manufacturing, with smaller, but important contributions from the remaining areas. By 2020, wind turbine costs may decline by 15% compared to 2011 levels (Mott Macdonald, 2011) and perhaps by more than this if oversupply pushes down manufacturers' margins, or emerging market manufacturers gain larger shares of the European and North American markets.

The key cost reduction areas for wind turbines (Douglas-Westwood, 2010) are:

- **Towers:** These are an important part of the wind turbine cost (up to one-quarter), but are a relatively mature component. Most are rolled steel, with costs being driven by steel prices. However, increased competition, the integration of lightweight materials and the more distributed location of manufacturers that will be possible as markets expand means tower costs may come down, perhaps by 15% to 20% by 2030.

- **Blades:** Wind turbine rotor blades can account for one-fifth of turbine costs. The key driver behind blade design evolution is weight minimisation as this reduces loads and helps improve efficiency. Using more carbon fibre in blades, as well as improving the design of blades (with production efficiency and aerodynamic efficiency in mind) can help reduce weight and costs, although the high cost of carbon fibre is a problem. Cost reductions of 10% to 20% could be possible by 2020.

- **Gearboxes:** Typically represent 13% to 15% of wind turbine costs The R&D focus for gearboxes is to improve reliability and reduce costs. Vertical integration of gearbox manufacturing by wind turbine suppliers should help reduce costs. Cost reductions may also stem from the increasing share of gearless drive generators using permanent magnet synchronous motors. Overall, cost reductions could reach 15% by 2020.

- **Other components:**[22] The most significant remaining components are

[22] *See Figure 4.4.*

the generator, control systems (including pitch and yaw systems), transformer and power converter. These components, as well as the other miscellaneous components of the turbine, all have opportunities for cost reductions through increased manufacturing efficiency and R&D efforts. These components could see cost reductions of 10% to 15% by 2020.

The cost reduction potentials in percentage terms are likely to be similar for onshore and offshore wind turbines, as the technology improves and designs become further standardised. Significant savings are expected to be realised through the mass production of wind turbines, the vertical integration of turbine manufacturers as they bring more components "in-house" and learning effects. The absolute reduction in costs for offshore wind turbines will be somewhat higher than for onshore turbines (on a per kW basis) given their higher overall cost.

One area where offshore wind farms will have a cost advantage is through scale. Offshore wind projects have the possibility to be very large compared to onshore wind farms and this will allow very competitive prices for large wind turbine orders.

Cost reductions for grid connections

The cost of grid connection is not likely to decline significantly for onshore wind farms. However, offshore developments can expect to see cost reductions as the scale of wind farms developed increases and as the industry capacity increases. The cost of long distance grid connections for wind farms far from shore could be reduced by using HVDC (high-voltage direct current) connections. Costs are coming down for these connections and lower losses could make them more economical overall, even taking into account the cost of converting the DC to AC onshore. The costs for the internal grid connection are estimated to be constant and only contribute a minor share of the investment costs associated with an offshore wind farm.

Cost reductions for foundations

The foundations can account for 7-10% of onshore wind farm costs and 15% to 20% (EWEA, 2009) or more for offshore wind farms. The largest cost components of foundations are cement and steel. Actual foundation costs will therefore be strongly influenced by these commodity prices. However, some cost reductions are still possible as costs will increase somewhat less proportionately than the increase in swept rotor area, so larger turbines will help reduce specific installation costs somewhat (EWEA, 2009). Other cost reductions can come from economies of scale, reduced material consumption (through more efficient designs) and reduced materials cost (materials substitution). It has been estimated that if steel costs decline by 1-2%/year and can result in a 5-10% reduction in overall foundation costs (Junginger, 2004).

The potential for reducing the cost of offshore wind turbine foundations is higher than for onshore. Offshore foundations are typically at least 2.5 times more expensive than onshore ones (EWEA, 2009). The trend to larger wind turbines, improved designs, reduced installation times and larger production lines for foundations will help reduce costs.

However, for shallow, fixed foundations (predominantly monopiles), cost reductions will be modest. For deeper offshore foundations the dynamics are more complicated. Fixed seabed foundations in greater than 20 m of water become increasingly expensive as deeper piles are required and wave and current forces can be greater. Significant cost reductions are therefore not obvious. It is likely that fixed seabed foundations will be uneconomic beyond a depth of around 40 m and floating foundations will be required.

Floating foundations are more expensive than shallow monopole foundations, but cost reduction potentials are significantly larger, as a range of innovative designs are being explored. Today's floating foundations are predominantly demonstrator projects. As experience is gained and R&D advances, designers will be able to identify foundation types with the greatest potential. The costs of floating foundations could decline by 50% by 2030 (Douglas-Westwood, 2010), although they are still likely to be a third more expensive than shallow water monopole foundations.

Other cost reductions

The remaining project costs for onshore wind farms are typically in the range of 8% to 18%, with 10% typical for wind farm based on 2 MW wind turbines (EWEA, 2009). Offshore, this proportion is higher and likely to be in the range of 25% to 35%. Modest cost reductions can be expected for the remaining electrical installation, controls, civil works, consultancy and projects costs onshore, but the potentials offshore are larger as the industry learns from experience. Costs could be reduced by between 20% and 30% by 2030 (Douglas-Westwood, 2010).

Installation and commissioning costs, particularly for offshore wind farms, could be reduced, despite the increasing size and weight of turbines making this process more difficult. Specialised installation vessels will provide reduced installation times.

However, the largest cost reduction possibility is the so-called "all in one" installation, where the wind turbine is fully assembled onshore, transported to the already installed foundation and installed in one piece. This technique is just beginning to be evaluated, with two projects to date having used this method: the Beatrice Demonstrator in Scotland and the Shanghai Bridge project in China. Turbine installation costs offshore could be reduced by as much as 30% by 2030 (Douglas-Westwood, 2010).

Speeding up the installation process and electrical installations should help reduce commissioning time significantly, reducing working capital requirements and bringing forward the date when first revenue from electricity sales occurs.

Cost reductions due to increased efficiency

The capacity factor for a wind farm is determined by the average wind speed at the location and the hub height. The energy that can be harvested is also a function of the swept rotor area. Thus, tall turbines with larger rotor areas in high average mean wind speed areas will have the highest capacity factors and energy yields. One of the main advantages of offshore wind power is its ability to obtain increased capacity factors compared to equivalent capacity onshore installations. This is due in part to opportunities to place the wind farms in high average wind speed environments, but also because objections to very tall wind turbines are sometimes less of an issue.

Considerable information on wind resource mapping across Europe and the USA has been accumulated and it is extending to other areas of the world, where the development of wind power has the potential to contribute to the energy mix. Increased access to wind mapping information will have a significant impact on maximising yield and minimising generation cost by reducing the information barrier to identifying the best sights for wind farm development.

Continuing improvements in the ability to model turbulence with computational fluid dynamics (CFD) can help improve designs and increase the responsiveness of machines in turbulent conditions. At the same time, the use of a radar on top of the nacelle to "read" the wind 200 to 400 metres in front of the turbine can allow appropriate yaw and pitch adjustments in anticipation of shifts or changes in the wind. It is thought that these improvements will both increase efficiency and reduce wear and tear on the machine by reducing the frequency and amplitude of shear loads on the rotor.

Cost reductions in offshore wind power: A summary

Currently, the capital cost of offshore wind is around two times higher than onshore wind. If offshore wind is to become truly competitive, capital and O&M costs need to be reduced. The outlook for cost reductions is good and when combined with the ability to achieve higher capacity factors than onshore, it means that the LCOE of offshore wind could come down significantly in the long term.

The main drivers for cost reductions will be continued design improvements, the upscaling of wind turbines, the continuing growth of offshore wind capacity (learning effects) and the development and high utilization rates of purpose-built installation vessels. Other factors that will help reduce costs are stable commodity prices, technological development of HVDC converter stations and cables, standardisation of turbine and foundation design, and economies of scale for wind turbine production. An overview of key factors influencing cost reductions for offshore wind farms is presented in Table 5.2.

It is expected that offshore wind power installations will move further offshore in order to maximise electricity generating capability through the utilisation of stronger and more consistent winds. In some cases, this shift is in order to site the wind farm closer to main consumption centres (e.g. London Array), and to provide reduced impact from visual obstruction and noise-related issues.

Shifting to further offshore and deeper water environments with more extreme offshore weather conditions that are unfamiliar and unpredictable can result in significantly higher costs for all components

Table 5.2: Summary of cost reduction opportunities for offshore wind

	Specific offshore wind developments	Exogenous development
Wind turbine	Upscaling Improved design Standardisation Economies of scale	Further development of onshore turbines Steel price
Grid Connection	Standardising the design of HVDC cables Applicability of XLPE insulation to HVDC cables Advances in valve technology and power electronics	Further development and diffusion of submarine HVDC interconnectors
Foundation	Standardisation Economies of scale	Steel price
Installation	Learning-by-doing Development and structural purpose-built ships Optimisation of ship use Standardisation of turbines and equipment	Oil price

Source: Junginger, 2004.

Table 5.3: Different estimates of the potential for cost reductions in the installed cost of onshore wind, 2011 to 2050

	2015	2020	2025	2030	2035	2040	2045	2050
				(%)				
IEA				-18				-23
EWEA	-11	-22	-28	-29				
GWEC	-5 to -6	-9 to -12		-16 to -18				
Mott MacDonald		-12				-23		
US DOE				-10				

Sources: DOE, 2008; GWEC and Greenpeace, 2010; EWEA, 2011c; IEA, 2009 and Mott MacDonald, 2011 of offshore wind power due to the associated risk; high prices will continue until adequate experience is gained.

5.2 OVERALL COST REDUCTION POTENTIALS

There are currently no major supply bottlenecks in the wind turbine industry, at least globally, as the result of the rapid expansion of manufacturing capacity in all critical areas. It is projected that wind turbine prices will decline in the coming years as a result, but to what extent is difficult to gauge and depends on the impact of turbine manufacturers based in emerging economies on OECD markets.

It is thus possible, perhaps even likely, that wind turbine costs will revert to a trend similar to the one evident between the 1980s and 2004. The IEA and GWEC assume that the learning rate will be slightly lower than this historical average at 7% (IEA, 2009 and GWEC, 2011). Table 5.3 presents projections of the cost reductions for total installed wind farm costs between now and 2050 from a variety of sources. Projected cost reductions vary depending on the base year of the analysis, with recent studies using base years of 2009, 2010 or 2011 but also due to different assumptions about engineering costs, learning rates, and global deployment of wind in the future. Cost reductions to 2015 are in the range of 5% to 11%, while by 2020 the estimated cost reduction range widens to 9% to 22%.

Estimates of the cost reduction potential for offshore wind are quite uncertain given the fact that the offshore wind industry is just at the beginning of its development. Recent analysis has identified cost reduction potentials of 11% to 30% by 2030, depending on how rapidly the industry expands (Douglas-Westwood, 2010). The key to reducing costs will be through learning effects, more R&D, wind turbine capacity increases, expansion of the supply chain, greater dedicated installation capacity (to reduce reliance on offshore oil and gas industry) and more competition.

However, cost reduction potentials could be higher, as supply chain constraints and lack of competition have been estimated to have inflated installed costs by around 15% (Mott MacDonald, 2011). In this scenario, learning effects, moving to larger wind farms with larger turbines, increased supply chain development, and greater competition – as well as potential breakthroughs from novel wind turbine designs and foundations – could see costs fall by 28% by 2020 and by 43% by 2040. However, these reductions remain highly uncertain and variations of plus or minus 20% in 2040 are possible. Taking into account the increased capacity factors achieved by offshore wind turbines as they get continually larger means that capital costs (undiscounted) per MWh generated could drop by 55% by 2040 (Mott MacDonald, 2011).

6. Levelised cost of electricity from wind power

The levelised cost of energy (LCOE) is the primary metric for describing and comparing the underlying economics of power projects. For wind power, the LCOE represents the sum of all costs of a fully operational wind power system over the lifetime of the project with financial flows discounted to a common year. The principal components of the LCOE of wind power systems include capital costs, operation and maintenance costs and the expected annual energy production (Figure 6.1). Assessing the cost of a wind power system requires a careful evaluation of all of these components over the life of the project.

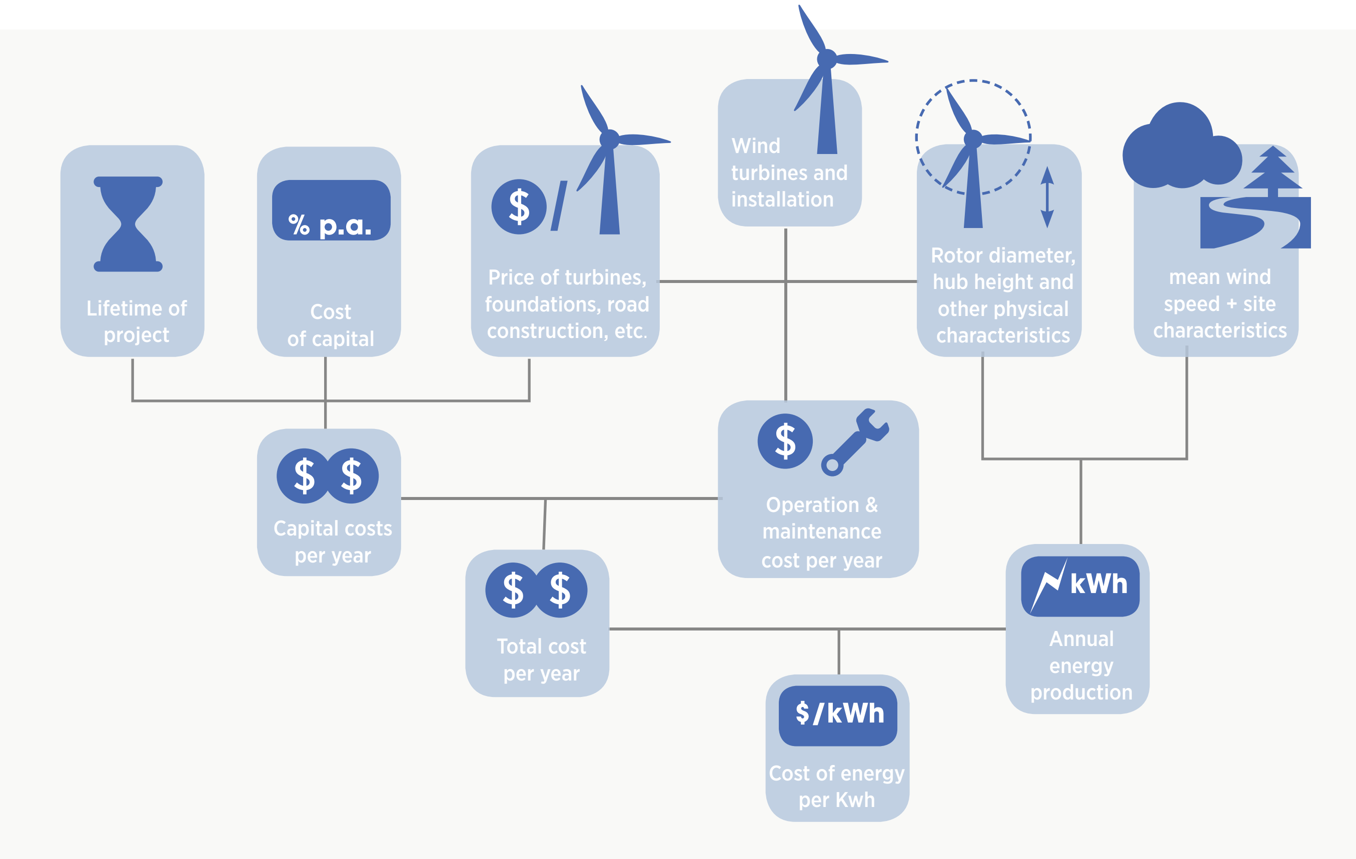


Figure 6.1: The economics of wind systems

Source: Based on EWEA, 2009.

6.1 COST STRUCTURE OF LARGE-SCALE WIND FARMS

The key parameters that define the LCOE for wind power systems are the capital costs, wind resource quality, technical characteristics of the wind turbines and the discount rate. Other costs are the variable costs, including operations and maintenance costs. Of these parameters, the capital cost is the most significant, with the wind turbines themselves accounting for 64% to 84% (EWEA, 2009) of the total investment costs for onshore wind farms in Europe. A breakdown of the capital cost structure for onshore and offshore wind power systems are shown in Figure 6.1.

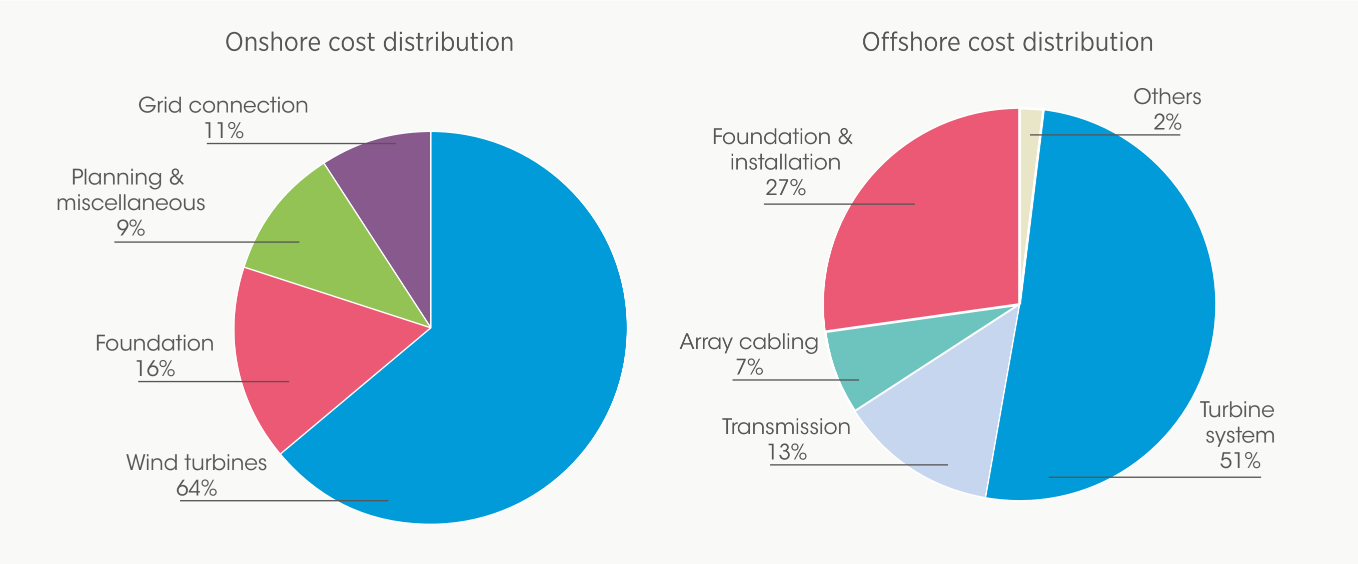


FIGURE 6.2: CAPITAL COST BREAKDOWNS FOR TYPICAL ONSHORE AND OFFSHORE WIND SYSTEMS

Source: Blanco, 2009.

6.1.1 The capital costs of onshore and offshore wind farms

The overall capital cost for onshore wind farms depends heavily on wind turbine prices. They account for between 64% and 85% of the total capital costs and most, if not almost all, variations in total project costs over the last ten years can be explained by variations in the cost of wind turbines. Grid connection costs, foundations, electrical equipment, project finance costs, road construction, etc. make up most of the balance of capital costs.

Based on the data and analysis presented earlier (Chapter Four) wind turbine costs ranged from less than USD 700/kW in China up to around USD 1 500/kW in developed countries in 2011. The total installed capital costs, including all other cost factors, are as little as USD 1 300/kW in China and in the range USD 1 850 to USD 2 200 in the major developed country markets of the United States, Germany and Spain. Table 6.1 presents the assumptions for onshore wind capital costs for typical projects in Europe, North America and China/India for 2011, as well as the assumed values for 2015.

Offshore wind costs remain high at around USD 4 000/kW or more, but installed capacity is still very low, and offshore wind offers the opportunity to have higher load factors than onshore wind farms, increasing the electricity yield. However, O&M costs will remain higher than onshore wind farms due to the harsh marine environment and the costs of access. It is assumed that costs will decline by 8% between 2011 and 2015 to around USD 3 700/kW on average, with costs in the range USD 3 500 to USD 3900/kW.

TABLE 6.1: TOTAL INSTALLED COSTS FOR ONSHORE WIND FARMS IN CHINA/INDIA, EUROPE AND NORTH AMERICA, 2010, 2011 AND 2015

	2010	2011 (2010 USD/kW)	2015
China/India	1 100 to 1 400	1 050 to 1 350	950 to 1 250
Europe*	1 850 to 2 100	1 800 to 2 050	1 700 to 1 950
North America	2 000 to 2 200	1 950 to 2 150	1 800 to 2 050

*Note: * These are typical values for the larger European wind markets in 2010 (Germany, Spain, Sweden and the United Kingdom).*

6.1.2 O&M costs for onshore and offshore wind farms

The overall contribution of O&M costs to the LCOE of wind energy is significant. Data for seven countries show that O&M costs accounted for between 11% and 30% of the total LCOE of onshore wind power. The lowest contribution was in the United States and the highest in the Netherlands (Figure 6.3).

Best practice O&M costs are in the order of USD 0.01/kWh in the United States. Europe appears to have a higher cost structure, with best practice of around USD 0.013 to USD 0.015/kWh. However, average O&M costs in Europe are higher at around USD 0.02/kWh. No changes in O&M costs are assumed in North America between now and 2015, while O&M costs in Europe begin to converge on the European best practice level.

Robust data for the O&M costs for offshore wind farms has yet to emerge. However, current wind farms have costs of USD 0.025 to USD 0.05/kWh in Europe (ECN, 2011). There are opportunities for cost reductions, particularly through increases in wind farm scale, but it remains to be seen to what extent costs can be reduced. O&M costs are assumed to decline by 5% by 2015.

6.2. RECENT ESTIMATES OF THE LCOE OF ONSHORE AND OFFSHORE WIND

The LCOE of onshore wind has fallen strongly since the first commercial wind farms were developed. In the United States, the cost of electricity generated from wind fell from about USD 0.30/kWh in 1984 to a low of around USD 0.055/kWh in the United States in 2005 (Wiser and Bolinger, 2011). A similar trend occurred in Europe, where the LCOE of wind declined by 40% between 1987 and 2006 for wind farms on good coastal sites.

However, the supply chain constraints and demand growth that led to wind turbine cost increases from

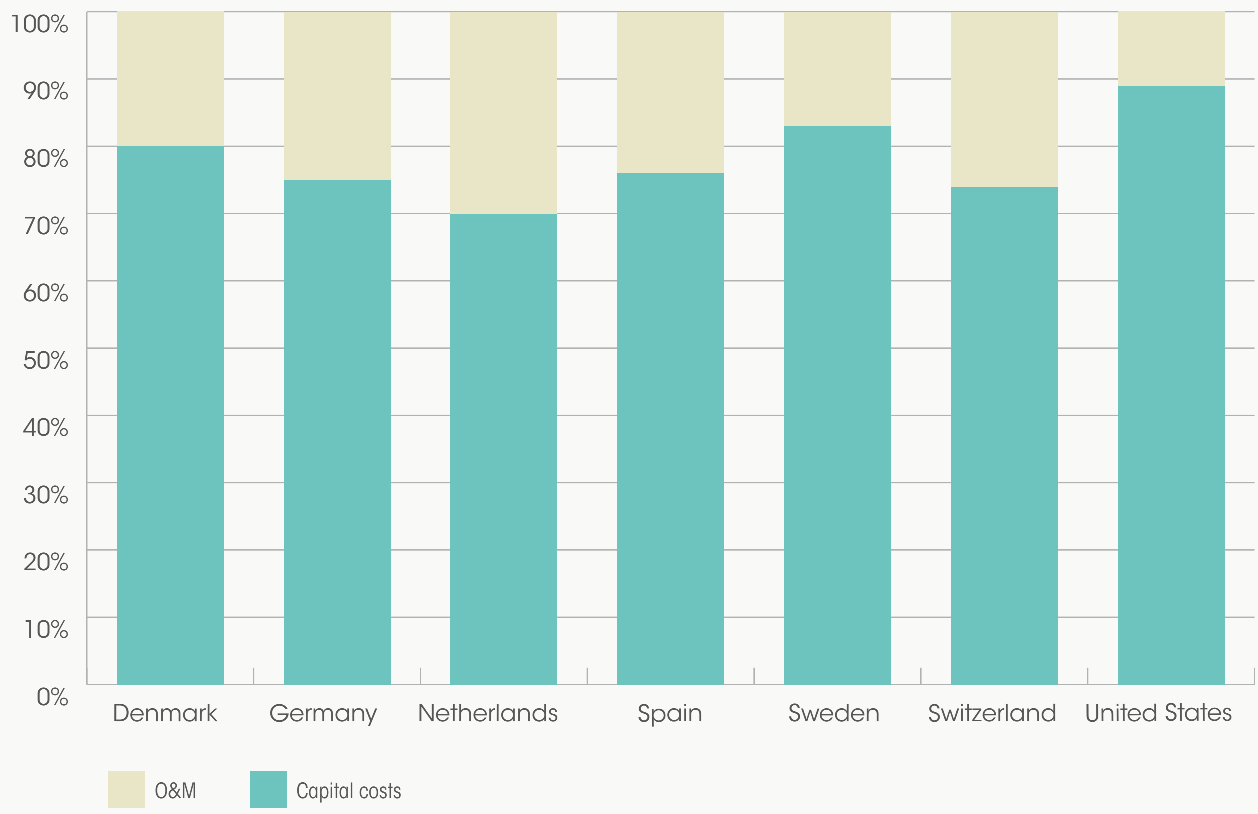


Figure 6.3: Share of O&M in the total LCOE of wind power in seven countries

Source: IEA Wind, 2011b.

2006 also resulted in a slight growth in the LCOE of onshore wind between 2005 and 2010, despite improving capacity factors (see Figure 6.4).

In the United States, this trend was particularly pronounced, with the capacity-weighted LCOE of wind power projects more than doubling from 2004/2005 to 2010.

Although there is considerable variation in the LCOE of projects installed in the United States, the general trend has been one of increasing costs. The capacity-weighted average prices reached an all-time low in 2002/2003, before rising to USD 0.073/kWh in 2010. This is up from an average of USD 0.062/kWh for projects built in 2009, and is more than twice the average of USD 0.032/kWh in 2002/2003 prices (Wiser and Bolinger, 2011).

According to the other sources in 2010, price of the utility scale wind farms worldwide ranged from USD 0.05 to USD 0.085/kWh, excluding the local and state taxes and depending on site-specific factors, such as the strength of the wind resource, turbine size and development and installation costs.

Other sources recently noted that the LCOE generated from wind is now below USD 0.068/kWh (€0.050/kWh) for most of the projects in high resource areas (United States , Brazil, Sweden, Mexico) (Cleantechnica, 2011). This compares to current estimated average costs of USD 0.067/kWh for coal-fired power and USD 0.056/kWh for gas-fired power.

Recent data for wind auctions in Brazil tend to suggest that these values are not unrealistic. There has been a steady decline in the price demanded in the wind auctions since 2009 (Figure 6.5). The 2009 auction saw prices of between USD 0.09 and USD 0.10/kWh, but by 2011 the price range was between USD 0.065 and US 0.070/kWh. However, although the trend in this data for Brazil is robust, the absolute values of the data have to be treated with caution.[23]

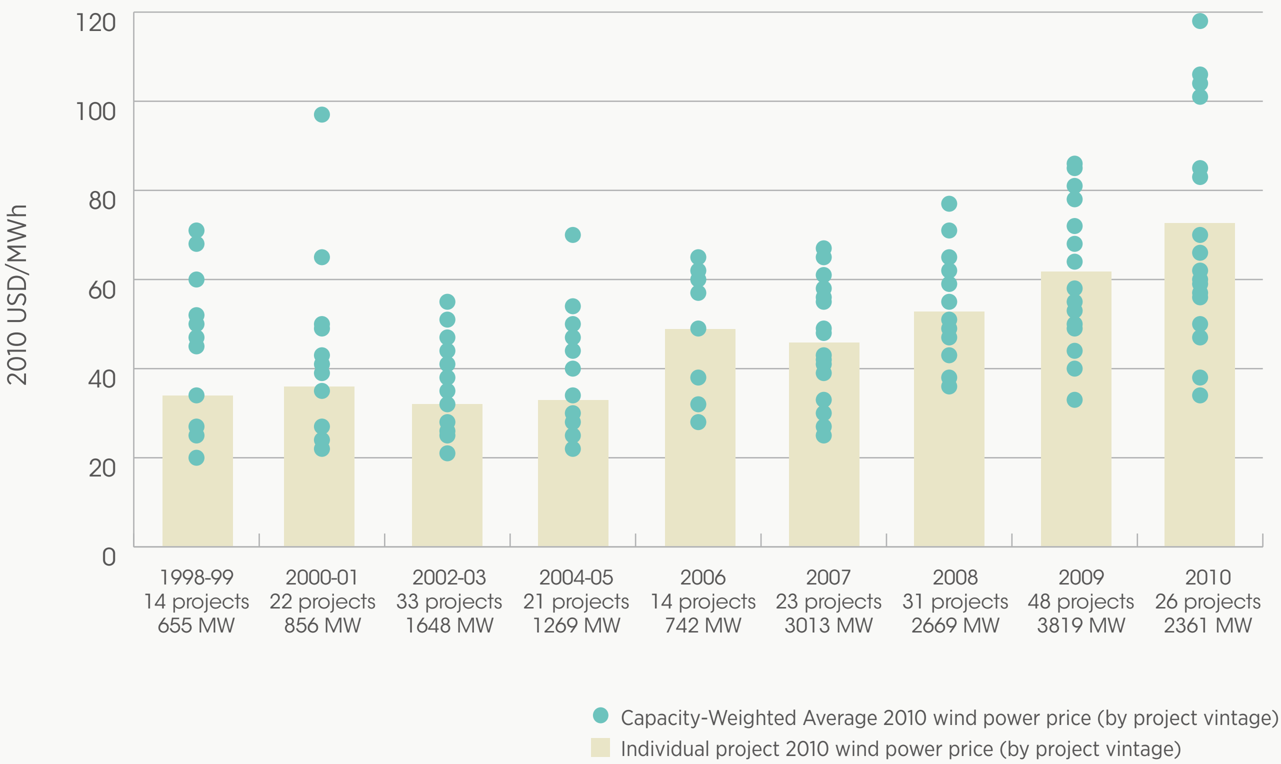


Figure 6.4: Wind Power Prices in the United States by start year, 1998/1999 to 2010

Source: Wiser and Bolinger, 2011.

[23] *Question marks also remain about whether some project developers can actually meet the auction prices.*

Our analysis based on the data and analysis presented earlier show that wind turbine and the total installed capital costs are decreasing again. Reductions in average O&M costs for onshore wind are also possible, with wind turbine manufacturers increasingly competing on warranties and O&M agreements. Recent analyses estimate the LCOE from onshore wind power projects to be USD 0.06 to USD 0.11/kWh (Lazard 2009). However, the exact value depends on project specifics (e.g. the wind turbines' capacity factor) and different sources often use different boundaries (i.e. some studies include tax incentives, others don't).

The LCOE of offshore wind power differs significantly compared to onshore wind power. While the cost of electricity generated from a typical onshore wind power shows a gradual reduction, having falling by 15% since Q2 2009, that of offshore wind has increased (see Figure 6.6) (BNEF, 2011b). This divergence is due to the higher capital costs of offshore wind developments in recent years.

As can be seen from Figure 6.6, the trend in offshore wind LCOE differ significantly from onshore wind, and are increasing gradually rather than decreasing. The main reason for this is the increasing distance from shore. As offshore wind farms are going to be located far from shore, costs increase in all aspects of the supply chain. Turbine prices are increasing due to design improvements to achieve high reliability in the harsh sea environment and larger, more sophisticated wind turbines in order to increase capacity factors. The construction and cabling costs are also increasing as a function of sea depth and distance from shore.

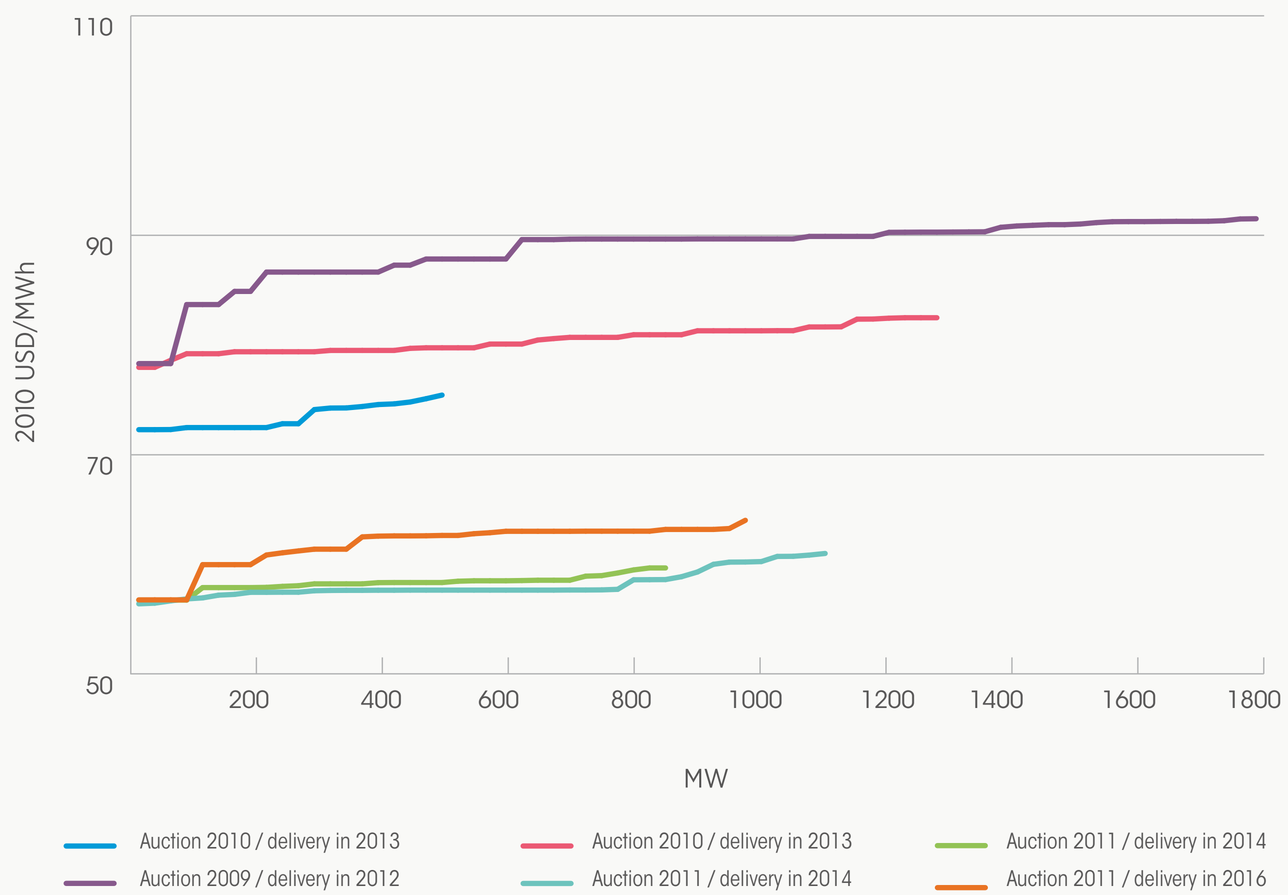


Figure 6.5: Wind auction prices in Brazil, 2009 to 2011

Source: CCEE, 2012.

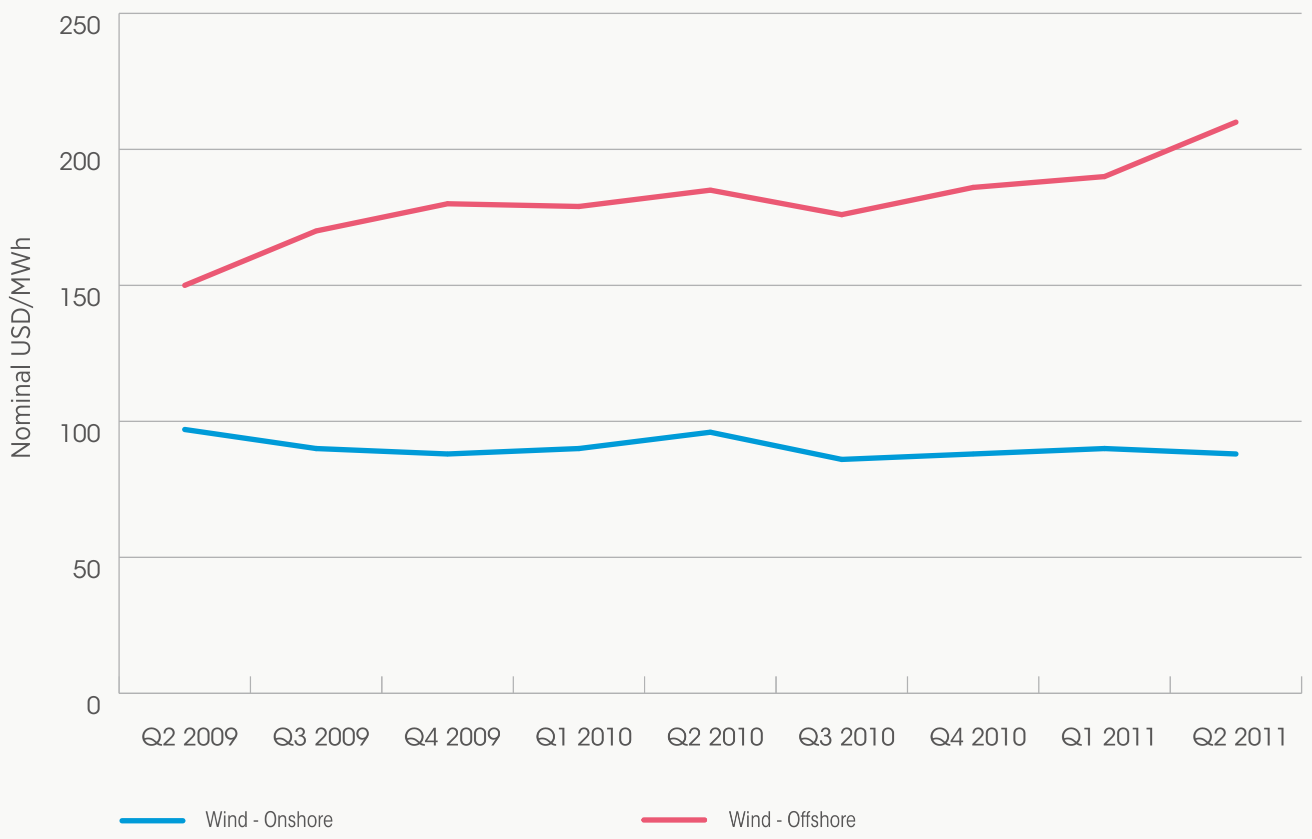


Figure 6.6: Wind power LCOE trends for period from Q2 2009 to Q2 2011 .

Source: BNEF, 2011b.

6.3. LCOE ESTIMATES FOR 2011 TO 2015

The estimated cost of wind power varies significantly, depending on the capacity factor, which in turn depends on the quality of the wind resource and the technical characteristics of the wind turbines. Capacity factors can vary significantly onshore and offshore, with higher capacity factors achievable in general offshore, particularly in Europe.

Onshore wind

The LCOE for onshore wind is presented in Figures 6.7 and 6.8 for Europe and North America. High and low assumptions for the capital costs are taken from Table 6.1 and are based on the data presented earlier. The LCOE of onshore wind for Europe and North America does not vary significantly as slightly lower capital costs for typical European projects are offset by lower O&M costs in the United States in particular. In contrast, the very low capital costs of projects in China and India mean that, for a given capacity factor, the LCOE of wind is 31% to 45% lower than in North America and 36% to 46% lower than in Europe.

The estimated LCOE of wind for Europe in 2011 was between USD 0.10 and USD 0.13/kWh. This is based on the assumption that the typical load factor in Europe for new projects in 2011 was in the range of 25% to 30% for onshore projects (IEA Wind, 2011).[24] The cost reductions assumed by 2015 reduce the LCOE of wind by between 6% and 7% for a given capacity factor.

[24] *Analysis by the IEA Wind Implementing Agreement is based on typical projects in 2008. However, this is likely to be representative of projects in 2011.*

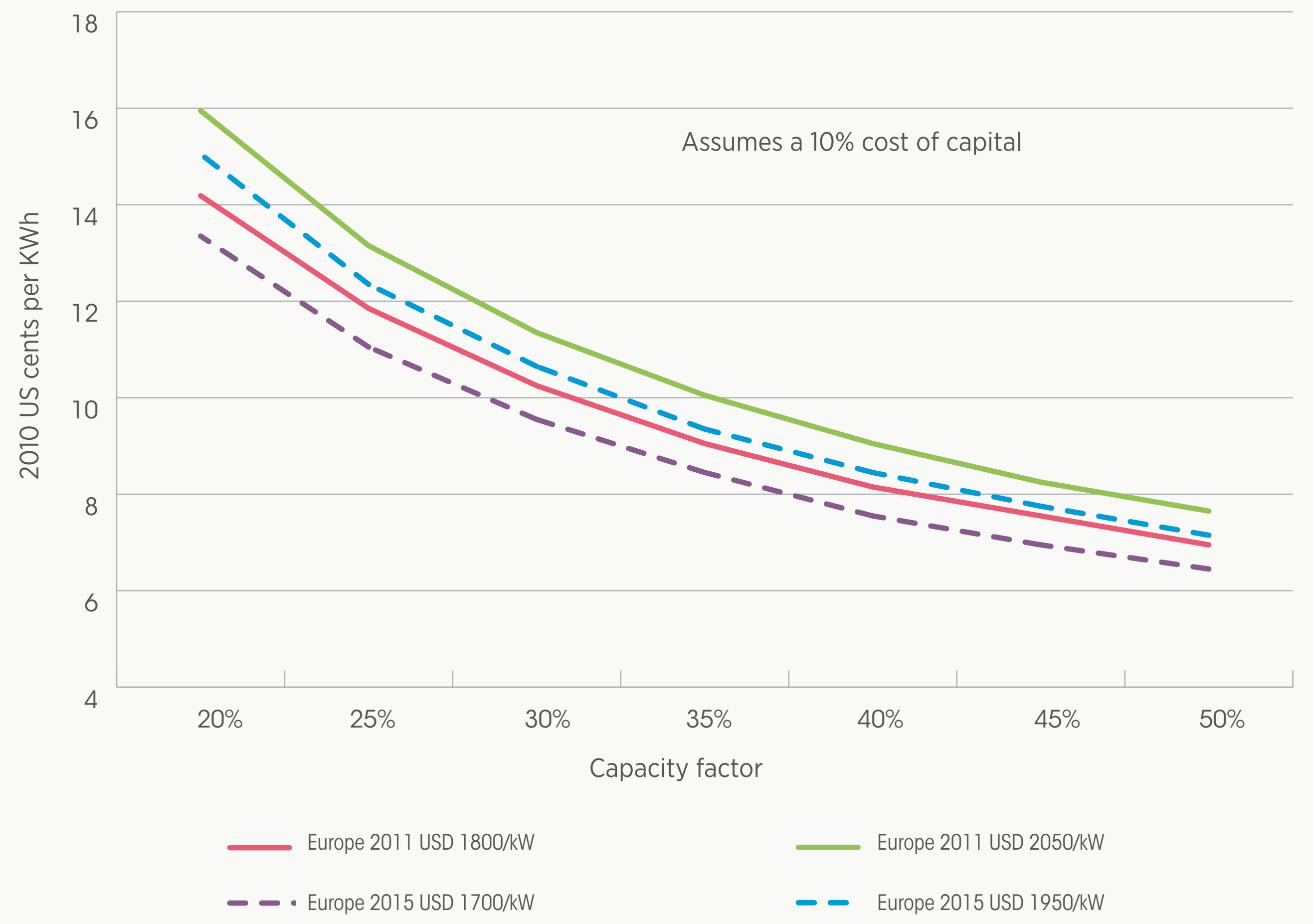


Figure 6.7: The LCOE of wind for typical European onshore wind farms, 2011 to 2015

Note: Assumes a 10% discount rate, a 20 year lifetime, a 0.1% decline in production per year (wear and tear) and O&M costs of USD 0.02/kWh that increase 1% per year for first ten years and then at 2% per year. For 2015, the assumed O&M costs are USD 0.0175/kWh.

The estimated LCOE of wind in North America in 2011, assuming a capacity factor of 30%, was between USD 0.10 and USD 0.11/kWh. However, the range of capacity factors reported for 2010 projects in the United States varied widely, from as little as 20% to a high of 46% (Wiser and Bolinger, 2011). Using this range implies the LCOE for wind in North America ranged from as low as USD 0.07/kWh to a high of as much as USD 0.16/kWh. By 2015, cost reductions could reduce the LCOE of wind in North America by 5% to 9% for a given capacity factor. Given that a range of factors in the United States resulted in lower capacity factors than might otherwise have been expected (Wiser and Bolinger, 2011), the weighted average capacity factor could increase from 30% to 35% in 2015. This would reduce the LCOE of wind in North America to between USD 0.08 to USD 0.09/kWh in 2015, or by between 18% and 20% compared to the average value for 2011.

In China and India installed costs for onshore wind farms as low as one half that of the level seen in developing countries in 2010 and 2011. The LCOE of wind is therefore significantly lower than in Europe or North America for a given capacity factor. In India in 2010, the average capacity factor for data from four states with around four-fifths of total capacity in India was 20%, but there has been a trend towards higher capacity factors over time. This trend is expected to continue in the future (GWEC/WISE/IWTMA, 2011). Assuming a capacity factor of 25% for new projects, the LCOE of wind in China and India in 2011 was between USD 0.07 and USD 0.08/kWh (Figure 6.9). This is 34% to 43% lower than the LCOE of wind in Europe and North America for the same capacity factor. However, given the higher average capacity factors of new projects in Europe (in general) and in North America, the actual difference in LCOE will be lower than this.

Figure 6.8: The LCOE of wind for typical North American onshore wind farms, 2011 to 2015

Note: Assumes a 10% discount rate, a 20 year lifetime, a 0.1% decline in production per year (wear and tear) and O&M costs of USD 0.01/kWh that increase 1% per year for first ten years and then at 2% per year. For 2015, the assumed O&M costs are USD 0.0085/kWh.

China and India already have very competitive installed costs for wind projects compared to the norm in developed countries. The opportunities for cost reductions, although still possible, are smaller than in developed countries. There is even the potential for average installed costs to rise somewhat by 2015 if manufacturing costs in emerging economies start to raise the cost of wind turbines and engineering projects in general, or if the supply situation becomes tighter.

Sensitivity to the discount rate used: Onshore wind

The analysis in this section assumes that the average cost of capital for a project is 10%. However, the cost of debt and the required return on equity, as well as the ratio of debt-to-equity varies between individual projects and countries. This can have a significant impact on the average cost of capital and the LCOE of a wind power project.

In the United States, the quarterly average required return on equity for wind projects between the fourth quarter of 2009 and the fourth quarter of 2010, inclusive, ranged from a low of 8% to a high of 14.5%. While over the same period, the quarterly average cost of debt for wind projects ranged from a low of 4.9% to a high of 11%.[25] Making the simple assumption that the debt-to-equity ratio is between 50% and 80% and that debt maturity matches project length results in project discount rates of between 5.5% and 12.6%.[26]

Table 6.2 presents the impact of varying the discount rate between 5.5% and 14.5% for wind power projects in the United States at different capacity factors. The near halving of the discount rate to 5.5% reduces the LCOE of the wind generated by between 9% and 16% depending on the capacity factor. In contrast, increasing the

[25] *This data comes from the Renewable Energy Financing Tracking Initiative database and was accessed in November 2011. See https://financere.nrel.gov/finance/REFTI*

[26] *These assumptions aren't representative of how projects are structured, but in the absence of comprehensive data are used for illustrative purposes.*

discount rate to 12.6% increases the LCOE of the wind generated by between 26% and 30%, depending on the capacity factor. This asymmetry is due to the impact of O&M costs and highlights the importance of working to reduce these over time.

Offshore wind

The LCOE ranges for offshore wind are presented in Figure 6.10. The LCOE of offshore wind is around twice that of onshore wind for a given capacity factor in Europe and North America. However, a better comparison is one assuming a 10% higher capacity factor for offshore wind. In this case the LCOE of offshore wind is 43% to 91% more expensive than onshore wind. Assuming a 15% higher capacity factor for wind results in the LCOE of offshore wind being 26% to 75% more expensive.

The LCOE of offshore wind, assuming a 45% capacity factor and USD 0.035/kWh O&M cost, is between USD 0.15 and USD 0.165/kWh. This range drops to USD 0.139 to USD 0.152/kWh when the capacity factor is 50%. The high O&M costs of offshore wind farms add significantly to the LCOE of offshore wind farms and cost reductions in this area will be critical to improving their long-term economics.

The total installed cost of offshore wind farms is assumed to decline by 8% by 2015 and O&M costs from an average of USD 0.035/kWh to USD 0.03/kWh. These cost reductions translate into the LCOE from offshore wind being between 8% and 10% lower in 2015 than in 2011. The LCOE from offshore wind is likely to remain higher than onshore wind, even taking into account the higher capacity factors, for the foreseeable future and will probably always be more expensive given the challenges involved in reducing capital costs and O&M costs. However, with the increased competition for good onshore wind sites close to demand centres in Europe and North America growing, offshore wind has a vital role to play in continuing the expansion of wind power capacity, particularly in Europe.

Table 6.2: LCOE of wind at different capacity factors and discount rates

	Capacity factor				
	25%	30%	35%	40%	45%
	LCOE (2010 US cents per kWh)				
5.5% discount rate	9.65	8.45	7.55	6.85	6.35
10% discount rate	11.55	9.85	8.55	7.65	6.95
12.6% discount rate	14.55	12.45	10.95	9.85	9.05
14.5% discount rate	16.05	13.65	12.05	10.75	9.85

Note: Assumes and installed capital cost of USD 1 950/kW and O&M costs of USD 0.02/kWh that increase 1% per year for first ten years and then at 2% per year.

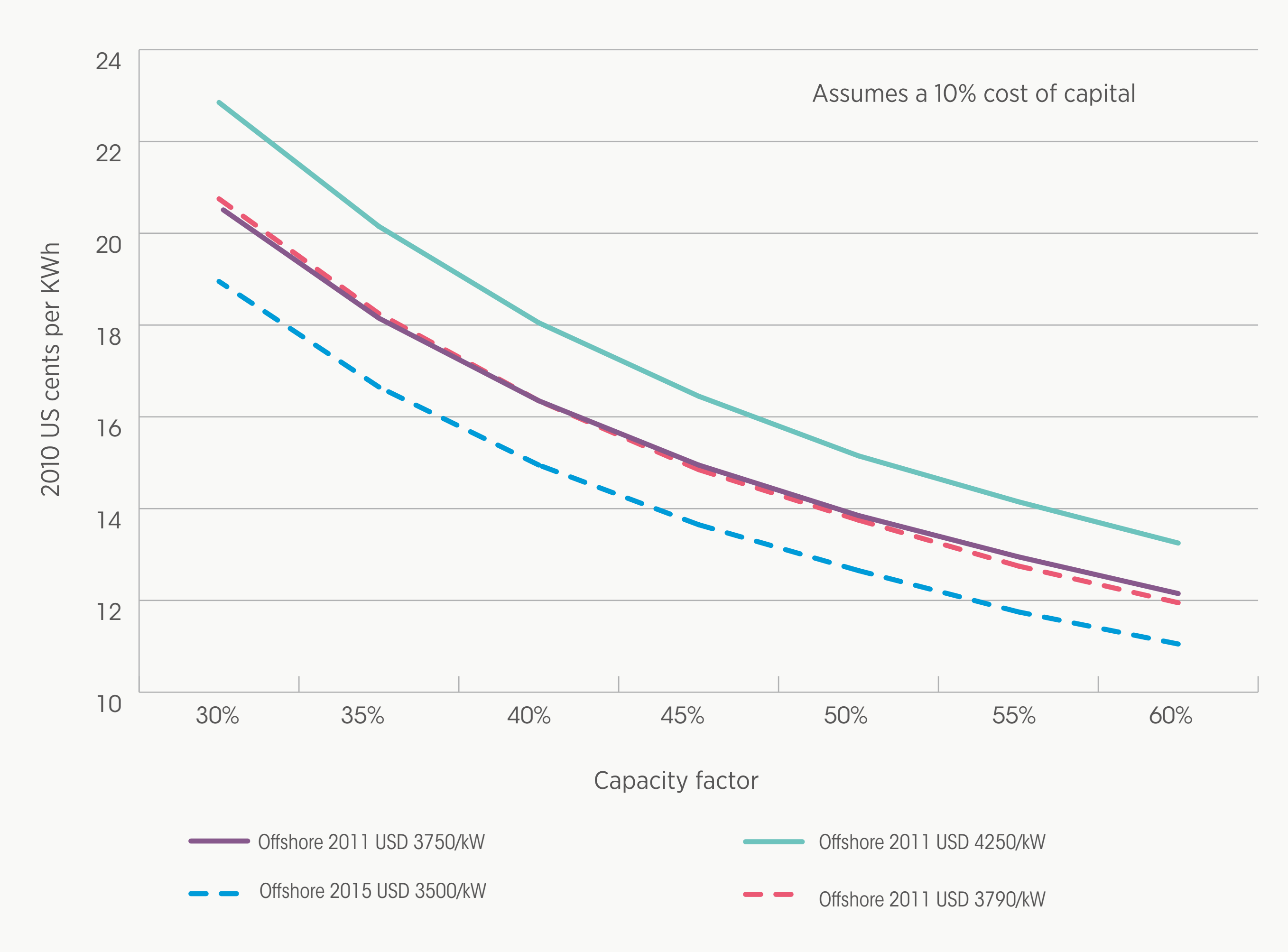


Figure 6.9: The LCOE of wind for typical offshore wind farms, 2011 to 2015

Note: Assumes a 10% discount rate, a 20 year lifetime, a 0.1% decline in production per year (wear and tear) and O&M costs of USD 0.035/kWh that increase 1% per year for first ten years and then at 2% per year. For 2015, the assumed O&M costs are USD 0.03/kWh.

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Acronyms

CAPEX	Capital expenditure
CIF	Cost, insurance and freight
DCF	Discounted cash flow
FOB	Free-on-board
GHG	Greenhouse gas
GW	Gigawatt
kW	Kilowatt
kWh	kilowatt hour
m/s	metres per second
MW	Megawatt
MWh	Megawatt hour
LCOE	Levelised cost of energy
O&M	Operating and maintenance
OPEX	Operation and maintenance expenditure
R&D	Research and Development
USD	United States dollar
WACC	Weighted average cost of capital

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