ENERGY TECHNOLOGY SYSTEMS ANALYSIS PROGRAMME

International Renewable Energy Agency

Wind Power

Technology Brief

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international cooperation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

About IEA-ETSAP

The Energy Technology Systems Analysis Programme (ETSAP) is an Implementing Agreement of the International Energy Agency (IEA), first established in 1976. It functions as a consortium of member country teams and invited teams that actively cooperate to establish, maintain, and expand a consistent multi-country energy/economy/environment/engineering (4E) analytical capability.

Its backbone consists of individual national teams in nearly 70 countries, and a common, comparable and combinable methodology, mainly based on the MARKAL / TIMES family of models, permitting the compilation of long term energy scenarios and in-depth national, multi-country, and global energy and environmental analyses.

ETSAP promotes and supports the application of technical economic tools at the global, regional, national and local levels. It aims at preparing sustainable strategies for economic development, energy security, climate change mitigation and environment.

ETSAP holds open workshops twice a year, to discuss methodologies, disseminate results, and provide opportunities for new users to get acquainted with advanced energy-technologies, systems and modeling developments.

Insights for Policy Makers

Wind, or the kinetic energy of air flow, has been used in transport, industry and agriculture for thousands of years. The rise of modern wind turbines, which harness this energy and turn it into electricity, is a story of scientific and engineering skill coupled with strong entrepreneurial spirit. Wind power continues to expand worldwide, reflecting the reduced cost of turbines, expanding policy support and growing investor recognition of the positive characteristics of wind generation. In 2014, wind power reached a more than 3% share of the world's electricity supply. In 2015, China led this development with capacity additions of 32.9 gigawatts (GW), followed by the United States (8.6 GW) and Germany (4.9 GW). By the end of 2015, more than 434 GW of wind power capacity had been installed worldwide (WWEA, 2016).

Efforts are being made to improve the economic efficiency of wind power facilities. Wind farms are being built to maximise energy production and to minimise capital and operating costs, while remaining within the constraints imposed by the site. Once the site constraints are defined, "micro-siting" is performed to optimise the layout design. For most wind power projects, the economics depend far more on the fluctuating costs of energy production than on infrastructure costs. For both onshore and offshore facilities, the dominant parameter for layout design is the maximisation of energy production (as opposed to, for example, whether turbines are located close to one another for ease of maintenance or grid connection).

The recent development of large onshore wind farms has reduced the number of remaining sites with good wind resource potential, especially in more densely populated areas of Europe. Some European countries are developing offshore wind power by taking advantage of the relatively shallow seabed adjoining the continent. Because wind speeds at sea are generally higher than those on land, and there are fewer obstacles at sea which can cause turbulence, offshore wind power is more efficient than onshore wind power. However, because offshore wind is an emerging sector and faces unique challenges related to working at sea, it has higher construction and operation costs and hence a higher overall generation cost. Nevertheless, offshore wind generation is expanding. By the end of 2014, cumulative global offshore wind capacity was approximately 8.8 GW (GWEC, 2015).

Like most renewable energy sources, wind power is capital-intensive, and reductions in capital costs are important for realising wind energy projects. Although wind operations have no fuel cost, reducing the operation and maintenance (O&M) costs is key to improving the economics of wind power. Some countries have introduced financial supports such as feed-in tariffs to secure greater income and to reduce investor risk. The levelised cost of electricity (LCOE) for typical wind farms in 2014 was in the range of USD 0.06–0.10 per kilowatt-hour (kWh) for onshore wind to USD 0.12-0.21 per kWh for offshore wind. The best wind projects in the world are consistently providing electricity for USD 0.05 per kWh, without financial support (IRENA, 2015a).

Small wind turbines (with a rated power of less than 50-100 kilowatts (kW), as defined by the International Electrotechnical Commission and some countries) use mature technology and have a relatively simple structure, making them relatively straightforward to maintain. However, they are usually less efficient than large turbines. Generally, small turbine technology is used for stand-alone electricity systems and is suitable for rural electrification where a grid connection is not available or required. Wind-diesel hybrid systems can be effective in small or off-grid areas, making use of existing conventional diesel-generating infrastructure while reducing fuel and fuel-transport costs and improving the stability of power supply.

Technological innovation is a key factor for future wind power development. Although the technology is relatively mature, further room exists for development. Pilot facilities, for example, are increasingly incorporating energy storage and information technology systems, such as two-way telecommunications between a control centre and remote wind plants, to control power output. To further strengthen wind power development, policy makers should be aware of the latest technological advances.

HIGHLIGHTS

- **Process and Technology Status –** A wind turbine's blades convert kinetic energy from the movement of air into rotational energy; a generator then converts this rotational energy to electricity via electromagnetic induction. The wind power that is generated is proportional to the dimensions of the rotor and to the cubing of the wind speed. Theoretically, when the wind speed is doubled, the wind power increases by a factor of eight. The main factors of the output power are the wind speed and the length of the blades. The size of wind turbines has continued to increase, and the average capacity of new grid-connected onshore turbines rose from 0.05 megawatts (MW) in 1985 (EWEA, 2011) to 2.0 MW in 2014 (Broehl, Labastida and Hamilton, 2015). The largest commercially available turbines to date reach 8.0 MW each, with a rotor diameter of 164 metres.

  The three major elements of wind generation are the turbine type (vertical/horizontal-axis), installation characteristic (onshore/offshore) and grid connectivity (connected/stand-alone). Most large wind turbines are up-wind horizontal-axis turbines with three blades. Most small wind turbines are also horizontal-axis. Innovative designs for vertical-axis turbines are being applied in urban environments, particularly in China. With aerodynamic energy loss of 50-60% at the blade and rotor, mechanical loss of 4% at the gear, and a further 6% electromechanical loss at the generator, overall generation efficiency is typically 30-40% at wind power facilities.

- **Costs –** Despite increases or fluctuations in some cost components, the Levelised Cost of Electricity (LCOE) for wind power has not increased. In some countries where wind conditions are good and where conventional electricity generation costs are high, onshore wind power is cost-competitive with new conventional power plants. The weighted average LCOE for wind power in 2014 was between USD 0.06 per kWh in China and USD 0.12 per kWh in the rest of Asia. The weighted average LCOE in the rest of the world is also within this range, while the best wind projects provide electricity for USD 0.05 per kWh without financial support.

  Installation and O&M costs are the main elements of the electricity cost for wind power. For onshore wind, turbine costs dominate, with the rotor blades and tower accounting for nearly half of the total cost of a turbine. After peaking in 2009, turbine prices have declined due to market competition and lower commodity prices. Preliminary turbine price projections for 2014 are USD 676 per kW in China and between USD 931 and USD 1 174 per kW in the United States (IRENA, 2015a). Grid connection costs – including electrical work, electricity lines and connection points – vary depending on the site specifics and on the network or regulatory regime. The main construction cost is for the turbine foundation. Other capital costs include costs for development, engineering and licensing.

For onshore wind, the regional weighted average installed cost in 2014 was between USD 1 280 per kW and USD 2 290 per kW. O&M typically accounts for 20-25% of the LCOE for onshore wind, ranging from USD 0.005 per kWh to USD 0.025 per kWh. Grid connection and construction cost shares are higher for offshore wind than for onshore wind. For a typical offshore wind system in 2014, total installed costs were in the range of USD 2 700-5 070 per kW, and the LCOE was in the range of USD 0.10-0.21 per kWh.

Comparison of capital cost breakdown for typical onshore and offshore wind power systems

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

Major factors in reducing the LCOE for wind power are larger turbines and large-scale installation of wind farms. Because larger turbines harness strong wind at higher altitudes, they produce more electricity per unit of installation area, thereby reducing both the number of turbines and the land area needed per unit of output. Large-scale installation of wind farms increases the economies of scale and reduces costs for transport, installation and O&M. Reducing the weight of rotor blades has great potential for reducing turbine costs, as do improving the aerodynamic efficiency and material selection. Carbon fibre is a major candidate for reducing weight and increasing aerodynamic efficiency, but it remains expensive.

The costs of grid connection depend greatly on the site configuration. For offshore wind, the potential for reducing the grid connection cost is higher because of the long-distance transmission line needed to connect to the electricity network on land. One option for reducing costs is to use a high-voltage direct current (HVDC) connection. For onshore wind, smart integration of decentralised generation into local and regional grids has the potential to lower system costs substantially, reducing the need for large power networks.

- **Potential and Barriers –** Because of the global availability of the resource, wind power has huge potential. An estimated 95 terawatts (TW) or more remains to be developed onshore, and offshore wind has an even larger resource potential, as well as less of an environmental impact. Some countries have introduced financial supports for wind power, such as feed-in tariffs, to secure income and to reduce investor risk. Critical barriers to wind power include long and unpredictable waiting times for permitting and authorisation. To reduce such risks, policy makers can introduce appropriate regulatory schemes and set a specific, predictable schedule for the administrative process. Environmental impacts associated with wind development include concerns about noise and visual impact as well as impacts on migratory species. Communication with the public is key to mitigating these concerns. Developers need to communicate with stakeholders based on proper environmental impact assessments. Proper siting of wind farms can also mitigate visual impacts and impacts on migratory species. Involvement of local communities, particularly through local ownership, is key for high social acceptance.

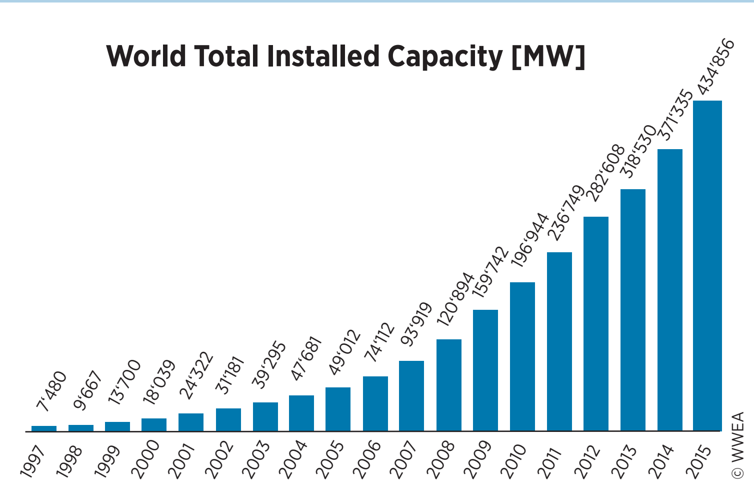
An important issue for managing power systems that integrate large amounts of wind energy is the variability of the power output. One way to achieve a higher share of wind generation in a grid system is to operate wind turbines or wind farms using integrated transmission systems and power output prediction systems, including weather forecasting. The development of standards and certifications can help to improve the performance of small wind systems, especially in developing countries.

Introduction

Following the invention of the electric generator, engineers began harnessing wind energy to produce electricity. Wind power generation succeeded in the United Kingdom (UK) and the United States in 1887-1888. However, modern wind power is said to have started in Denmark, where horizontal-axis wind turbines were built in Askov in 1891, and a 22.8 metre wind turbine for electric generation started operation in 1897. Since then, wind generation has spread from Europe and the United States to the world. Most new wind power projects have turbine capacities of around 2 MW onshore and 3-5 MW offshore.

Global installed wind generation capacity (including both onshore and offshore capacity) has increased nearly 50 times in the past two decades, from 7.5 GW in 1997 to more than 371 GW in 2014 (see figure 1) (WWEA, 2015a). Denmark, long a leader in wind power generation, installed the world's first offshore wind farm, consisting of 11 wind turbines of 0.45 MW each, in 1991 (Carbon Trust, 2008). By

Figure 1: World installed wind power capacity, 1997-2015



Source: WWEA, 2015a ; IRENA, 2015b

the end of 2014, the total installed offshore wind capacity worldwide was 8.8 GW (GWEC, 2015).

At the end of 2015, the top five countries in total installed wind power capacity were China (148 GW), the United States (74 GW), Germany (45 GW), India (25 GW) and Spain (23 GW). Nearly 64 GW of capacity was added worldwide in 2015, with the top additions in China (33 GW), the United States (8.6 GW), Germany (4.9 GW), Brazil (2.7 GW) and India (2.3 GW). The global capacity growth rate in 2014 was 14% (WWEA, 2016).

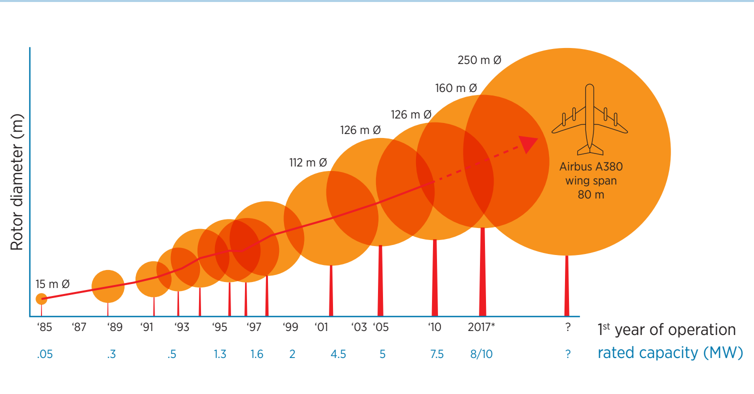
Wind Technologies and Performance

Wind power and basic elements of wind turbines

Wind – the movement of the air – is the result of temperature differences in different places. Uneven heating results in a difference in atmospheric pressure, which causes the air to move. The kinetic energy of the moving air (or wind) is transformed into electrical energy by wind turbines or wind energy conversion systems. The wind forces the turbine's rotor to spin, changing the kinetic energy to rotational energy by moving a shaft which is connected to a generator, thereby producing electrical energy through electromagnetism.

Wind power is proportional to the dimensions of the rotor and to the cube of the wind speed. Theoretically, when the wind speed doubles, the wind power increases eight times. The main factors of the output power are the swept area (related directly to the length of the blades) and the wind speed. Over time, the size of wind turbines has increased continually (see figure 2). In 1985, turbines had a rated capacity of 0.05 MW and a rotor diameter of 15 metres (EWEA, 2011).

Figure 2: Growth in capacity and rotor diameter of wind turbines, 1985-2016



* *expected*

Based on EWEA (2011) and subsequent market trends

The largest commercially available wind turbines to date reach 8.0 MW each, with a rotor diameter of 164 metres. The average capacity of newly installed wind turbines has increased from 1.6 MW in 2009 to 2.0 MW in 2014 (Broehl, Labastida and Hamilton, 2015).

Wind power systems are categorised primarily by the **grid connection** (connected/stand-alone), **installation characteristic** (onshore/offshore) and **wind turbine type** (vertical/horizontal-axis). The specific system configuration is determined mainly by the wind condition (especially wind speed), land availability (or where the plant is sited), grid availability, turbine size and height, and blade size.

For vertical-axis turbines, used primarily for small generation capacities, the axis of rotation is vertical to the wind flow/ground. The turbines are independent of wind direction, and some can generate electricity at both low wind speeds and low noise levels, making them particularly suited to urban areas. In addition, heavy components, such as the generator, can be mounted at ground level. This results in easier maintenance and lighter-weight towers and is expected to contribute to the stability of floating foundations for offshore wind. However, vertical-axis turbines are less efficient at turning wind energy into mechanical power, and some require a starting device. Moreover, it is difficult to control the rotation speed.

Horizontal-axis turbines are being used commercially all over the world. The rotating shaft is mounted parallel to the wind flow/ground, and the turbines can have two types of rotors: up-wind and down-wind. The advantage of up-wind turbines is that they are hardly influenced by the turbulence caused by the tower. However, a yaw mechanism is needed to align the turbine with the prevailing wind. Meanwhile, down-wind rotors for large turbines are emerging in Japan. Because they can sufficiently catch winds blowing upwards, they can be a promising technology for improving the stability and safety of floating offshore wind facilities.

The basic elements of the wind power system are the blades, the rotor hub, the rotor shaft, the nacelle, the rotor brake, the gearbox, the generator and controller, the tower and the transformer.

The **blades** capture and convert the wind's energy to rotational energy. The number of blades also influences the structure and ability of wind turbines. Typical large turbines are up-wind, horizontal-axis turbines with three rotor blades. Because of the better balance of gyroscopic forces, most modern wind turbines use three rotor blades; fewer blades would mean slower rotation, requiring more from the gear box and transmission. Modern blades are typically made from reinforced fibreglass and are shaped aerodynamically, similar to the profile of aircraft wings. Although carbon fibre-reinforced plastic is a stronger material, the cost remains high. Smaller blades can be made from (laminated) wood, which has strength and weight advantages.

The **rotor hub** transfers the rotational energy to the rotor shaft, which is fixed to the rotor hub. The other end of the rotor shaft is connected to the **gearbox**, which changes the low rotating speed from the blades to a high rotating speed for input to the generator. Direct-drive systems without a gearbox are also available, and their market share is growing in Europe and China. Advantages of gearless turbines include their compact structure, lower risk of breakdown and simpler maintenance.

Wind turbines incorporate a control system to prevent excessive rotation speeds in high wind, which could otherwise break the blades or other components. The two methods for controlling the speed of the blade, or delivering the power output from the blade to the rotating shaft, are pitch control and stall control. A pitch control system actively adjusts the angle of the blades to the wind speed. The rotor hub includes a pitch mechanism, and the control system features a brake. A stall system decreases the rotational speed by using the aerodynamic effects of the blades when the wind speed is too high, lowering the efficiency to protect the turbine from damage.

The high-speed rotating shaft connected to the gearbox forces the shaft of the **generator** to rotate, converting the rotational energy to electricity through the use of electromagnetic induction. Typically, two types of generators are used with wind turbines: induction (or asynchronous) generators, which usually require excitation power from the network; and synchronous generators, which can start in isolation and produce power corresponding directly to rotor speed.

The rotor shaft, rotor brake, gearbox and generator components are housed within a **nacelle**, which is directly connected to the blades at a high elevation and is one of the main structures of the wind generating system. To rotate the nacelle so as to align the wind turbine with the direction of wind, the wind turbine has a mechanism called a yaw system. Modern large systems are installed with an active yawing system which is controlled by an electric control system with a wind direction sensor.

The rotor blades, rotor hub and nacelle are supported by and elevated on a **tower**. The tower height is determined by the rotor diameter and the wind conditions of the site. Many towers are made from steel tubes which allow access to the nacelle inside the tower, even in bad weather. Newer tower types include the "space frame tower", which improves the logistics of installation and transport (GE, 2014). In large wind turbines, the towers contain electric cables, a ladder or lift for maintenance, and occasionally a control system.

The **control system** has three main functions: controlling turbines (*e.g.* the rotating speed and yaw direction), monitoring and collecting operational data (*e.g.* on weather conditions, or output/input data for the system, including electricity voltage and current, rotating speed, yaw direction, vibration frequency of blade and nacelle) and communicating with operators.

A **transformer** is usually placed at ground level and transforms the electricity from the generator to the required voltage on the grid.

The aerodynamic loss of energy at the blade/rotor is about 50-60%, the mechanical loss of energy at the gear is 4% and the electromechanical loss at the generator is 6%. Overall, the efficiency of wind power generation is 30-40% (NEDO, 2013).

Onshore and offshore wind farms

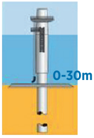
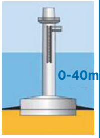
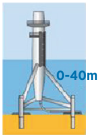
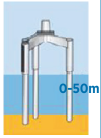
In general, a power generating facility which contains a number of wind turbines is called a "wind farm". The basic elements of the wind farm are wind turbines, monitoring facilities, substations and transmission cables. If they are offshore, wind farms also need port facilities for maintenance.

Recently, particularly in Europe, offshore wind farms have gained higher market shares as a result of supportive government policies, inspired by the idea that offshore wind is faster and more stable than onshore wind. However, the capital and maintenance costs of offshore wind farms are several times higher than for onshore wind farms.

The noticeable difference between onshore and offshore wind farms is the foundation. An onshore wind turbine stands on a concrete foundation, whereas offshore turbines have their foundations in the water (floating) or on the sea bed (fixed-bottom). Fixed-bottom foundations can have varying types of structures: monopile, jacket, tripod, gravity-based and suction bucket (see figure 3). The monopile structure is the simplest and hence the most common, but can only be used in shallow water (up to 30 metres in depth) (IEA, 2013).

Floating foundations are typically used at depths exceeding 50-60 metres, because the cost of fixed-bottom foundations becomes prohibitive in deeper waters. Floating structures are currently in the demonstration phase. Offshore wind farms are designed to withstand elements of the severe marine environment,

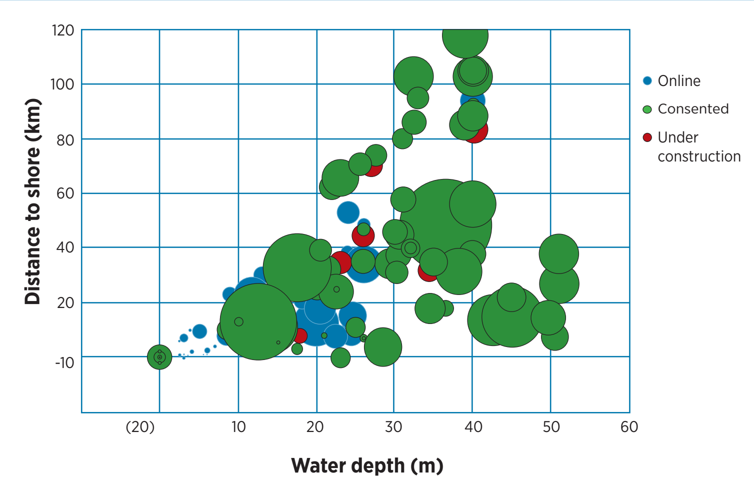
Figure 3: Summary of the different fixed-bottom foundations available for offshore wind turbines

	High-rise pile cap	Monopile	Concrete gravity base	Tripod	Tri-pile	Jacket	Suction Bucket
Design							
Example	**Sakata (JP)**	**Kamisu (JP)**	**Choshi (JP)**	**Longyuan Rudong intertidal (CH)**	**Bard Off-shore 1 (DE)**	**Kitakyushu (JP**	**Dogger Bank (UK)**
Pros	• Cap protects against maritime collisions	• Simple design	• Cheap • No drilling	• More stable than monopile	• Can be installed by traditional jack-up barge	• Stability • Light	• Less steel • No drilling
Cons	• Limited water depth • Complex manufac-turing	• Diameter increases signifi-cantly with depth • Drilling	• Seabed prepara-tion required	• More complex installation	• Cost	• Cost	• Not applicable to hard seabeds
Comments	• Common in onshore industry	• Most wide-spread foundation type • Limitations in water depth	• Currently only used in shallow water	• High production costs due to complex structure and weight	• High production costs due to complex structure and weight	• Com-mercially attractive > 35m due to their flexibility and low weight (40–50% less steel than monopiles)	• Yet to be deployed at scale

Source: Carbon Trust, 2014

such as waves and seawater, and have additional operational requirements, such as access to the turbine. Efforts to reduce maintenance costs therefore are critical. Figure 4 shows the water depth and distance to shore of offshore wind farms.

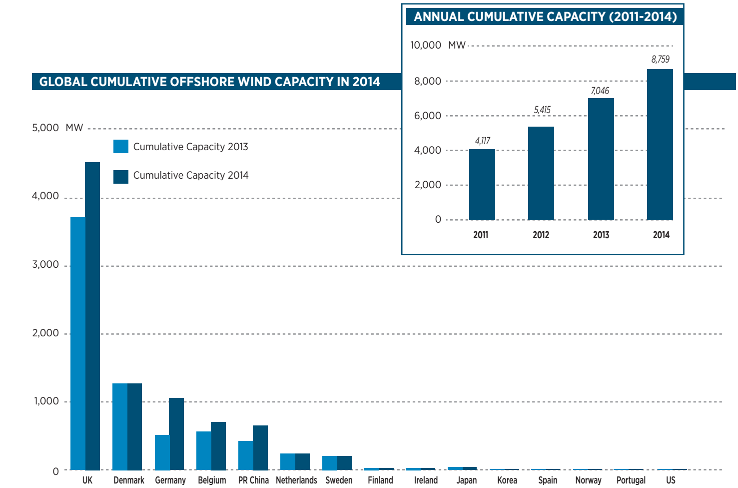
Figure 4: Average water depth, distance to shore and size of offshore wind farms (online, under construction and consented), end-2014



Source: EWEA, 2015

In 2014, the global installed capacity of offshore wind generation was 8.8 GW, with more than 90% of the installations in Europe (see figure 5).

Figure 5: Global cumulative installed capacity of offshore wind energy, 2014



	UK	Denmark	Germany	Belgium	PR China	Netherlands	Sweden	Finland	Ireland	Japan	Korea	Spain	Norway	Portugal	US	
Total 2013	3,680.9	1,271	520	572	429	247	212	26	25	50	5	5	2	2	0.02	**7,046**
New 2014	813.4	0	529	141	229	0	0	0	0	0	0	0	0	0	0	**1,713**
Total 2014	4,494.3	1,271	1,049	713	658	247	212	26	25	50	5	5	2	2	0.02	**8,759**

Source: GWEC, 2015

Small wind turbines

There is no internationally agreed upon definition of small wind turbines. However, the International Electrotechnical Commission (IEC) defines a small wind turbine as having a rotor swept area of less than 200 square metres, equating to a rated power of some 50 kW. Other national organisations in major small wind markets such as China, the United States and the UK define a small wind turbine as having a rated power of less than 100 kW. Until around 1980, most wind turbines had a capacity of less than 100 kW.

Small wind turbines generally require a higher capital cost per kW and have a lower efficiency (load factor) compared to big wind farms. However, small wind turbines are beneficial for electricity storage or off-grid electric supply in rural/

grid-isolated areas where expensive diesel generators are being used. Small wind turbines have been used mainly for off-grid electricity generation and water pumping in isolated areas.

The horizontal-axis small wind turbine is a proven technology which usually uses permanent magnet generators and direct-drive technology. It continues to dominate the small wind turbine market. In 2011, 74% of manufacturers supplied the horizontal-axis turbines, 18% supplied vertical-axis turbines and 6% tried to provide both types. The average horizontal-axis model was estimated at 10.8 kW in capacity, while the average vertical-axis model was 7.4 kW (WWEA, 2013). Innovative vertical-axis turbine designs are being used mainly in urban environments, particularly in China (GlobalData, 2015).

A major challenge in installing a small wind turbine is assessing the wind resource. The resource assessment process is similar to that for larger turbines; however, it is expensive due to the high cost of management tools and long-term measurement efforts. Generally, small wind turbines are installed as stand-alone units, not as wind farms, which dramatically increases the planning costs per unit installed.

The height of the tower is also a key factor for small wind turbines. To reduce the negative effects of turbulence caused by surrounding obstacles, a taller tower is better; however, it has a higher cost. Most small wind turbines are below 30 metres in height. Further innovation to reduce costs and to improve the efficiency of turbines at lower heights are key challenges for the development of small wind technology.

As of the end of 2013, more than 755 MW of small wind power capacity was installed worldwide, with 41% of the facilities sited in China, 30% in the United States and 15% in the UK (WWEA, 2015b).

Current Costs and Cost Projections

Even though wind power has several cost components that fluctuate or are increasing – especially related to the installation cost, such as the rising costs of materials, labour and civil engineering, as well as the costs of scaling up and improving wind turbines – the electricity cost, or Levelised Cost of Electricity (LCOE), for wind power has not increased. In some countries where wind conditions are good and where conventional generation costs are high, onshore wind generation is cost-competitive with new conventional power plants.

The LCOE for wind power consists primarily of capital costs, operation and maintenance (O&M) costs, and expected annual energy production. The capital cost includes the wind turbine costs, grid connection costs, construction costs, and planning and miscellaneous costs (see table 1).

Table 1: Capital cost comparison for typical onshore and offshore wind power systems

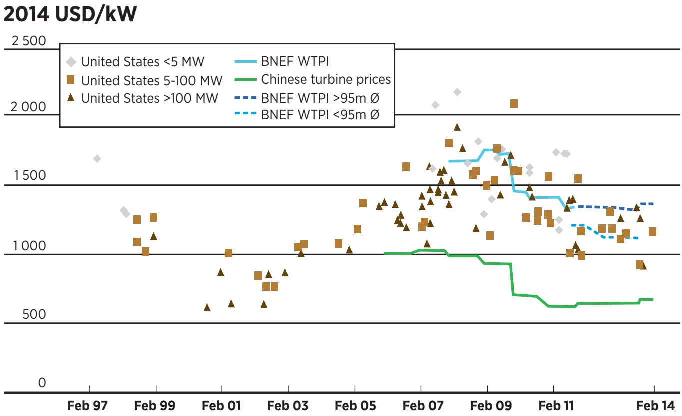
Cost share of: (%)	Onshore	Offshore
Wind turbine	64-84	30-50
Grid connection	9-14	15-30
Construction	4-10	15-25
Other capital	4-10	8-30
Capital cost (USD/kW)	1 280-2 290	2 700-5 070

Source: IRENA, 2015a

For onshore wind systems, turbine costs dominate, with the rotor blades and tower accounting for nearly half of the total cost of a turbine. After the 1980s, when wind turbines entered a stage of mass production, prices declined (see figure 6). However, the rising price of commodities, such as steel and copper, led turbine prices to increase continuously between 2004 and 2009. After peaking in around 2009, turbine prices again declined due to market competition and lower commodity prices. In 2014, preliminary wind turbine prices were USD 676 per kW in China and USD 931-1 174 per kW in the United States (IRENA, 2015a).

Grid connection costs – including electrical work, electricity lines and connection points – vary depending on the site specifics and on the network or regulatory regime. The cost of the foundation is the main element of the construction cost. Other capital costs include development and engineering costs, licensing

Figure 6: 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.

Source: IRENA, 2015a

procedures, and consultancy and permitting fees. The regional weighted average installed costs for onshore wind in 2014 were between USD 1 280 and USD 2 290 per kW (IRENA, 2015a).

The cost breakdown is different for offshore wind systems. Although turbine costs are the largest part of the total installed cost of onshore wind power, for offshore wind they are typically less than half. Instead, the grid connection and construction cost shares are higher. Total installed costs for offshore wind systems in 2014 ranged between USD 2 700 per kW and USD 5 070 per kW (IRENA, 2015a).

For small wind power systems, the installed cost is relatively high. For example, the average installed cost of a small wind system in 2013 was USD 5 873 per kW in the UK and USD 6 940 per kW in the United States (WWEA, 2015b).

The O&M costs of wind power are relatively low compared to thermal power plants because of zero fuel costs. However, O&M costs still account for 20-25%

of the LCOE for wind power, and include the costs for insurance, periodic and unscheduled maintenance, spare parts, grid connection and administration (EWEA, 2009). Because the possibility of component failures increases year by year, O&M costs tend to increase as well. The O&M cost of offshore wind is higher than for onshore wind because of higher costs for accessing and maintaining the site at sea. The O&M cost of typical onshore wind is relatively lower in North America than in Europe (see table 2) (IRENA, 2015a). Meanwhile, the O&M cost of offshore wind in Europe is likely to be double that of onshore (ECN, 2011). However, it should be noted that the availability of data for O&M costs is not as rich as that for installed costs.

Table 2: Comparison of O&M cost in North America and Europe

Region	Onshore	Offshore
	USD/kWh	
North America	0.005-0.015	–
Europe	0.013-0.025	0.027-0.054

Source: IRENA, 2015a and ECN, 2011

The LCOE for wind power varies depending on the quality of the wind resource, the selection of technology and the characteristics of the site. Generally speaking, the wind speed offshore is higher than on land, so offshore wind farms tend to be more efficient than onshore wind farms. However, this efficiency gain only partially offsets the higher investment costs for offshore wind, so the LCOE for typical offshore wind farms in 2014 was higher than for onshore wind farms (see table 3). The best wind projects in the world are consistently providing electricity for USD 0.05 per kWh, without financial support (IRENA, 2015a).

Table 3: Comparison of LCOE for typical onshore and offshore wind power facilities, 2014

	Onshore	Offshore
LCOE (USD/kWh)	0.06-0.12	0.10-0.21

Source: IRENA, 2015a

Cost reduction potential

The main ways to reduce the LCOE for wind power are larger turbines and large-scale installation of wind farms. Because larger turbines harness strong wind at higher altitudes, they produce more electricity per unit of installation area, thereby reducing both the number of turbines and the land area needed per unit of output. Large-scale installation of wind farms increases the economies of scale and reduces costs for transport, installation and O&M. Optimally decentralised installation of wind power systems without long connection lines or electricity network upgrades may reduce grid costs.

Larger turbines help to reduce the LCOE for a low-wind-speed site and partially offset the higher cost of the turbines. Towers are a large part of the turbine cost and have matured as a technology, offering comparatively little cost-reduction potential without significant design innovations. One of the main ways to cut turbine costs is reducing the weight of rotor blades. Other key elements for cost reduction are aerodynamic efficiency and material selection. Cost-reduction potential could increase if carbon fibre becomes less expensive.

The costs of grid connection depend greatly on the site configuration and scale of each wind farm. Offshore wind has greater potential for reductions in grid connection cost because of the longer transmission lines needed to connect to the electricity network on land. One option for reducing offshore costs is the use of high-voltage direct current (DC) connections (reducing the transmission loss compared to the use of alternate current (AC) transmission). Other potentials for cost reduction include mass production, larger wind farms, and technology development, especially in materials.

Offshore wind is key for the further deployment of wind power, especially in Europe and Asia. As with onshore wind, a major part of the cost reduction potential is investment costs. Economies of scale, particularly scaling up turbine sizes, is a key issue for cost reduction. The introduction of larger turbines in UK waters resulted in an 11% decrease in the levelised costs of offshore wind projects from 2010 to 2014, ahead of projections. The cost of access to offshore wind sites tends to be high, and the share of logistics costs in the LCOE for offshore wind is higher than that for onshore wind. Improving logistics infrastructure in both the installation and operation stages is a potential means of reducing the LCOE. In addition, an inter-operator maintenance concept for offshore – *i.e.* the use of joint fleet and logistics infrastructure – offers further cost reduction potential (Fichtner and Prognos, 2013).

Potential and Barriers

Despite wide variation in the strength and speed of wind, the world's total wind energy resource is extremely large. One estimate suggests that using only 1% of the planet's land area for wind energy would be enough to equal roughly all power-generation capacity worldwide today (WEC, 2013). Offshore wind generation offers even greater resource potential, as well as less environmental impact, than onshore wind. The combined global potential of onshore and offshore wind is estimated to be at least 95 terawatts (TW) (WWEA, 2014). In rural areas in particular, small wind power has great possibilities for development. Wind-diesel hybrid systems can be effective in small or off-grid areas by making use of conventional diesel generating systems, reducing the costs of fuel and fuel transport, and improving supply stability.

Wind energy is emerging as a major power source alongside other renewable as well as conventional energy sources. European countries have led this trend, and the wind market has also grown rapidly in the United States, due mainly to policy support. More recently, China and India have entered the field, and many other countries are introducing wind generation as well. One assessment projects that global wind capacity will reach 750 GW in 2030 and 1 550 GW in 2030 (WEC, 2013)

As wind technology has matured, no major technical constraints remain in the generating system to limit expansion. The cost of wind generation is relatively low compared to other renewable power sources, and, under certain conditions, wind power is cost-competitive even without taking account of externalities like environmental and health factors. The three major barriers to wind power development relate to policy and regulation, the environment, and supply stability or grid integration.

Like other renewable energy sources, wind power is capital-intensive. Developers must spend large sums at the initial stage of development, mostly before operations begin. Long and unpredictable permitting and authorisation periods are a critical barrier in some countries. To reduce the investment risk, policy makers can introduce appropriate regulatory systems and set a specific, predictable period of time for the administrative process.

The environmental issues associated with wind power development include concerns about noise, visual impact and impacts on migratory species (such as birds and bats) from collisions during operation. Communication with the public is key to mitigating these concerns. Developers need to communicate with stakeholders based on proper environmental impact assessments. The recent development of aerodynamic turbine designs (*i.e.* efficiency improvement) has reduced operational noise. Proper siting and configuration of wind farms can help reduce concerns about visual impacts and impacts on migratory species. Involvement of local communities, in particular through local ownership, is key for high social acceptance.

Another critical issue is how to manage the stability of wind power output, especially for grid-connected systems. The Spanish experience offers useful lessons for managing higher shares of variable generation from wind power in the transmission system. Spain introduced the Control Centre for Renewable Energies, operated under the grid system operator, as well as a wind power output control system based on wind power forecasting.

For small wind turbines, most of the opportunity for continued reductions in manufacturing cost may come from economies of scale, as observed in China. The maintenance cost is linked to the quality of the equipment. Growing small wind markets should be supported by quality assurance, based on sound standards and certification processes. Development of standards and certifications will support better performance and improved safety of small wind systems.

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SUMMARY TABLE – KEY DATA AND FIGURES

Technical performance	Typical current international values and ranges		
Energy input / output	Air flow (wind) / Electricity		
Technologies	**Onshore wind**	**Offshore wind**	**Small wind**
Rotor size, m	~ 90	~ 150	
Typical size per turbine (capacity), kW	2 000	4 000	1.6
Total cumulative capacity, GW	24 (2001), 198 (2010), 368 (2014) (GWEC, 2015)		
Annual installed capacity, GW	6.5 (2001), 39.0 (2010), 51.5 (2014) (GWEC, 2015)		
Capacity factor, %	20-30 (China/India), 25-35 (Europe), 30-45 (North America)	40-50	
CO_2 emissions, gCO_{2eq}/kWh	Occurring during manufacturing only: 8-20		

Costs	Typical current international values and ranges (2014 USD)		
Typical cost breakdown	**Onshore wind**	**Offshore wind**	**Small wind**
Wind turbine	64-84%	30-50%	
Grid connection	9-14%	15-30%	
Construction	4-10%	15-25%	
Others	4-10%	8-30%	
Installed cost, USD/kW	1 280 – 2 290	2 700 – 5 070	3 100 – 4 400
Operation and maintenance cost, USD/kWh	0.005 – 0.025	0.027 – 0.054	0.01 – 0.05
LCOE, USD/kWh	0.06 – 0.12	0.10 – 0.21	0.15 – 0.35
Forecast	Global on-shore wind capacity 2030: 1990 GW, global off-shore wind capacity 2030: 280 GW (IRENA, 2016)		
	Global cumulative small wind capacity: 2 GW (2020) (WWEA, 2015)		

Disclaimer

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