# 4 WIND POWER

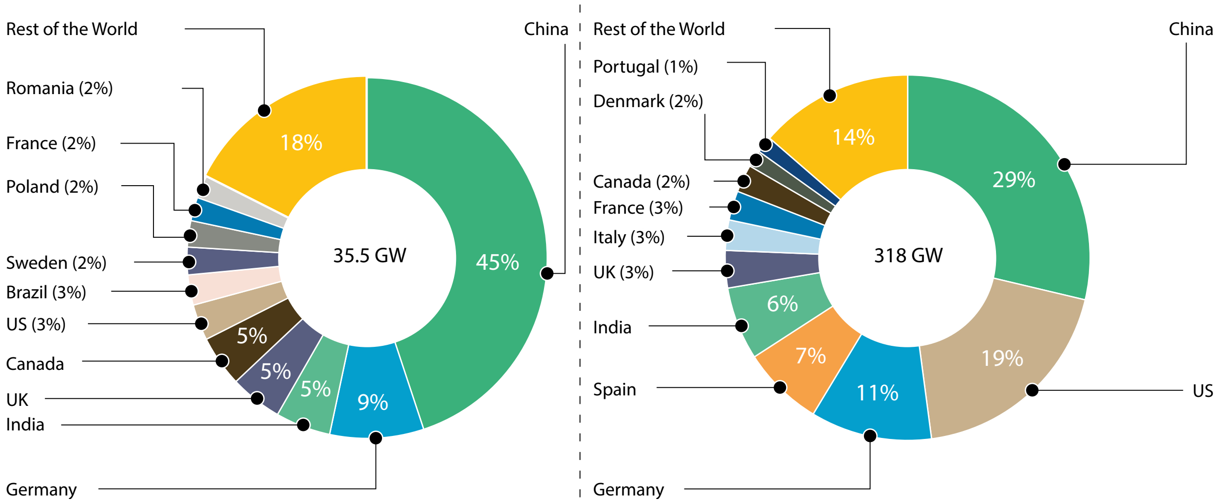
| | 2010 | | 2013 | | 2014 | | 2010-2014 (% change) | |
|---|---|---|---|---|---|---|---|---|
| | Offshore | Onshore | Offshore | Onshore | Offshore | Onshore | Offshore | Onshore |
| New capacity additions (GW) | 1.0 | 37 | 2.0 | 33 | 1.2 | 40+ | n.a. | n.a. |
| Cumulative installed capacity (GW) | 3.2 | 193 | 7.4 | 310 | 8.6 | 350+ | 169% | 81% |
| Weighted average installed cost ranges (2014 USD/kW) | 3 700 – 5 600 | 1 330 – 3 060 | 2700 – 6 530 | 1 340 – 2 330 | 2 700 – 5 070 | 1 280 – 2 290 | -9% to -27% | -4% to -25% |
| Weighted average LCOE range (2014 USD/kWh) | 0.10 – 0.32 | 0.06 – 0.13 | 0.13 – 0.20 | 0.06 – 0.12 | 0.10 – 0.21 | 0.06 – 0.12 | n.a. | -7% to -12% |

Notes: 2014 deployment data are estimates. n.a. = data was not available or not enough data to provide a robust estimate. Offshore wind cost ranges are for all projects. Onshore wind cost ranges are for regional weighted averages.

## Highlights

- Onshore wind is now one of the lowest-cost sources of electricity available, with weighted average LCOE by region of between USD 0.06 to USD 0.09/kWh.
- The best wind projects around the world are consistently delivering electricity for USD 0.05/kWh without financial support.
- Technological improvements at the same time as installed cost declines mean that the LCOE of onshore wind is now within the same cost range, or even lower, than for fossil fuels.
- Wind turbine prices in developed countries have fallen by around 30% since their peak in 2008/2009, while Chinese wind turbine prices fell by 35% from their peak in 2007.
- The regional weighted average installed costs for onshore wind range from around USD 1 280 to USD 2 290/kW. China and India have weighted average installed costs 35% to 44% lower than in other regions.
- The installed costs and the LCOE of offshore wind projects has stabilised, after rising through much of the last decade. Cost reductions are expected by project developers out to 2020, but offshore wind will remain more expensive than onshore.

### Figure 4.1: New capacity additions in 2013 and cumulative installed capacity at the end of 2013 by country.




*Source*: IRENA Renewable Cost Database

## Introduction

Wind power technologies are differentiated based on the axis of the wind turbine – vertical or horizontal – and their location – onshore or offshore.[16] The amount of power generated by a wind turbine is predominantly determined by the nameplate capacity (in kW or MW), the intensity of the wind resource, the height of the turbine tower and the diameter of the rotor.

The main factors driving the evolution of the levelised cost of electricity (LCOE) of wind power systems are capital costs, financing costs, operation and maintenance (O&M) costs and the expected annual energy production. The cost of wind power must take into consideration a careful assessment of all of these components over the life of the project. The following sections look at the latest trends for these LCOE drivers.

## Wind power deployment

Total installed wind capacity reached 318 GW globally by the end of 2013 (IRENA Database, 2014). Cumulative installed capacity has increased by around one-fifth per year for a decade. China has the largest share of installed wind capacity – 29% at the end of 2013. It is followed by the United States (19%), Germany (11%), Spain (7%) and India (6%).

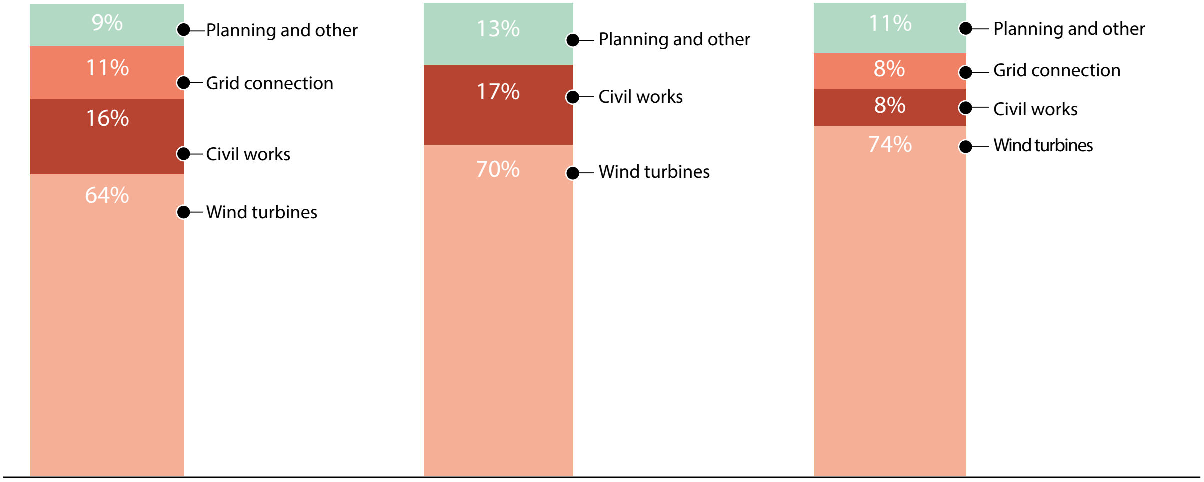
[16] *For the utility-scale market horizontal axis turbines are used exclusively.*

China accounted for around 45% of new annual capacity additions in 2013, followed by Germany with 9%, Canada, India and the United Kingdom, each with 5% of the total new capacity added in 2013 (Figure 4.1). The year 2013 was the first year since 2000 in which global new capacity additions for wind were lower than the previous year (by 24%). Policy uncertainty in key European markets and the United States was the main driver behind this slowing in growth in 2013. However, the wind market is set for a recovery in 2014, as new capacity added in 2014 looks set to be at least 40 GW and may be even higher (BNEF, 2014b; WWEA, 2014). Depending on the final figures, new capacity additions in 2014 could be 18% to 40% higher than in 2013. China, the United States, India and Germany will account for most of this installed capacity. However, Canada, Brazil and Mexico are expected to have installed record capacities in 2014 (BNEF, 2014b). Thus, it is expected that global wind installed capacity rose to at least 360 GW at the end of 2014 (BNEF, 2014b and GWEC, 2014).

## Wind power capital costs

Wind turbines (including towers and installation) are the main cost item in developing a wind project. At the upper end of the cost range, wind turbines can account for as much as 84% of the total installed cost for onshore wind farms, although higher values are possible (Table 4.2). The capital

FIGURE 4.2: COMPARISON OF ONSHORE WIND FARM'S INSTALLED COST BREAKDOWN




*Sources*: Blanco, 2009; E. on Climate & Renewables, 2013; and UNFCCC CDM Database, 2014

costs of a wind power project can be distilled into the following major categories:

» Turbine cost: This includes rotor, blades, gearbox, generator, power converter, nacelle, tower and transformer;

» Civil works: This includes construction costs for site preparation and the foundations for the towers;

» Grid connection costs: This includes transformers and sub-stations, as well as the connection to the local distribution or transmission network;

» Planning and project costs: These can represent a significant proportion of total costs;[17] and

» Other capital costs: These include the construction of roads, buildings, control systems, etc.

The most important developments in the wind market are related to technology improvements to ensure a range of wind turbine options are available that allow project developers to choose the designs that yield the lowest LCOE given the local site characteristics. Original equipment manufacturers (OEMs) are therefore focusing on the following:

[17] *These include costs such as development costs and fees, licenses, financial closing costs, feasibility and development studies, legal fees, rights of way fees, owners insurance, debt service reserve, and construction management not associated with the engineering, procurement and construction contract.*

» Maximising blade lengths and aerodynamics, while minimising weight, to achieve the highest capacity factors at the lowest possible cost.

» Meeting the increasing demand for taller towers, especially from European markets, with tower technology development adapted to this new demand.

With wind turbine cost reductions slowing, rotor diameter growth remains the main tool for achieving LCOE gains moving forward, with the exception of markets such as Brazil and others, where good quality wind resources allow for different strategies for attaining low LCOE. European markets are driving the demand for taller towers to enable the development of marginal wind sites and to take advantage of forested land available for development (MAKE Consulting, 2013).

Figure 4.2 presents the breakdown in total costs for onshore wind farms from three sources. For these three examples, wind turbines account for between 64% and 74% of total installed costs. Furthermore, grid connection costs can vary between 8% and 11%, construction and civil works from 8% and 16%, while other capital costs typically range between 4% and 10%.

Table 4.1 presents a detailed capital cost breakdown for the 20 MW San Matias wind farm in Mexico. The wind turbine accounts for around 60% of total installed costs, civil works and grid connection for 22%, planning and other project development costs for 10%.

Offshore wind farms have significantly higher grid connection and construction costs, and other project costs than onshore wind farms. These items account for a higher share of total installed costs than in onshore wind farms, lowering the cost share of wind turbines to between 30% and 50% for typical projects (Table 4.2). The offshore location significantly increases construction and grid connection costs due to the nature of offshore work, but also due to the increased costs to protect equipment and installations from the harsh marine environment. However, offshore wind projects benefit from less intermittent wind and can often have higher capacity factors; thus, they harvest more energy than onshore projects.

### Table 4.1: Capital cost breakdown for a 20 MW onshore wind farm in Mexico

| | | 2014 USD million | Share |
|---|---|---|---|
| **Civil works and grid connection** | **Civil works of wind turbines** | 8.15 | 18.2% |
| | **Measurement tower** | 0.09 | 0.2% |
| | **Construction costs** | 0.31 | 0.7% |
| | **Construction indirects costs** | 1.11 | 2.5% |
| | **Land rent** | 0.17 | 0.4% |
| **Sub-total** | | **17.57** | **22.0%** |
| **Wind turbines and installation** | **Turbines price** | 20.64 | 46.1% |
| | **Transportation of the wind turbines** | 2.27 | 5.1% |
| | **Electrical infrastructure of wind turbines** | 7.74 | 17.3% |
| **Sub-total** | | **22.91** | **68.5%** |
| **Planning & management** | **Management cost** | 0.46 | 1.0% |
| | **Administrative cost** | 3.80 | 8.5% |
| **Sub-total** | | **4.27** | **9.5%** |
| **TOTAL COST** | | **44.74** | **100.0%** |

*Source*: IRENA Renewable Cost Database

### Table 4.2: Comparison of capital cost breakdown for typical onshore and offshore wind power systems in developed countries

| Cost share of: | Onshore (%) | Offshore (%) |
|---|---|---|
| Wind turbine[1] | 64-84 | 30-50 |
| Grid connection[2] | 9-14 | 15-30 |
| Construction[3] | 4-10 | 15-25 |
| Other capital[4] | 4-10 | 8-30 |

*Sources*: Blanco, 2009; EWEA, 2009; Douglas-Westwood, 2010; and MAKE Consulting, 2011

[1] Wind turbine costs include the turbine production, transportation and installation.

[2] Grid connection costs include cabling, substations and buildings.

[3] Construction costs include building roads and other related infrastructure required for installation of wind turbines.

[4] Other capital costs include development and engineering costs, licensing procedures, consultancy and permits, SCADA (Supervisory, Control and Data Acquisition) and monitoring systems.

## Wind turbine costs

The wind turbine is the largest single cost item of the total installed cost of a wind farm. Wind turbine prices have fluctuated with economic cycles and with the price of commodities such as copper and steel, which can make up a sizeable part of the final cost of a wind turbine. The average turbine price in the United States for projects higher than 100 MW was USD 755/kW for projects delivered between 2000 and 2002 (Wiser and Bollinger, 2014). In 2009, the cost of wind turbines peaked in the United States at USD 1 728/kW and in Europe at around USD 1 890/kW.

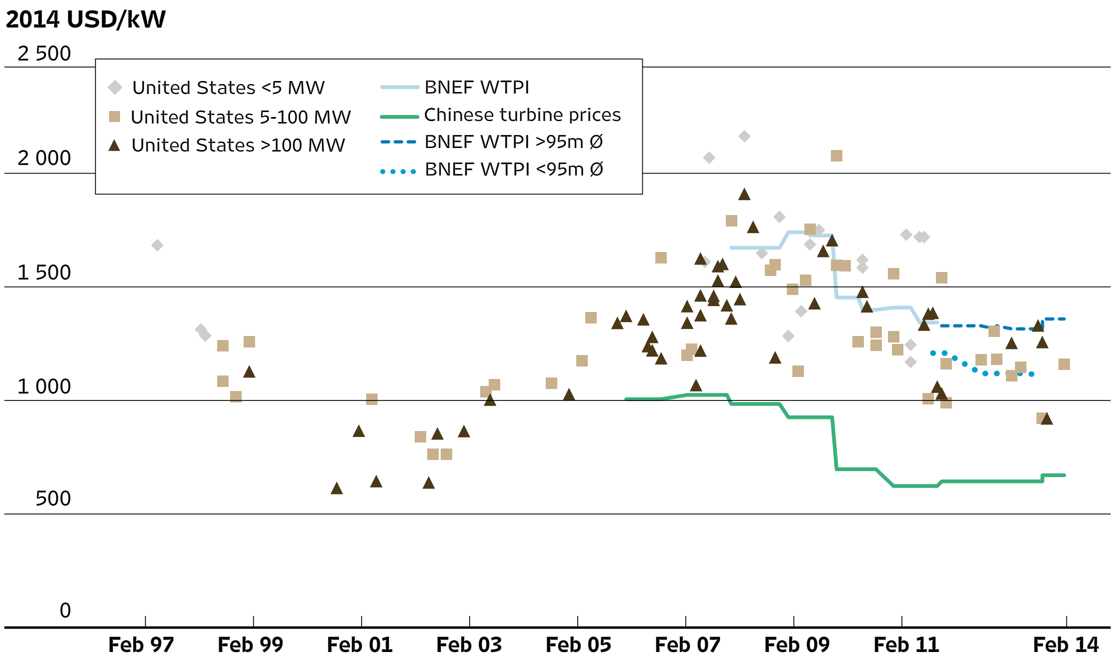
This cost increase was driven by three components. First of all, it followed the rising costs for materials (e.g. steel and cement), labour and for civil engineering. Secondly, tight supply drove up prices and allowed higher profit margins for wind turbine manufacturers, who started receiving more orders and struggled initially to meet new demand. Finally, technology improved; wind turbine manufacturers introduced larger, more expensive turbines, with higher towers and more capital-intensive foundations, but which also achieved higher capacity factors.

As presented in Figure 4.3, wind turbine prices began to decrease after the peaks of around USD 1 890/kW in Europe and USD 1 728/kW in the United States for contracts signed in 2008/2009 (Wiser and Bollinger, 2014).

Preliminary data for projects in 2014 suggest prices of between USD 931 and USD 1 174/kW in the United States, which would represent a decline of more than 30% compared with peak prices (Wiser and Bollinger, 2014). Bloomberg New Energy Finance (BNEF) has introduced separate turbine price indices for turbines with rotors of less than 95 metres in diameter and those with a diameter greater than 95 metres. The BNEF wind turbine price index (WTPI) decreased 35% for wind turbines of less than 95 metres in diameter and 20% for wind turbines with rotor diameters greater than 95% metres, resulting in an overall average decrease of 28%, which is in line with data from the United States (Figure 4.3).

The decline in wind turbine prices occurred at a time when wind turbine technology had improved significantly due to larger rotor diameters and higher towers, allowing for higher electricity output. However, the period after the Great

Figure 4.3: Wind turbine prices in the United States and China, compared to the BNEF turbine price index, 1997-2014




*Sources*: Wiser and Bollinger, 2014; CWEA, 2013; BNEF, 2014c; and Global Data, 2014.

Note: BNEF WTPI represents the half-year average for non-Asian markets, while the United States data are for the specific month of a particular turbine contract and the Chinese data are annual averages.

Recession has meant less pressure on commodity prices. In addition to lower materials costs than at the peak of turbine prices, the market for turbines has also become more of a buyers market.

These events have driven down costs and increased competition in the wind markets. Manufacturers from emerging markets, especially China, have added to this downward pressure as once renewable energy rose higher on the agenda of policy-makers in China, the push to develop domestic wind turbine manufacturers led to an increase of production capacity above internal demand. Wind turbine prices in China were at USD 1 036/kW in 2007 and experienced a steep decline to USD 628/kW in 2011, only to rebound to USD 676/kW in 2014. Thus, Chinese wind turbine prices have dropped 35% in comparison to peak prices in 2007 (CWEA, 2014).

As mature wind markets approach plateaus in deployment and policy uncertainty weighs on developed markets, new sources of higher growth in installed wind capacity are expected to increasingly come from emerging wind markets such as Mexico, Brazil and South Africa, among others. Chinese wind turbine manufacturers will face pressure to develop international markets, as their planned output is unlikely to be met by domestic demand. This is likely to add downward pressure on wind turbine prices internationally and is already allowing developing countries to reap the benefits of deploying wind power systems at the lowest possible cost. In this way, countries less endowed with financial resources to develop strong wind sectors could enjoy a latecomer advantage in wind markets, as learning investments have been made.

## Total installed costs onshore

The cost reductions in wind turbine prices have been flowing into installed project costs. Data for 2013 suggest that total installed costs in the United States have fallen from a peak average of around USD 2 300/kW in 2009 to USD 1 657/kW in 2013, a 28% drop from peak prices (Wiser and Bollinger, 2014). However, these data are from a

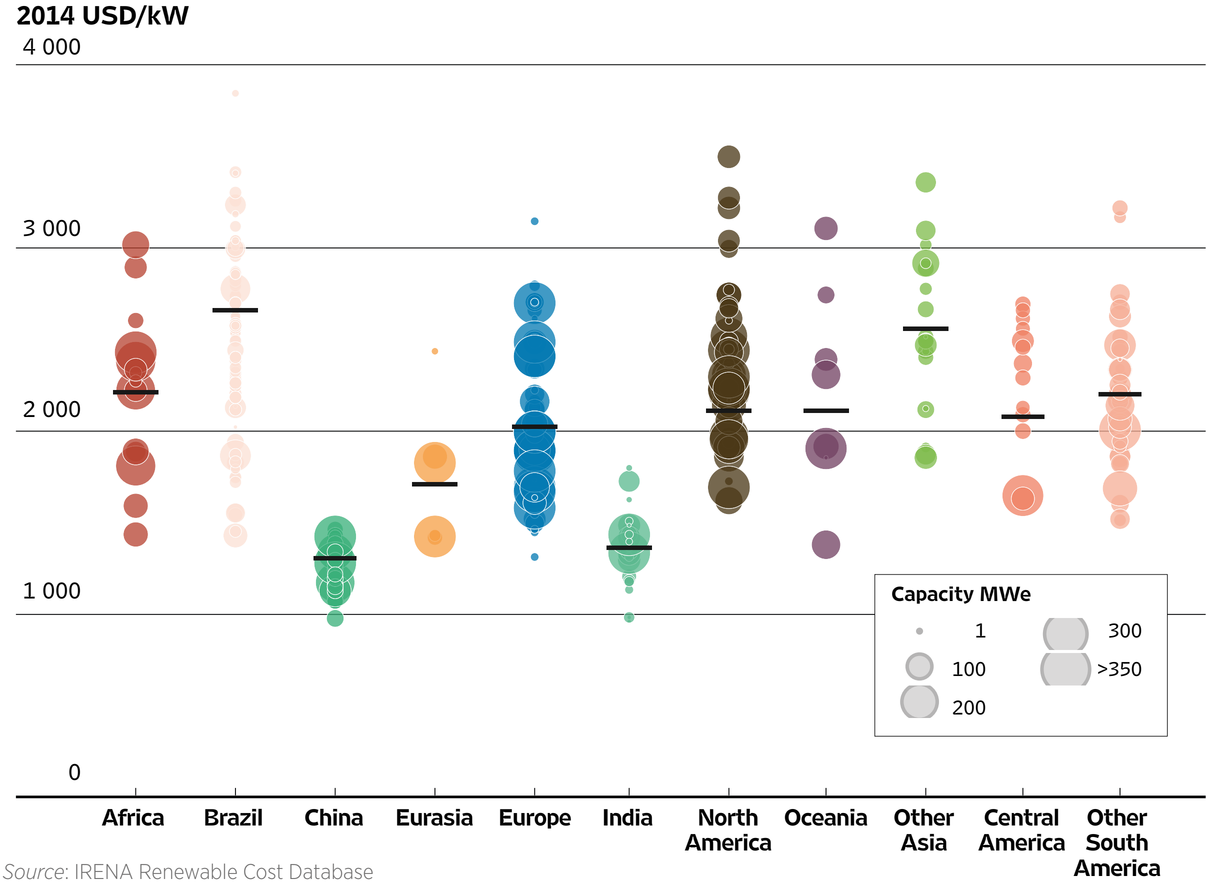
Table 4.3: Average total installed costs of new wind farms in selected OECD countries, 2013

| | New capacity in 2013 (GW) | Cost (2014 USD/kW) |
|---|---|---|
| **Australia** | 0.68 | 1 427 - 2 384 |
| **Austria** | 0.37 | 2 403 |
| **Canada** | 1.60 | 2 296 |
| **France** | 0.73 | 2 065 |
| **Germany** | 2.95 | 1 999 |
| **Italy** | 0.45 | 2 452 |
| **Japan** | 0.05 | 2 900 |
| **Mexico** | 0.62 | 2 102 |
| **Netherlands** | 0.24 | 1 928 |
| **Norway** | 0.07 | 1 978 |
| **Portugal** | 0.31 | 1 891 |
| **Switzerland** | 0.01 | 2 900 |
| **United Kingdom** | 1.64 | 1 874 |
| **United States** | 1.13 | 1 657 |

*Sources*: IEA Wind, 2014; IRENA Renewable Cost Database; Global Data, 2014; and Commission de Regulation de l'Energie, 2014

Note: Data for the United Kingdom is for 2012/2013.

Figure 4.4: Total installed costs and weighted averages of commissioned and proposed wind farms by country and region, 2013-2014




*Source*: IRENA Renewable Cost Database

small sample of projects built in 2013 and may not be fully representative. Early data for 16 projects accounting for 2 GW to be commissioned in 2014 and 2015 suggest average costs of installed wind at USD 1 779/kW, still significantly below peak prices in 2009. Costs vary as a function of project size, turbine size and region. Economies of scale are observed as project costs at the lower end of the ranges for project and turbine size exhibit higher costs (Wiser and Bollinger, 2014).

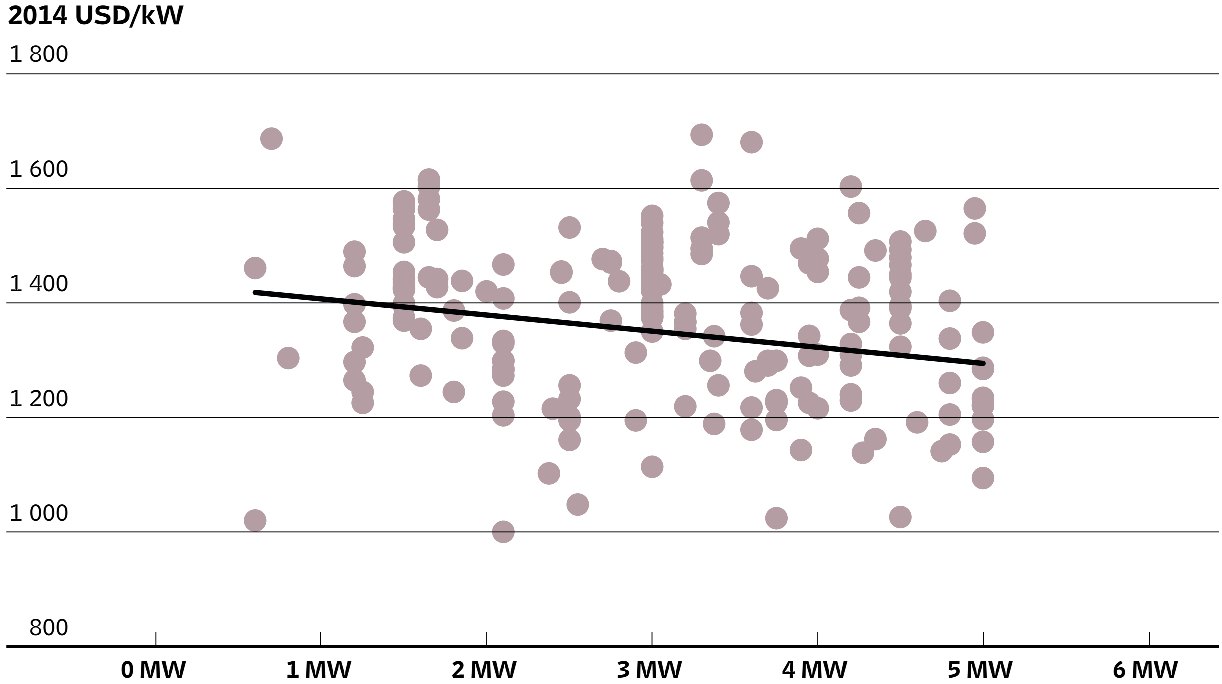
Average installed costs in China between 2011 and 2014 were the lowest in the world and averaged USD 1 310/kW in 2013 and 2014. India also has low installed costs, which averaged around USD 1 370/kW in 2013 and 2014 (Figure 4.4). It should be noted that total installed cost ranges outside of China and India are very wide. China and India benefit from a low-cost local manufacturing base, some policy support for deployment and low materials and labour costs. It will be difficult, if not impossible, for other countries to replicate these cost advantages, so price differentials are likely to persist.

Average total installed costs in Eurasia were USD 1 710/kW in 2013 and 2014 and USD 2 200/kW in South America, excluding Brazil. Average installed costs in Chile in 2013 and 2014 are estimated to have averaged USD 2 010/kW, while in Argentina they were around USD 2 340/kW. Average installed costs in Brazil are estimated to have averaged USD 2 650/kW in 2013 and 2014, with preliminary data for 2014 suggesting a trend to significantly lower values. Brazil's highly competitive and sustained auction system will see installed costs drop rapidly. The total installed costs in 2015 are projected to average USD 1 840/kW in Brazil, and by 2017 they might be as low as USD 1 600/kW.[18]

With modest deployment in much of Other Asia, average costs remain relatively high. The

[18] *Note that throughout this chapter where project level data is presented, if in a given year the coverage of the IRENA Renewable Cost Database is not high enough to be statistically representative the data is supplemented by a "balance" entry based on the national average for that year.*

**Figure 4.5: Total installed costs of commissioned small wind farms in India (<5 MW), 2000-2013**




*Source*: IRENA Renewable Cost Database

average cost of installed wind farms in Other Asia averaged around USD 2 560/kW in 2013 and 2014. Deployment in Oceania for which data is available in the IRENA Renewable Cost Database is concentrated in Australia, where a wide range of costs were in evidence, with average installed costs of USD 2 110/kW. The average installed cost of wind farms in Africa was around USD 2 210/kW, with some projects proposed having quite competitive cost structures.

India has deployed large numbers of small wind farms of up to 5 MW. Figure 4.5 presents data for proposed and commissioned small wind farms in India for the period 2000 to 2013. The average cost of these projects is around USD 1 344/kW. There is some evidence of economies of scale even for these small wind projects.

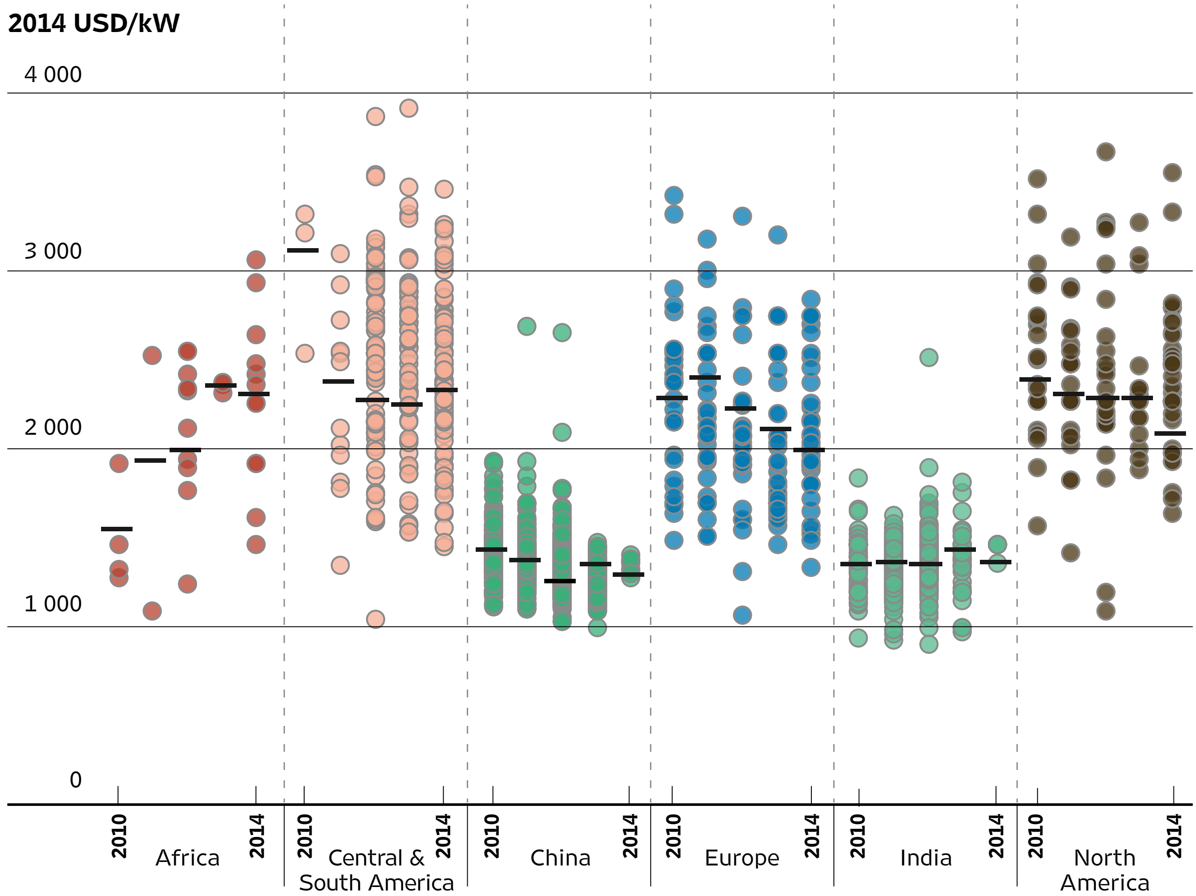
Figure 4.6 shows that between 2010 and 2014 the ranges of installed costs have shown a slight tendency towards narrowing in China and India, while this is not true in other regions. In comparison to installed costs in 2010, all countries and regions in Figure 4.6 have experienced cost declines except Africa and India. However, the market in Africa is very thin and the results are heavily dependent on the country of new projects and their site specific cost characteristics. Installed costs in India in 2014 were fractionally higher than in 2010. The decline in installed costs by 9% between 2010 and 2014 in China, with costs in India broadly stable, suggests that onshore wind costs are approaching a mature level in these markets. This is most likely due to the lower cost structure of onshore wind in China and India compared to the rest of the world.

In South America, total installed costs fell by 25% between 2010 and 2014, although for the period 2011 to 2014 (where more data are available for comparison) the decline is 2%. In the more mature markets of Europe and North America, total installed costs are estimated to have fallen by around 12% between 2010 and 2014.

For the eight developed countries presented in Figure 4.7 for which data is available between 2011 and 2014, the range in installed cost declines in 2014 compared with 2011 is between 8% and 30%. However, the spread in installed costs among the eight selected countries is relatively important, as installed costs in France are USD 1 430/kW in 2014 and in Australia they are higher than USD 2 500/kW.

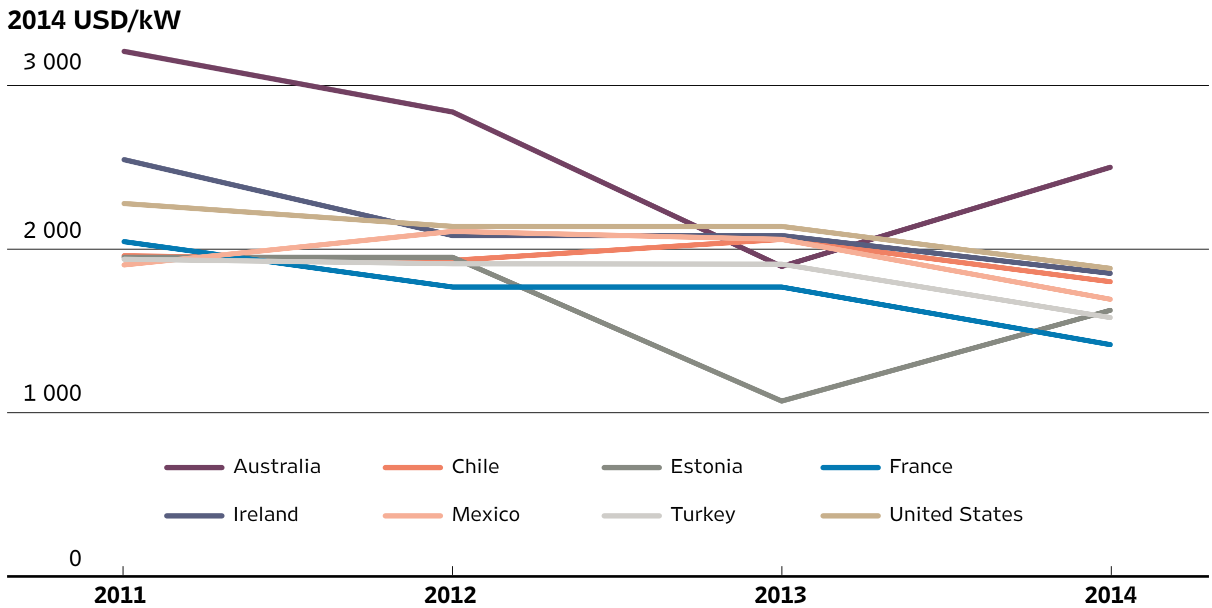
Installed costs of wind farms are declining with the exception of Africa and India as already discussed, pointing to the fact that markets for onshore wind have become more competitive and are passing through wind turbine cost reductions. The potential for positive spillovers from India and China with their

Figure 4.6: Evolution of total installed costs and weighted averages of commissioned and proposed large wind farms by country and region, 2010-2014




*Source*: IRENA Renewable Cost Database

Figure 4.7: Evolution of total installed costs of commissioned and proposed large wind farms in selected OECD countries, 2011-2014




*Source*: IRENA Renewable Cost Database

low-cost turbines to other developing countries is possible, but will be dependent on local market features and policy decisions. The wide range in installed costs among different regions is one indicator that a global market for wind systems is still in its infancy, but also reflects country-specific cost structures that are likely to ensure the degree of convergence in costs will be limited in a number of cases.

## Total installed costs offshore

There were 7 GW of installed offshore wind systems at the end of 2013, 2.2 % of total installed capacity (IRENA, 2014) with an estimated 1.2 GW added in 2014. Europe accounted for around 6.6 GW of the capacity at the end of 2013, while China and Japan accounted for the remainder. Most of the installed offshore turbines in Europe use monopile foundations (76%), followed by gravity foundations (12%), tripod systems (5%) and jacket foundations (5%) (EWEA, 2014). Offshore wind technology is hampered by higher costs than onshore wind. The higher cost is the result of increased investment in deploying cables offshore, building foundations at sea, transportation of materials to more remote areas, and installing foundations, equipment and the turbines at sea. The turbines are also somewhat more expensive as they are designed to withstand the harsh marine environment. Higher upfront investments are also required in order to avoid expensive O&M costs due to interventions at sea. Still, O&M costs are higher than for onshore turbines (Douglas-Westwood, 2010).

Offshore total installed costs have risen over time, in part due to projects shifting further offshore, towards deeper water and increased site complexity. The average nameplate capacity has increased, from 2.9 MW in 2007 to 4.1 MW in 2012 as larger machines reduce installation costs per MW and can also help reduce O&M costs. Increased capacity factors due to higher hub heights and rotor diameters, in addition to other technology improvements, will help to mitigate the increase in installed costs of offshore wind if projects continue to be sited further from logistics bases and in deeper water (Navigant Consulting, 2013).

The wind turbine remains the largest cost component for an offshore wind project, but its share typically accounts for less than half (30-50%) of the total capital costs (Douglas-Westwood, 2010). The foundations, electrical infrastructure, installation and project planning account for the remainder (Table 4.2). The average installed costs between 2000 and 2014 for commissioned and proposed offshore wind projects were slightly more than USD 4 700/kW in OECD countries, while in China the cost was approximately USD 2 400/kW, as a result of the deployment of cheaper tidal projects (Figure 4.9). The proposed projects for 2015 to 2020 are targeting lower costs, of around USD 4 100/kW on average, but rely on large projects to achieve economies of scale. It remains to be seen whether these projects can deliver on their cost estimates.

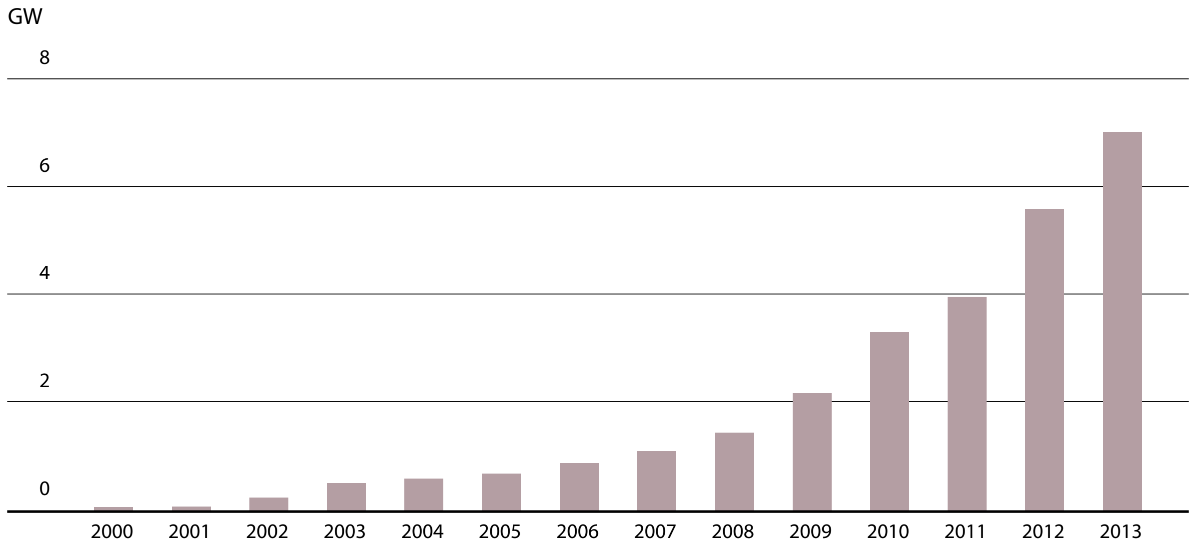
## Wind power capacity factors

With increasing wind speeds, the amount of kinetic energy available for a wind turbine increases, which allows for an improved electricity output. The kinetic energy in wind is a cubic function of wind speed. A doubling of wind speed could therefore, potentially, increase the power output of a wind turbine by a factor of eight (EWEA, 2009). Thus, developers have an incentive to place wind farms in areas with high average wind speeds.

In addition, at greater heights, the wind speed is higher. For instance, a fivefold increase in the height of a wind turbine above the prevailing terrain can double its electricity output. Increased height also allows for larger rotor blade diameters, which is important because the maximum energy that can be harnessed by a wind turbine is roughly proportional to the swept area of the rotor. By doubling the rotor diameter, the swept area – and therefore the potential power output – is increased by up to a factor of four.

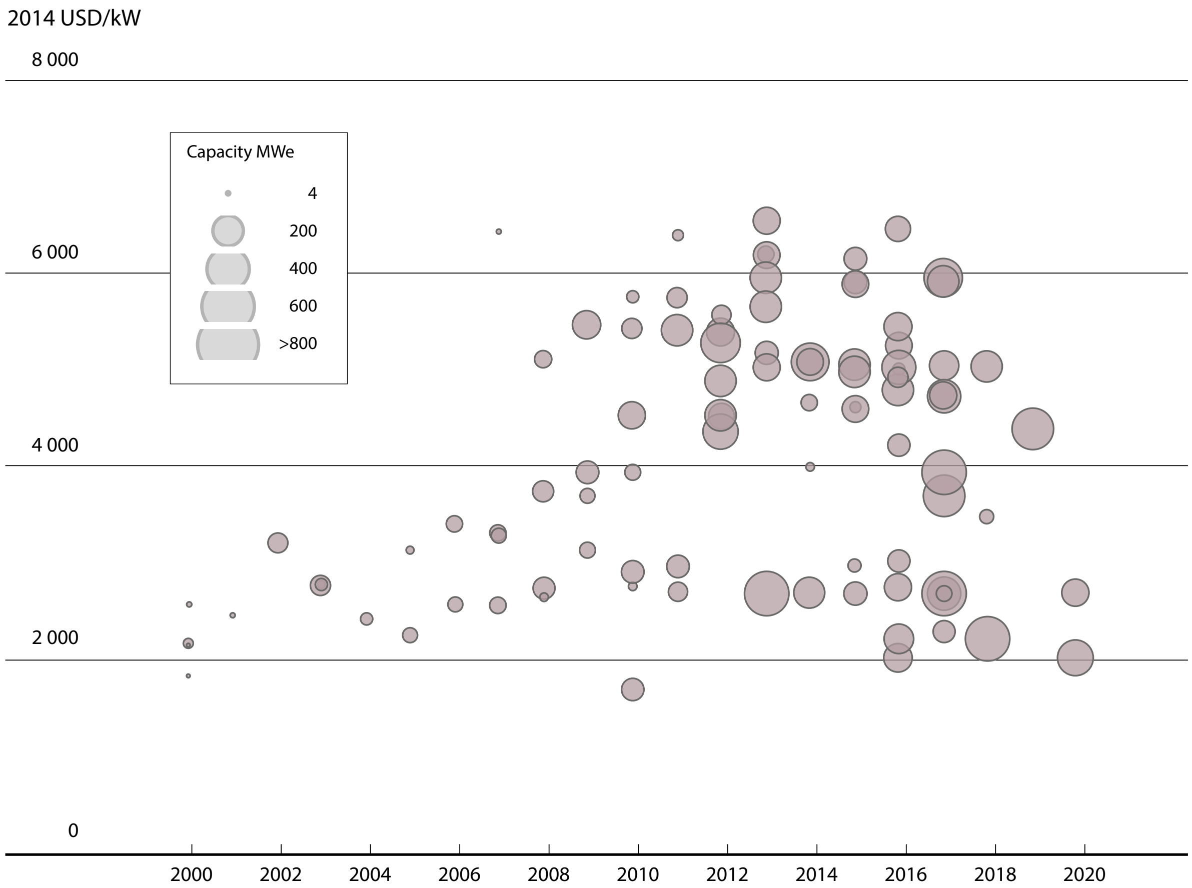
For these reasons, higher hub heights and larger swept areas have played a role in increasing the average capacity factors of wind farms. However, capacity factors are also driven by the overall quality of the wind resource at the site (e.g. annual average wind speed), inter-annual variability in the resource quality and curtailment (if any) of

**Figure 4.8: Cumulative offshore wind installed capacity at the end of 2013**




*Source*: IRENA

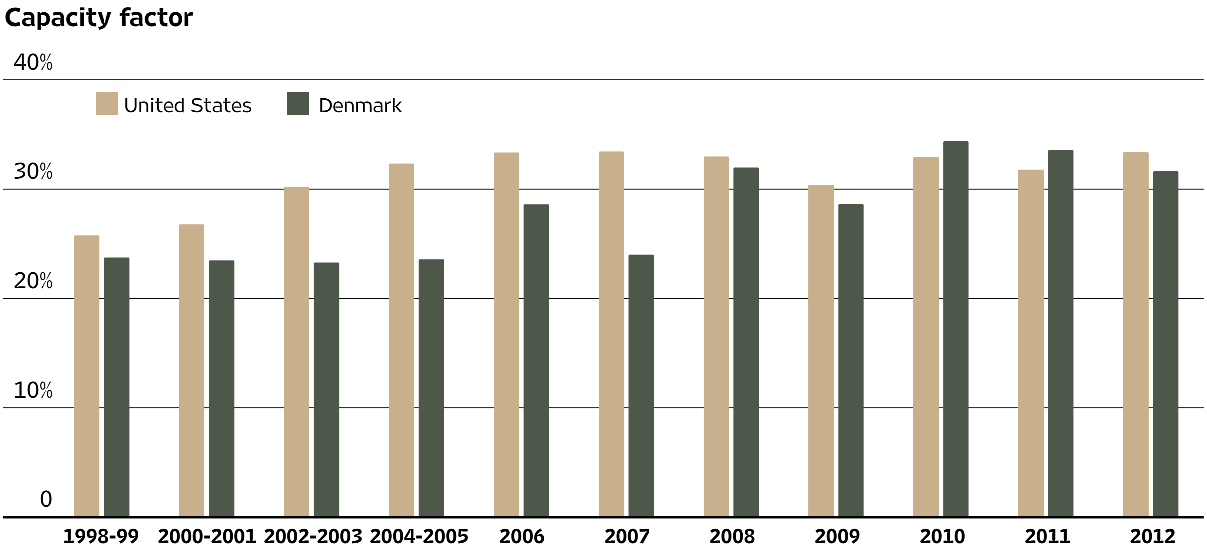
**Figure 4.9: Weighted average total investment costs for commissioned and proposed offshore projects, 2000-2020**




*Source*: IRENA Renewable Cost Database

wind output due to limitations in the flexibility of the local electrical system. Data for the United States show that capacity factors have risen less than technology advancements might suggest, an average of 32.1% for 2006 to 2013 compared with 30.3% for 2000 to 2005 (Figure 4.10). The primary driver for this more modest increase in capacity factors than what might otherwise have been expected is that lower wind speed technologies have allowed projects to increasingly be sited at somewhat lower quality wind resource sites. Also impacting this trend has been wind project output

Figure 4.10: Project capacity factors by commercial operation date




Note: Data for the United States present capacity factors in 2013 for wind turbines installed from 1989 onwards. Data for Denmark present average capacity factors for wind turbines installed from 1998 onwards.

*Sources*: Wiser and Bollinger, 2014; Danish Energy Agency, 2014; and GlobalData, 2014

curtailment in the United States as penetration levels have increased (Wiser and Bollinger, 2014).

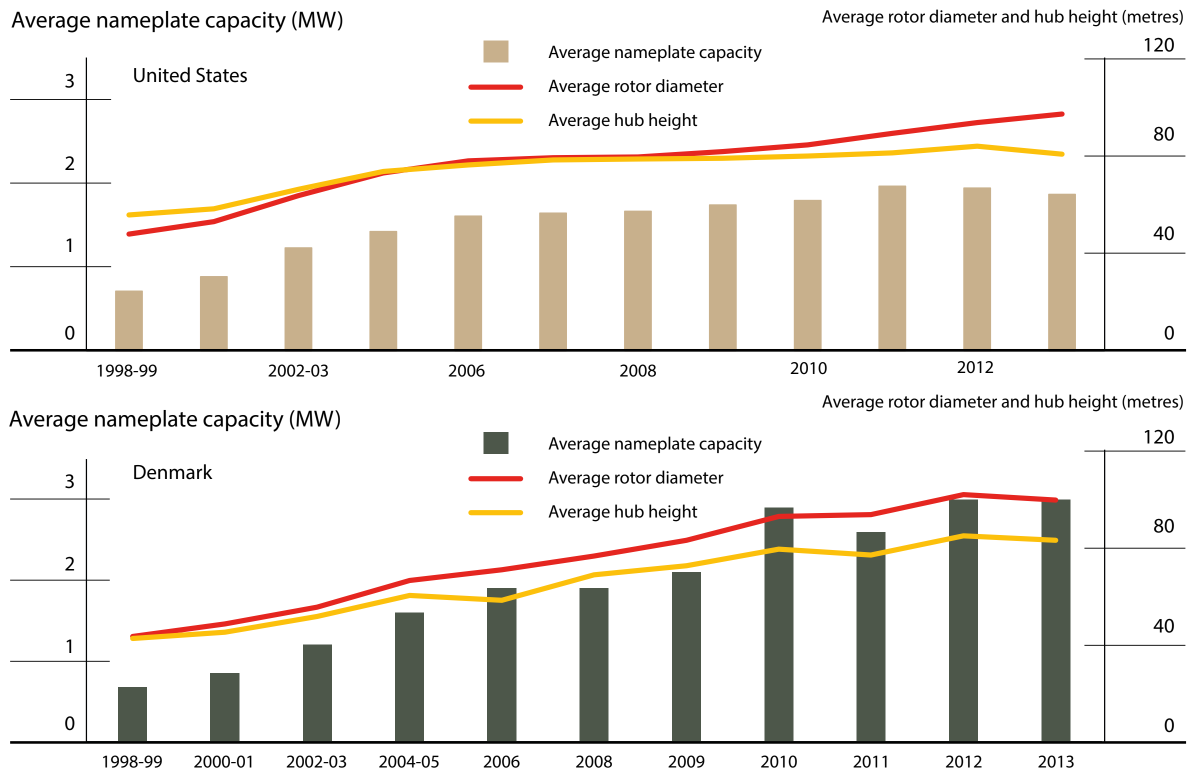
In this respect, the data for Denmark more clearly show that improved technology has led to higher capacity factors, assuming that the average wind resource exploited has been stable or been poorer. Wind turbines in Denmark had an average capacity factor of 23.7% in 1998-1999 and 31.6% in 2012, an increase of one-third (Figure 4.10). Figure 4.11 presents the technological features that have led to improved capacity factors in both the United States and Denmark. In the United States, nameplate capacity has increased by 161% in 2013 in comparison to 1998, and average rotor diameter has increased by more than 100% during the same period, while hub height increased by 44%. In Denmark, the average nameplate capacity has increased by more than 340% in 2013 in comparison to 1998. Furthermore, average rotor diameter increased by 129% and average hub height by 95% in the same period.

Figure 4.12 presents the ranges for wind farm capacity factors for current and proposed projects by country and region. Weighted average capacity factors varied by region from around 24% in China and India to around 43% in Brazil. In China, curtailments due to grid constraints mean that average capacity factors for dispatched generation are often closer to 20%. By comparison, projects commissioned in 2012 in the United States had average capacity factors of 33.4% in 2013, with ranges of between 18% and 54% (Wiser and Bollinger, 2014). The capacity factor ranges for Africa and South America excluding Brazil are similar to those in the United States.

Figure 4.13 presents the data in the IRENA Renewable Cost Database for total installed costs, plotted against capacity factors. A strong correlation is apparent, when examining data at a global level, suggesting that project developers look to site projects in a manner that minimises LCOE, by accepting more expensive project development costs to access better resources. However, the correlation is much weaker at a regional level. This suggests that it is typically the overall resource quality and the opportunities for project development in a given area that are driving the trade-off between costs and capacity factors, although there is some evidence that project developers will search for opportunities to tap a better resource at the expense of higher grid connection and/or project development costs.

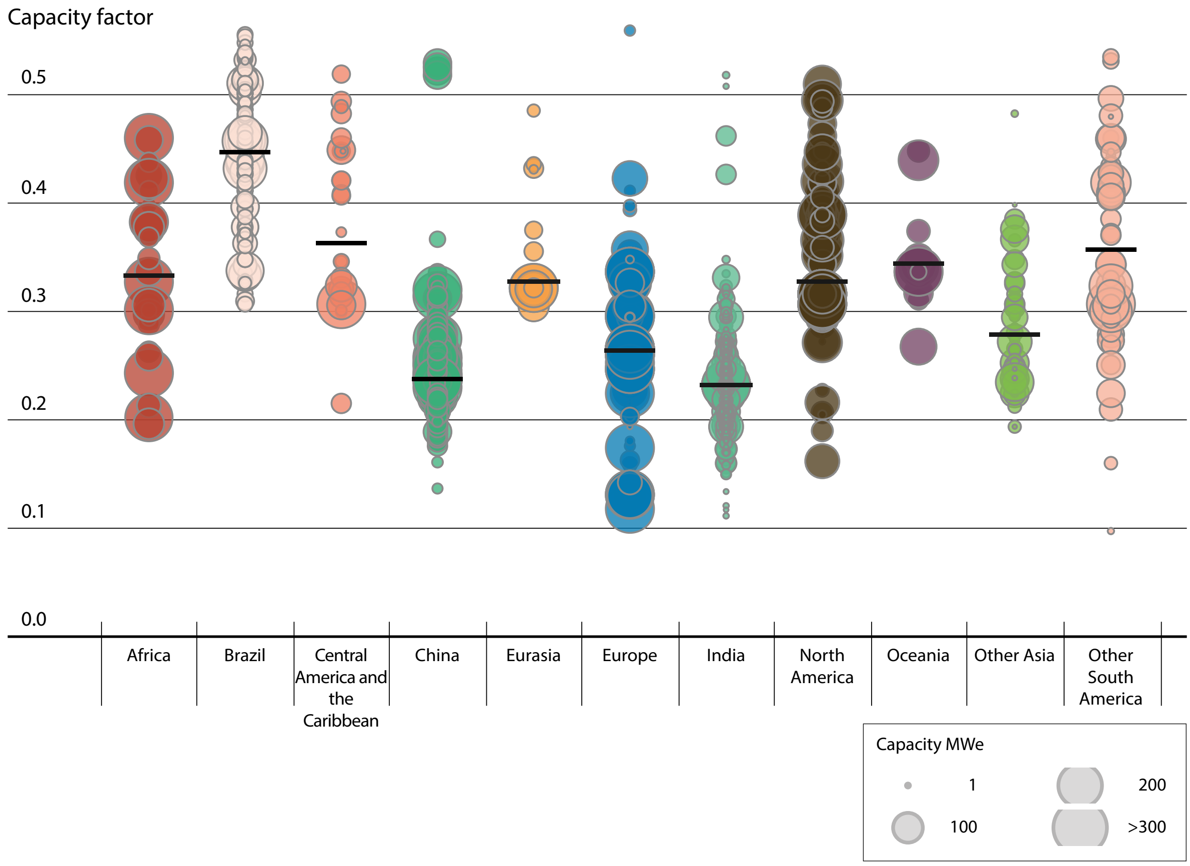
One of the most interesting recent technological developments within the wind industry is the launch of wind turbines capable of yielding higher electricity outputs at sites with lower quality wind

**Figure 4.11: Average turbine nameplate capacity, rotor diameter and hub height for turbines >100 kW (1998-2013) in the United States and Denmark**



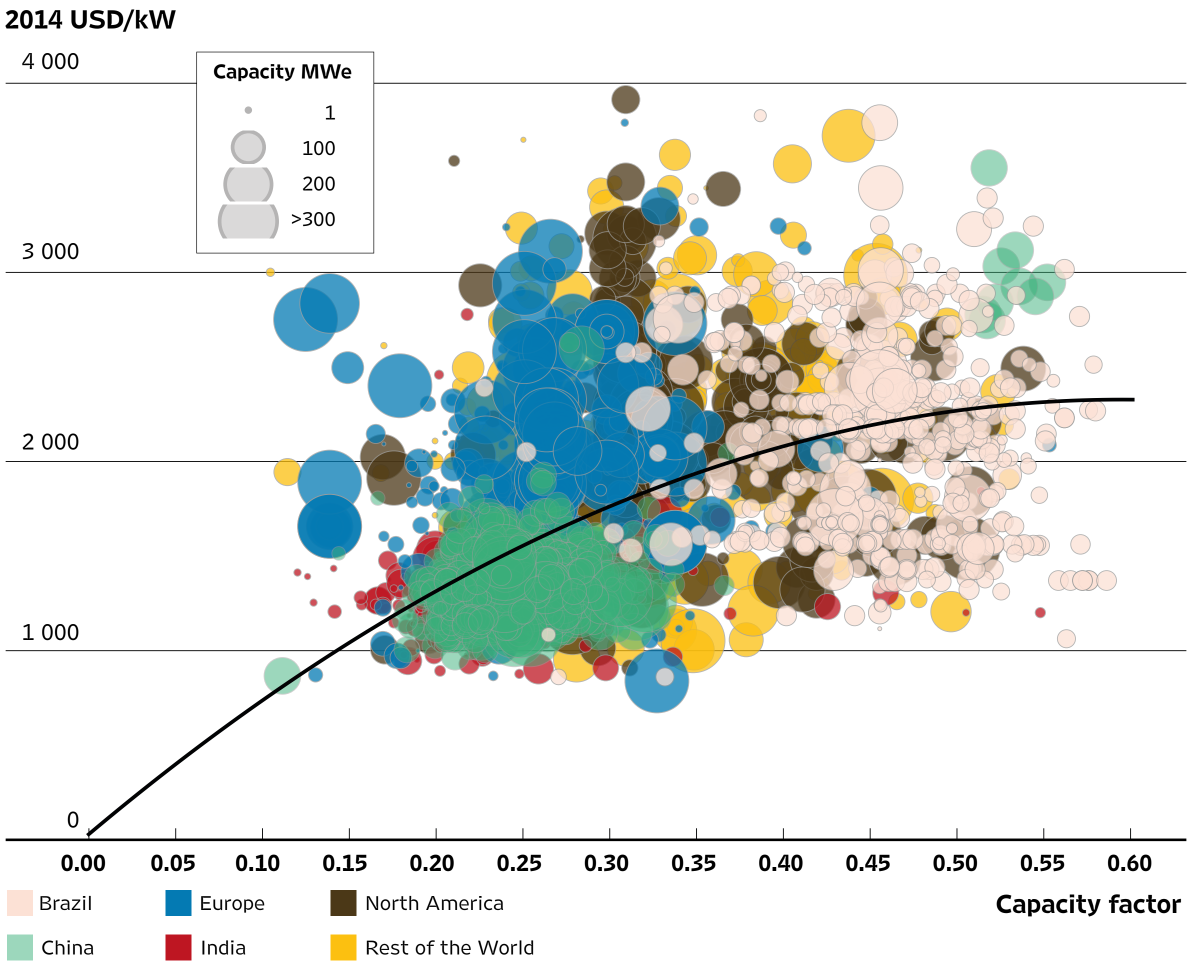

*Sources*: Wiser and Bollinger, 2014; Danish Energy Agency, 2014; and GlobalData, 2014

**Figure 4.12: Capacity factors by project and weighted averages for commissioned and proposed wind farms, 2010-2014**




*Source*: IRENA Renewable Cost Database

### Figure 4.13: Total installed onshore wind farm costs relative to project capacity factors by region




*Source*: IRENA Renewable Cost Database.

resources. Given the low-hanging fruit of high wind speed sites has often been harvested in the first push of wind deployment in some countries, these technological improvements might bring a new impetus to deployment in lower wind speed sites. These new turbines provide capacity factors in low wind speed sites that are equal to those previously observed at high wind speed sites, with earlier technology. These developments are already giving a second life to markets that were struggling with poorer wind resource sites and may help launch exciting new markets (Chabot, 2014).

## Operations and maintenance costs of wind power

The fixed and variable 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 wind power systems (EWEA, 2009).

Data for actual O&M costs from commissioned projects are not widely available. Even where data are available, care must be taken in extrapolating from historical O&M costs, given the dramatic changes that have occurred in wind turbine technology over the last two decades. Another issue is that although data for maintenance costs are often available, the cost data for operations (e.g. management costs, fees, insurance, land lease payments, local taxes, etc.) is not systematically collected. As a result, good data on total O&M costs is not typically available.

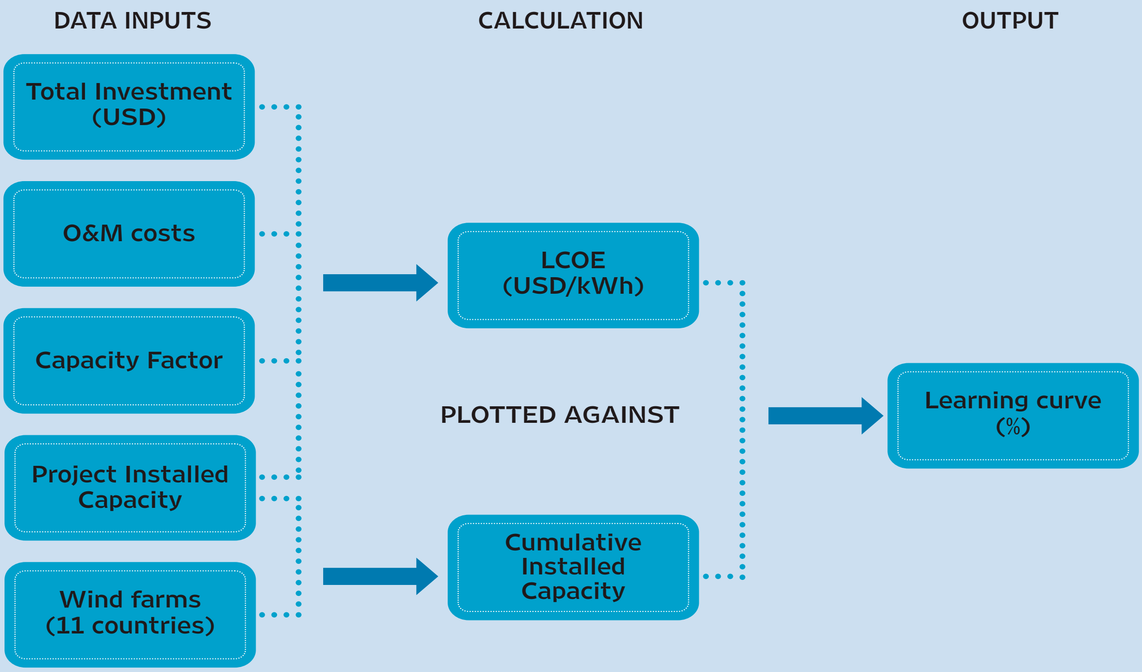
However, given these caveats, it is clear that annual average O&M costs of wind power systems have declined substantially since 1980. BNEF has compiled data for the maintenance costs of more than 6.4 GW of installed onshore wind capacity, and concluded that between 2008 and 2013 full-service contract prices fell by 36% (Figure 4.15). The BNEF index and recent data for reported

## BOX 4.1

### Updating the analysis of the global wind learning curve

IRENA is in the process of updating the out-of-date learning curve analysis for onshore wind installed costs. IRENA is also extending the analysis by developing a comprehensive global learning curve for the levelised cost of electricity for onshore wind power systems. The learning rates for wind are used extensively by the industry, energy and climate modellers, and policy makers in their analysis. Unfortunately, the current analysis either relies on outdated data or is not globally comprehensive, IRENA is aiming to fill this gap in wind deployment knowledge in order to improve decision-making related to wind deployment. The aim is to create the most comprehensive learning curve for wind technology to date, which will cover the period from the late 1970s to 2013 and more than 85% of cumulative installed capacity. The second part of the project aims at decomposing the cost reductions of wind systems by wind turbine price contribution, technology improvement, balance of system costs and operations and maintenance costs. Figure 4.14 presents a stylised overview of the project.

Figure 4.14: The process for developing a learning curve for wind based on LCOE

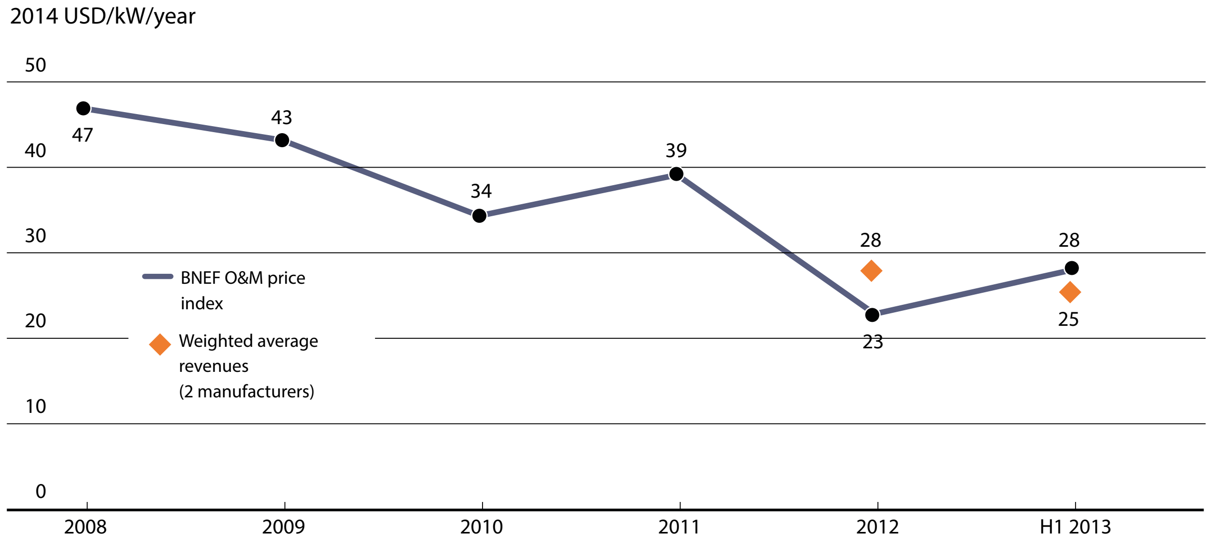



revenues from O&M contracts by two major manufacturers are around the same level, but show different trends.

In contrast, data compiled by the Energy Regulation Commission in France for total O&M costs, not just maintenance and local operations as in the BNEF index, in France between 2008 and 2012 were mostly stable at around 3% of total installed costs per year (Commission de Régulation de l'Energie, 2014). Total O&M costs reported by publicly traded developers in the United States were around USD 0.024/kWh in 2013, suggesting a lower cost structure than the average of the BNEF index. The order of magnitude in the United States for these total O&M costs suggest that half, or more, of total O&M costs come from operations costs, as reported maintenance costs for a large sample of installed projects compiled in the United States average around USD 0.01/kWh (Wiser and Bollinger, 2014).

Both the year a project was developed and the age of the project has an impact on O&M costs. In the United States, O&M costs for projects installed in the last decade are on average lower than for older projects in their first years of operation. However, O&M costs for all projects tend to increase as wind turbines get older.

Figure 4.15: Full-service O&M pricing 2008-2013 vs. weighted average O&M revenues of two manufacturers




*Sources*: BNEF, 2014 and GlobalData, 2014

Table 4.4 presents data for the O&M costs reported for a range of OECD countries. Data is not consistently reported and comparisons are made more difficult by uncertainty about whether the same boundaries are applied to O&M costs. An average value of around USD 0.02 to USD 0.03/kWh would appear to be the norm, but more systematic data collection is required to confirm these values.

O&M costs for offshore wind farms are significantly higher than for onshore wind farms due to higher costs involved in accessing and performing maintenance for wind turbines, cabling and towers offshore. Maintenance costs are also higher as a result of the harsh marine environment and a 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 (ECN, 2011).

Table 4.4: Estimated O&M costs in selected OECD countries

| | Variable (2014 USD/kWh) | Fixed (2014 USD/kW) |
|---|---|---|
| **Austria** | 0.04 | |
| **Denmark** | 0.0152-0.019 | |
| **Finland** | | 37-40 |
| **Germany** | | 67 |
| **Italy** | | 49 |
| **Japan** | | 75 |
| **The Netherlands** | 0.0137-0.0179 | 37 |
| **Norway** | 0.0211-0.039 | |
| **Spain** | 0.0284 | |
| **Sweden** | 0.0105-0.0348 | |
| **Switzerland** | 0.0453 | |

*Source*: IEA Wind, 2011b

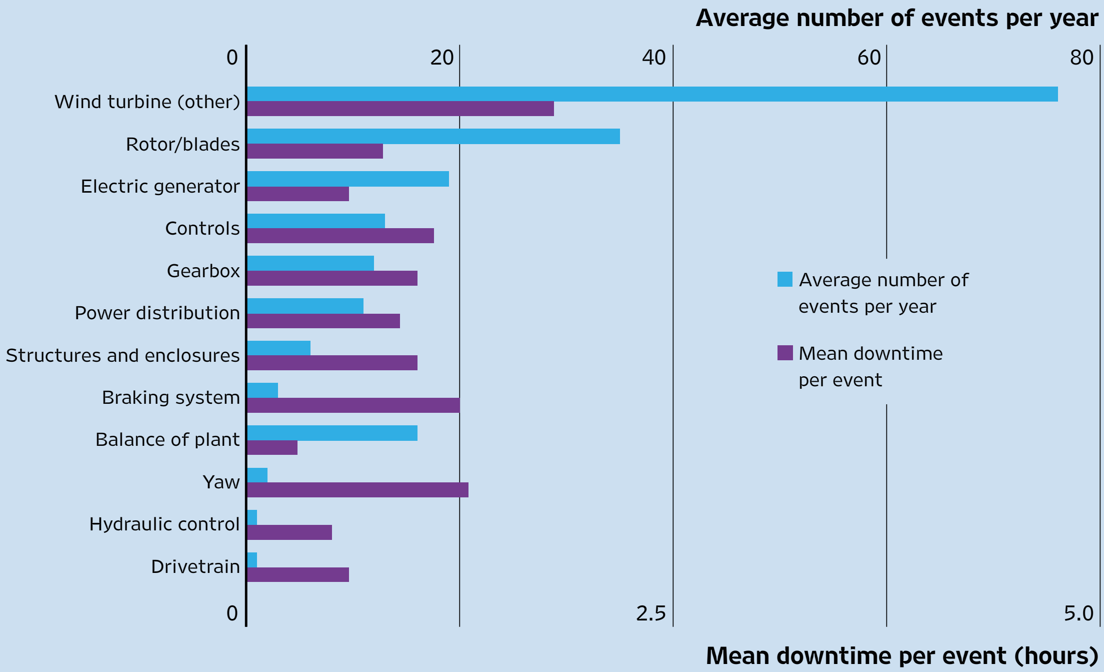
## BOX 4.2

### Wind turbine reliability and downtime

An analysis conducted by Sandia National Laboratories on a sample of 2.7% of large US wind turbines, equivalent to 2.4% of total installed capacity, has shown that the operational availability of wind turbines has increased from 94.8% in 2011 to 97.6% in 2013. Utilisation has increased from 78.5% in 2011 to 83% in 2013 and the capacity factor has increased from 33.4% in 2011 to 36.1% in 2013 for the plants surveyed. At the same time, the mean time between outage events is longer, rising from 28 hours in 2011 to 39 hours in 2013, while mean downtime has decreased from 2.5 hours in 2011 to 1.3 hours in 2013 (Figure 4.16).

Overall, a wind turbine is generating power 83% of the time, while 17% of the time is accounted for mostly by reserve shutdowns due to extreme wind speeds or other reasons (Hines, 2013).

Figure 4.16: Average number of events per year per turbine and mean downtime per event for surveyed plants in the United States, 2013



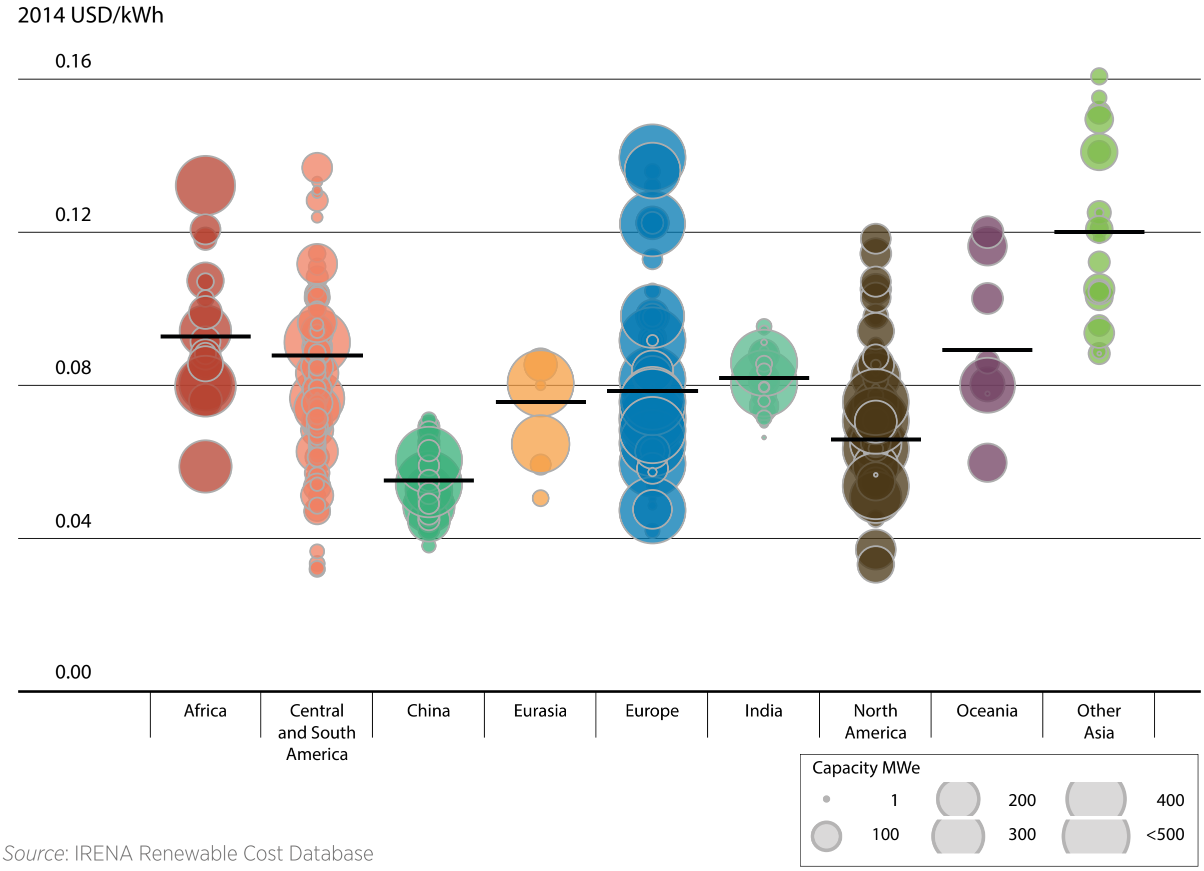

*Source*: Hines, 2013

The O&M market has become more dynamic, particularly in Europe, given the aging of the existing turbine fleet (MAKE Consulting, 2012) and the fact that an increasing number of turbines are coming to an end of their original O&M contract. At the same time, increased competition for O&M contracts has led to a decline in O&M costs as O&M contractors look to lock-in long-term service contracts (MAKE Consulting, 2012).

As turbines roll off warranty, OEMs have also become more flexible in their offering of services, offering more yield-based guarantees and aggressively trying to renew and extend existing contracts. Another important driver in the development of this market is that the cost of failure becomes larger with increased turbine sizes (MAKE Consulting, 2012). On a different note, emerging market countries rely extensively on OEMs for O&M services as local independent service providers (ISPs) have not developed significant market share yet. If their share of the market increases, this could translate into lower O&M costs (MAKE Consulting, 2012).

O&M strategies are increasingly relying on data analytics in order to indicate potential system problems that can lead to downtime or replacement costs. Equipped with these data, asset owners are increasingly able to use predictive analytics in order to manage their O&M strategies (Ingham, 2013). Analysis of wind turbines with a cumulative 100 000 years of operations data for onshore wind farms has determined that the most common failures are

FIGURE 4.17: THE LCOE AND WEIGHTED AVERAGES OF COMMISSIONED AND PROPOSED WIND PROJECTS BY COUNTRY AND REGION, 2013 AND 2014




*Source*: IRENA Renewable Cost Database

due to equipment breakdown and lightning strikes. The analysis concludes that most of the failures occurring on a wind farm are due to the electrical system, followed by mechanical issues, blades, gearboxes, generators and structural issues. The consolidated average downtime from these failures averaged 2.62 days per year.

## THE LEVELISED COST OF WIND ELECTRICITY

The LCOE of a wind power project is determined by total capital costs, wind resource quality, technical characteristics of the wind turbines, O&M costs, the economic life of the project and the cost of capital.

More specifically, the LCOE of wind power depends mainly on four items:

» Capacity factor: This is the result of the interaction of multiple variables, such as wind turbine design, operational availability, potential power curtailment and – most importantly – the quality and nature of the wind resource.

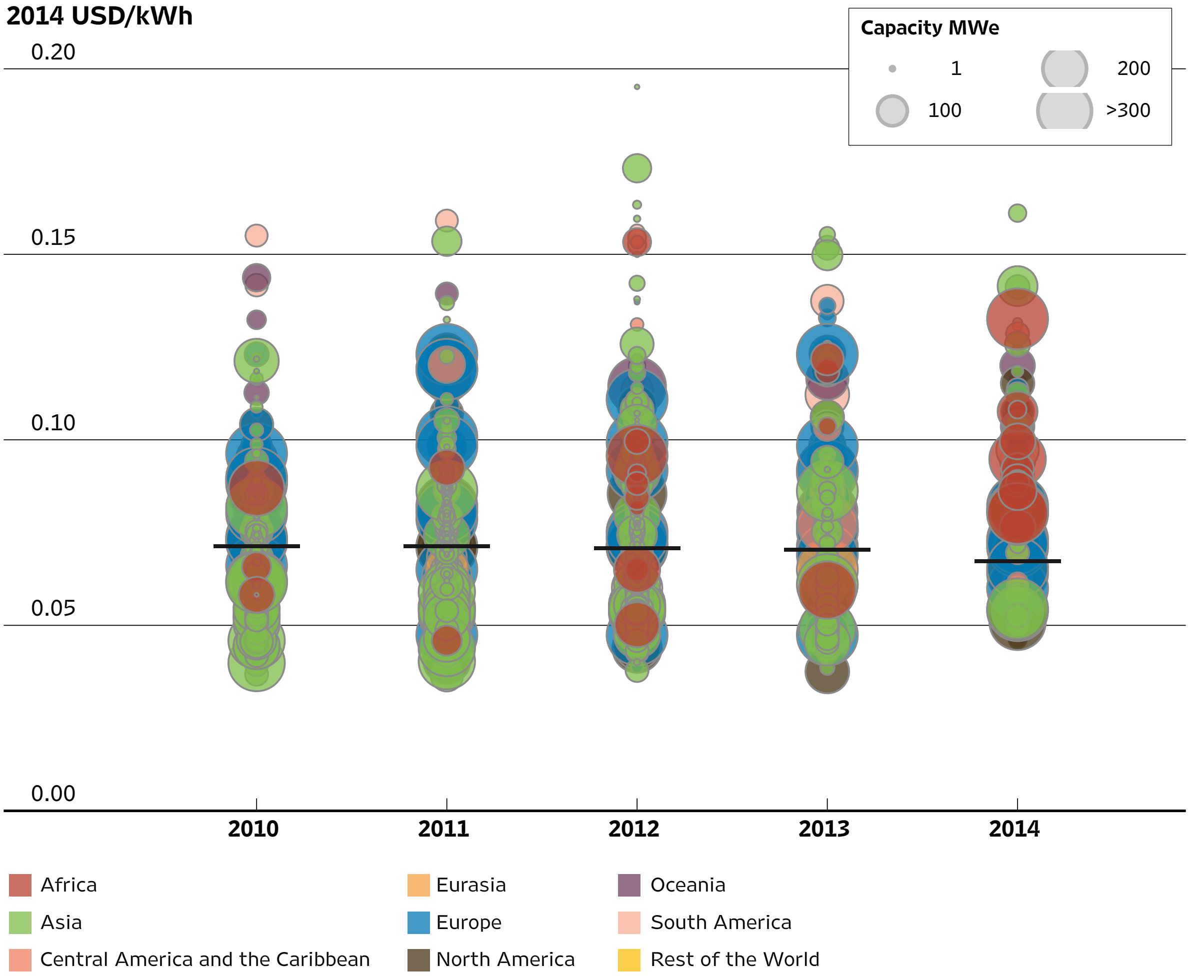
» Capital expenditure: The turbine cost has the greatest impact on the installed cost of a wind project. However, depending on the project, the infrastructure and grid connection costs can also contribute significantly to total costs.

» Weighted average cost of capital (WACC): This has an important impact on the LCOE calculations. The availability and cost of equity and debt, as well as their respective shares of total project funding and costs will determine the WACC.

» Operations and maintenance: Operational expenditures consist of both fixed and variable costs and can represent up to 20% to 25% or more of the total LCOE.

Based on the data and analysis presented in the earlier sections of this chapter, wind turbine costs in 2013 ranged from around USD 649/kW in China to around USD 1 360/kW (>95m) in developed countries. Wind turbine prices in 2014 are likely to be slightly higher than their 2013 values, in the range of USD 1 127/kW to USD 1 376/kW in developed countries.

**Figure 4.18: The global LCOE and weighted average of commissioned and proposed large wind farms (>5 MW), 2013 and 2014**



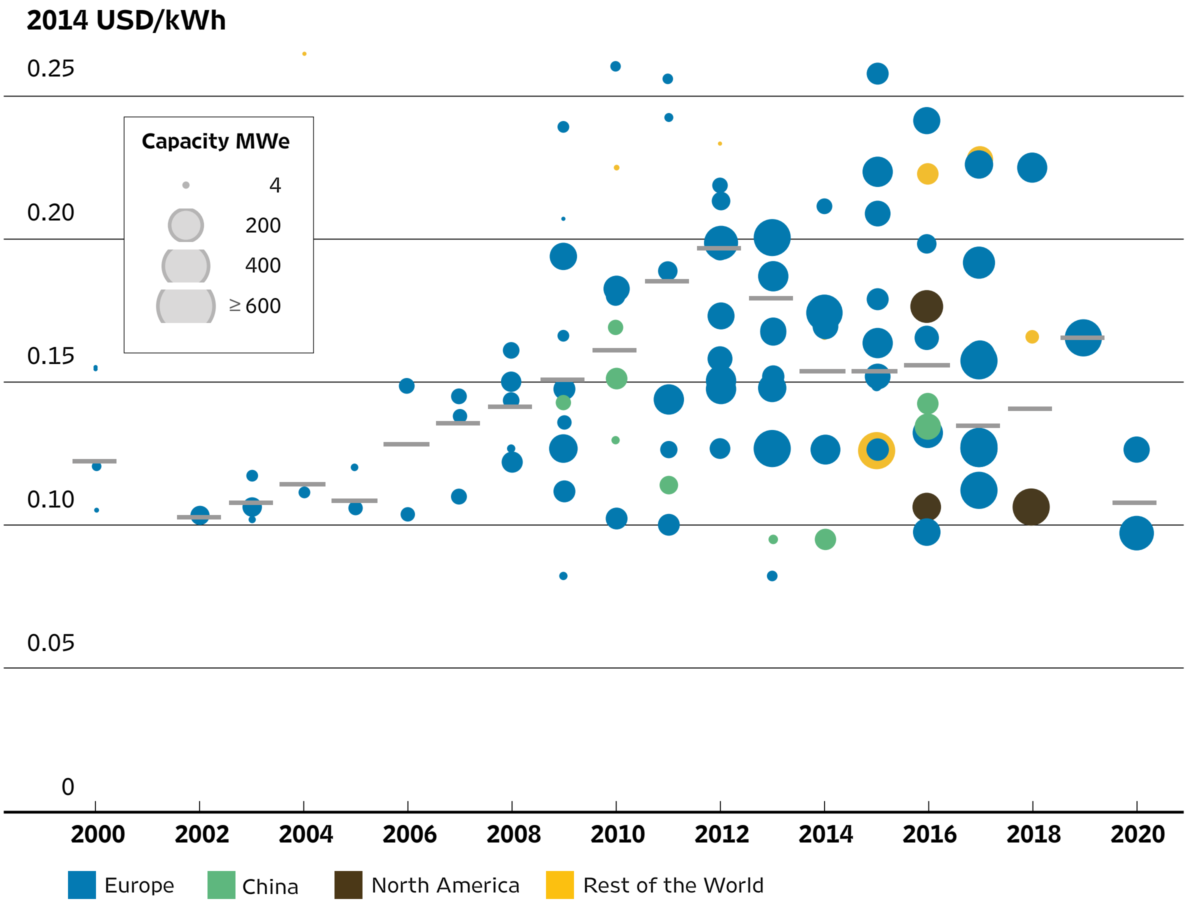

*Source*: IRENA Renewable Cost Database

Total installed costs continued to decline between 2010 and 2014, following lower wind turbine prices, with initial data for the United States suggesting that total installed costs have declined from around USD 1 993/kW in 2012 to around USD 1 675/kW for the projects with data for 2013, but may be closer to USD 1 780/kW for a more representative sample of projects in 2014 and early 2015. Similar cost reductions have occurred in other OECD wind markets.

Figure 4.17 presents the LCOE of wind power by region and country in 2013 and 2014, assuming a 7.5% or 10% WACC. As can be seen, the weighted average LCOE by country or region range from USD 0.06/kWh in China to USD 0.12/kWh in Other Asia. North America, with a weighted average LCOE of USD 0.067/kWh in 2013 and 2014, has the lowest average LCOE after China. Eurasia (USD 0.076/kWh), Europe (USD 0.08/kWh) and India (USD 0.08/kWh) had slightly higher LCOE structures than China and North America, but still have a range of very competitive projects. With weighted average LCOE of between USD 0.09 and USD 0.095/kWh Central and South America, Oceania and Africa are not far behind. The LCOE of individual projects typically spans a wide range within a region, but it is now common to see wind energy projects being built that deliver electricity at USD 0.05/kWh in 2014, with some projects perhaps achieving USD 0.04/kWh.

The combined effect of installed cost declines, technology improvements and deployment patterns on the LCOE of wind is presented in Figure 4.18. The global weighted average LCOE of wind has fallen by 7% between 2010 and 2014, which is slightly lower than the average decline in total installed costs over this period. In China and India, the range of wind power project LCOE is narrower

## FIGURE 4.19: THE LCOE AND WEIGHTED AVERAGES OF COMMISSIONED AND PROPOSED OFFSHORE WIND PROJECTS, 2000 TO 2020




*Source*: IRENA Renewable Cost Database

than in other regions, reflecting the narrower range of installed costs and capacity factors. In contrast, the wide range of project LCOE in other regions reflects the wider range of installed costs and, in particular, the wide range of capacity factors from 25% to 50%.

The global average LCOE of wind is driven by cost developments in China, given that China has been accounting for just under half of new capacity added for a number of years. As a result, although some regions have seen quite rapid LCOE declines, the global average has only declined by about 8% since 2009 and 7% since 2010, due to the fact that the very low project development costs in China and India have not fallen as rapidly as in other regions with higher cost structures. However, when examining the developments outside of Asia, a very different pattern emerges. For the rest of the world, excluding wind farm developments in Asia, the LCOE of wind has fallen by 16% between 2010 and 2014, despite the growth of deployment in new markets with higher cost structures than the average. Recent declines in the LCOE of wind power have been modest, but this has to be compared to just how competitive onshore wind is today. Most wind power projects developed today fall within or below the range of fossil fuel-fired electricity generation costs of USD 0.045 to USD 0.14/kWh, and wind is now one of the most competitive sources of electricity generation.

The LCOE of offshore wind has risen through time as total installed costs increased with greater distances from shore, increased water depths and increasingly complex projects (Figure 4.19). However, the LCOE of recent projects has stabilised in the USD 0.12 to USD 0.20/kWh range for most projects. The expectation is that in the future large projects planned to 2020 will achieve lower average costs. However, it remains to be seen if these ambitious projects can deliver on their proposed cost structure.