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# Global status of wind power generation: theory, practice, and challenges

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**ABSTRACT**

The existence of environmental concerns and constraints has led to a much greater necessity for the development of renewable energy resources. Wind energy resources are one of the most promising avenues for renewable energy generation, and the field has experienced significant technological innovation and growth over the past few years. This paper reviews various issues related to wind-power generation resources. Current trends, over the last two decades, of increasing wind turbine sizes, rated power-generation capacity, efficiencies, and the actual size of wind farm facilities are projected to continue. It is theorized that the current global installed capacity of wind power generation may increase from the current generation of 540 (2017) to 5800 GW by 2050. Wind energy potential, in terms of vertical wind speed profile, mean wind-speed distribution, turbulence effects and gust, are discussed in detail in this paper. A decreasing trend in the cost of initial capital investment and the levelized cost of energy (LCOE), for both onshore and offshore wind-power generation developments, are projected to continue, although this is regionally and economy-size dependent. Key challenges have been identified for the development of wind power generation in developed and under-developed countries going forward. New approaches/developments in the field and avenues for further research or actions that can be undertaken are also outlined in this paper. Materialization of such lines of actionsmay lead to an increase in global wind energy from its current level of around 4% of the electricity generation mix to roughly 40%.

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## 1. Introduction

The increase in global energy demands, escalating energy prices, and growing environmental concerns with regard to conventional sources of energy based on fossil fuels has emphasized the need to move energy production to renewable sources. Wind flow, at certain velocities, is a plentiful resource for the generation of pollution-free electricity. Electricity from wind energy is generated by wind turbines which harness the kinetic energy of the wind, providing the motive force to turn turbine blades via a rotor drive shaft (Farooq and Kumar 2013). The shaft connects the blades to gears in a generator inside the turbine, which turn with the movement of the blades (Maczulak 2009). The rotor diameter and size of the blades are crucial factors. Blades with larger sizes can cover a greater area, and therefore convert more electrical energy from the kinetic movement of the wind (Şahin 2004).

Wind turbines are broadly categorized by the directional rotation of the main rotor shaft, which can be either horizontal or vertical. This depends upon the direction of wind flow; i.e. upwind or downwind, and the actual location of the turbine, i.e. onshore or offshore (Arshad and O'Kelly 2013). Modern commercial wind turbines have horizontally aligned rotor shafts; the rotor blades rotate in a vertical plane. The rotor diameter and wind speed are the main input parameters for the rated power-generation capacity of a wind turbine (IRENA, 2012). Theoretically, if the wind speed doubles its energy yield increases eightfold.

The economic feasibility of wind power generation is the primary driver for site selection for developing wind energy parks. Apart from the level of wind at the site, other factors include: accessibility of transmission lines; the expected value of energy production; the cost of acquiring the land, and; environmental impact during operations (Sheikh 2010). Between 2000 and 2017, the approximate global wind-power capacity doubled every three years, reaching a total power generation level of 540 GW by the end of 2017(GWEC 2017; WWEA, 2016). During 2017, China, the USA and Germany were the industries' top players in terms of capacity installations and enhancements (GWEC 2017). One of the more optimistic scenarios foresees wind energy resources contributing almost 41% to global installed electricity generation capacity by 2050 (GWEC 2017). The market is still dominated by onshore wind farms, while significant wind resources are yet to be explored in developing countries in Asia and Africa (WWEA (World Wind Energy Association) 2016; REN21, 2017).

The offshore wind market is growing rapidly, especially in Europe. 18.81 GW of installed capacity was generated by the end of 2017 from global offshore wind resources. 4.93 GW was added to the total installed wind generation capacity in 2017 alone. Most of this occurred in Europe: offshore wind-power capacity reached 15.816 GW by the end of 2017 with 3.15 GW being added throughout the year (GWEC 2017). Energy production from wind is the fastest growing global source of renewable energy; however, there are still many hurdles to be overcome. Legislative barriers, poor policy frameworks, and insufficient

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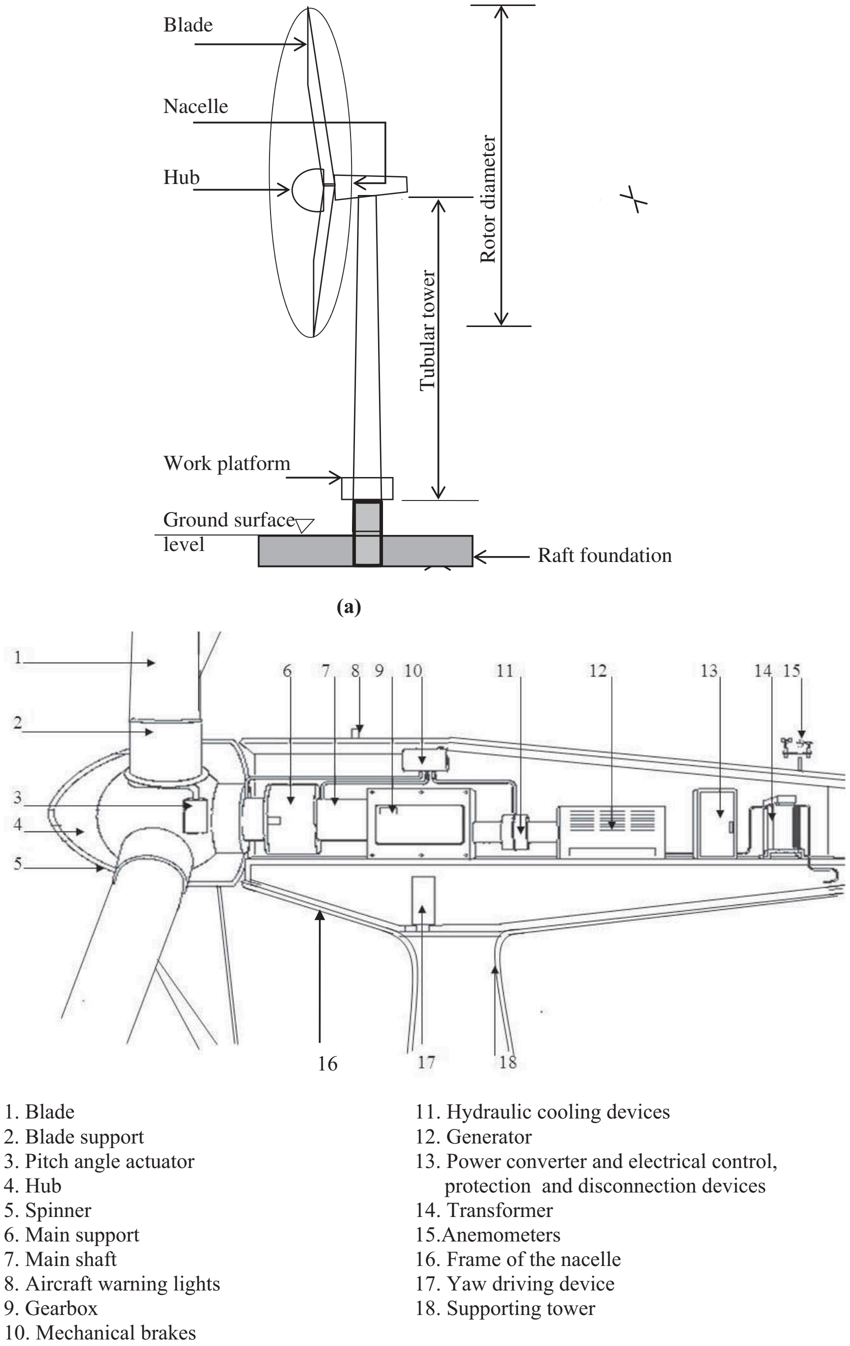
logistical and infrastructural support are all major issues in both developed and developing countries.

This review paper outlines the following aspects in relation to the wind energy production industry:

- Trends in geometric size and rated power-generation capacity of wind turbines;
- Characterization of wind velocity for the assessment of wind energy potential;
- Global trends of wind energy, including cost analysis;
- Jobs and investment trends in wind-power generation industry;
- Challenges and hurdles for the penetration of wind energy into energy markets;
- Some suggestions and recommendation for the rapid development of wind energy parks have been outlined, also.

## 2. Trends in geometric size and rated power capacity of wind turbines

Figure 1(a) shows the main components of an onshore wind-turbine system, including a tubular tower installed on a pad/raft foundation, rotor blades, and nacelle (hub). Modern wind



(b)

**Figure 1(a).** Major parts of the wind turbine system. (b) Electromechanical parts contained in nacelle (Arshad and O'Kelly, 2013).

turbines are installed with either pitch-regulated blades or variable rotational speed systems to allow optimization of power production over a wide range of prevailing wind speeds. The rotational speed of the main rotor shaft is typically in the range of 10 to 20 rev/min (Malhotra 2011). The nacelle (Figure 1(b)) contains key electro-mechanical components of the wind turbine, including the gearbox and generator. Further operational details of these components have been reported by Blanco (2009) and Tong (2010). In onshore plants, the nacelle is usually at a height equal to 1 or 1.2 times the rotor diameter, whereas in offshore plants the height is equal to 0.8 times the rotor diameter.

The rated output, rotor diameter and average height of wind turbines have progressively increased over the years, although the average size of turbines varies largely by country and region. Figure 2 shows the steady increase in rotor diameter and rated power capacity (RPC) of wind turbines installed over the last three decades. In particular, between 1990 and 2015, RPC increased from typically 0.5 to 7.5 MW and rotor diameter from ~40 to 150 m (EWEA, 2011)

Turbines in the capacity range of 1.5 to 3 MW are mainly used for onshore wind farms (Farooq and Kumar 2013; Kaldellis and Zafirakis 2011). Such wind farms are usually developed closer to demand centers in lower wind speed areas and the wind turbines are installed on taller towers with longer blades. Offshore wind turbines having 250 m rotor diameters and with RPC ≥ 20 MW are currently in the research and development phase (Arshad and O’Kelly 2013; REN (Resolute Energy Corporation) 2017).

## 3. Foundation systems for onshore and offshore wind turbine systems

For a horizontal-axis onshore wind turbine, three types of supporting structures are in common use (Manwell, McGowan, and Rogers 2010):

- Cantilevered pipe (tubular tower)
- Free-standing lattice (truss)
- Guyed lattice or pole.

Concrete raft/pad is a typical gravity based foundation (GBF) system used to support the tubular towers and which is the most popular arrangement for onshore installations of the modern wind turbines. GBFs are invariably cast-in-situ reinforced-concrete structures employed to resist the critical combination of vertical, horizontal, moment and torsional loading arising from the self-weight and wind loading acting on the wind–turbine structure. The GBFs are geometrically octagonal in plan, or may be square or circular, with a typical width of typically 15–20 m, and are commonly founded at 2–3 m depth below ground level (Arshad and O’Kelly 2018). Depending on the rated power-generating capacity of the wind turbine, the concrete volume required for one GBF may be up to 500 $m^3$. Where the near-surface soil strata have inadequate allowable bearing pressure, a hybrid system consisting of piled-raft foundation is usually used. The major design considerations for the GDFs include safety against uplift, overturning, sliding and bearing-capacity failure modes in addition to limit (differential) settlement (i.e. tilting of the support tower) over the project’s design life within allowable limits. An imperative design concern also involves the analyses of the foundation response to the dynamic loading generated during earthquake and/or by wind turbulence acting on blade and tower.

Lattice towers have the advantage of easy fabrication, less capital costs, ease of transportation, flexible erection, and lesser effect on ecology. However, they have many bolted connections which need to be torqued and checked periodically. For aesthetic reasons, lattice towers have almost disappeared from use for large, modern wind turbines.

Many small wind turbines are built with narrow pole/lattice towers supported by guy wires. The major advantage with such support structure is the cost-effectiveness due to lightweight fabrication. Whereas the disadvantages include a difficult access around the towers which make them less suitable in farm areas. Finally, this type of tower is more prone to destruction, thus conceding overall safety. Guyed lattice towers are constructed on the ground and raised with a crane or assembled vertically, one section at a time, with

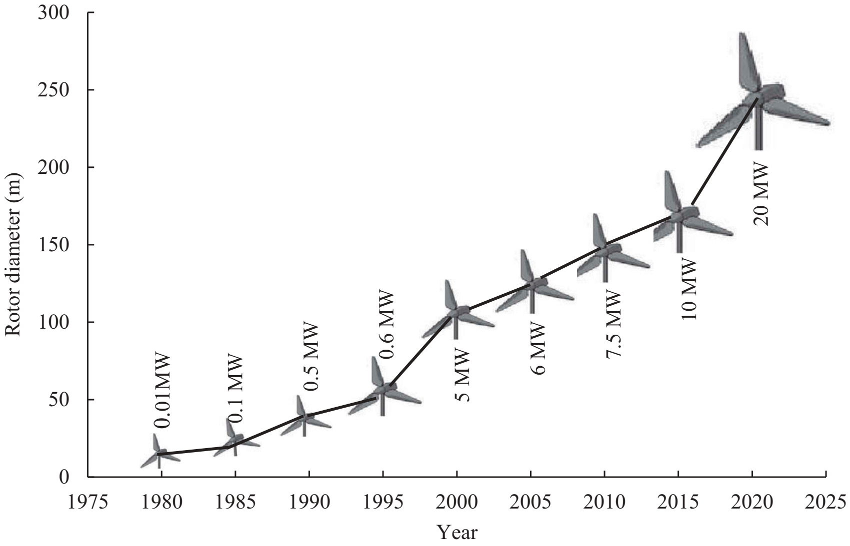


**Figure 2.** Increase in rotor diameter and rated power capacity of wind turbines.

a process known as stacking. These towers are mostly used for turbines with rotor diameters less than 8 m. A concrete foundation is required for the base of the tower and also for the guy wire anchor points. Guyed towers have been used very infrequently and mainly for medium or larger size wind turbines having rated capacity of 1–2 MW.

Support structures and foundations for offshore wind-farms are generally more complex than for their onshore counterparts as they involve greater technical challenges, including design requirements, for them to withstand the harsh marine environment and prolonged impact under large wave loading. Various support structure and foundation systems (see Arshad and O'Kelly 2013), which have been adopted from the offshore oil and gas industries, are usually categorized as either bottom-mounted structures (i.e. a structure rigidly connected to the seabed through a foundation system) or floating-support structures (which have no rigid connection to the seabed). The adoption of a particular foundation solution depends on local seabed conditions, water depth, and financial constraints (AWS Truewind, 2010).

From the various offshore foundation systems, monopiles are by far the most popular solution used in the world today; they amount to 75% of all such existing structures in comparison to only 5% for braced frame or tripod options (E.ON Climate & Renewables, 2011). However, it is estimated that by 2020 the prevalence of monopile structures will have reduced to 50–60% of all OWTs, as newly built braced frame and tripod systems will increase their share to 35–40% (Babcock and Brown Company, 2012). The main reason for this shift is due to the greater suitability of braced frame or tripod systems for deep sea locations, which provide consistently higher wind speeds and hence greater wind energy (Tempel and Molenaar, 2002). Further discussion on offshore wind turbine foundation systems is beyond the scope of this paper however, the same can be found in Arshad and O'Kelly (2013).

## 4. Characterization of wind velocity for the assessment of wind energy potential

Wind conditions are important in defining not only the loads imposed on a wind turbine's structural components but also in predicting the amount of future energy yield as a function of wind velocity (Arshad and O‘Kelly 2016). A realistic assessment of wind energy through statistical analysis of recorded wind data must be based on a realistic representation of: wind speed (preferably at hub height); speed frequency distribution; wind shear (i.e. rate of change in wind speeds with height); turbulence intensity (i.e. standard deviation of wind speeds sampled over 10-min period as a function of mean speed); wind direction distribution and also extreme wind gusts with return periods of up to 50 and 100 years (DNV(Det Norske Veritas) 2014 ). A representative instantaneous fluctuation in wind speed in the time domain is shown in Figure 3(a).

In general, wind conditions are characterized in terms of:

- Vertical wind profiles
- Mean wind speed distribution
- Turbulence effects

### 4.1. Wind speed profile

Generation of power from a wind turbine requires a continuous flow of wind at a rated speed. This is difficult to accomplish because the wind by its very nature is not constant and does not prevail at a steady rate, but fluctuates over short periods of time (Siddique and Wazir 2016). The speed of wind is also dependent on height above the ground as shown in Figure 3(b).

The vertical wind profile represents the variation of the wind speed with height above the ground and water surface levels in cases of onshore and offshore, respectively. The mean value of the 10-min wind speed data measured at a reference elevation of 10 m above mean sea level (and in the case of OWTs usually determined at hub height) is referred to as mean wind speed $\bar{U}_{10}$, from which the mean wind speed $\bar{U}_z$ at some other height $z$ above mean sea level can be approximated using either the *“power law“* or the *“logarithmic law“* given by (Akpinar and Akpinar 2005; Arshad and O‘Kelly 2016; Journe and Massie 2001; DNV (DetNorskeVeritas), 2014 ):

$$\bar{U}_z = \bar{U}_{10}\left(\frac{Z}{10}\right)^{\alpha} \tag{3}$$

$$\bar{U}_z = \bar{U}_{10}\frac{\ln\frac{Z}{Z_0}}{\ln\frac{10}{Z_0}} \tag{4}$$

where values of α ranges between 0.11 and 0.40 depending on site location, e.g. α = 0.11 for open sea conditions, 0.16 for grassland and 0.40 for city center/urban environments (Haritos 2007; Journe and Massie 2001; DNV, 2014 ) and $z_0$ is a roughness parameter with a typical value of 0.0001 for open-sea environments, 0.01 for mown grass, 0.3 for forests and up to 10 for city center/urban environments (DNV, 2014 ).

### 4.2. Mean wind speed distribution

Wind speed distribution quantifies the probability of different (mean) wind speeds occurring over a given time period at the site location (Morgon et al., 2011). Lacking a wind speed time series of sufficient length (see Figure 3(a)), the probability distribution of wind speed serves as the primary substitute for data when estimating design parameters, including power output and fatigue loads for the wind turbine structure. Under normal conditions, the following expression can be used for calculation of the mean wind speed $\bar{U}_{Z,T}$ with averaging period $T$ at height $z$ above the sea (or ground surface) level:

$$\bar{U}_{Z,T} = \bar{U}_{10}\left(1 + 0.137 ln\frac{z}{h} - 0.047 ln\frac{T}{T_{10}}\right) \tag{3}$$

where

$h$ = 10 m and $T_{10}$ = 10 min.

This expression converts mean wind speeds between different averaging periods. When $T$< 10 min, the expression provides the largest likely mean wind speed over the specified averaging period $T$. This conversion does not preserve the return period associated with $\bar{U}_{10}$.

For extreme mean wind speeds corresponding to specified return periods in excess of approximately 50 years, the following expression (Freya wind profile) can be used for conversion of the 1-h mean wind speed $\bar{U}_{1H}$(at height $h$ above sea (level) to the

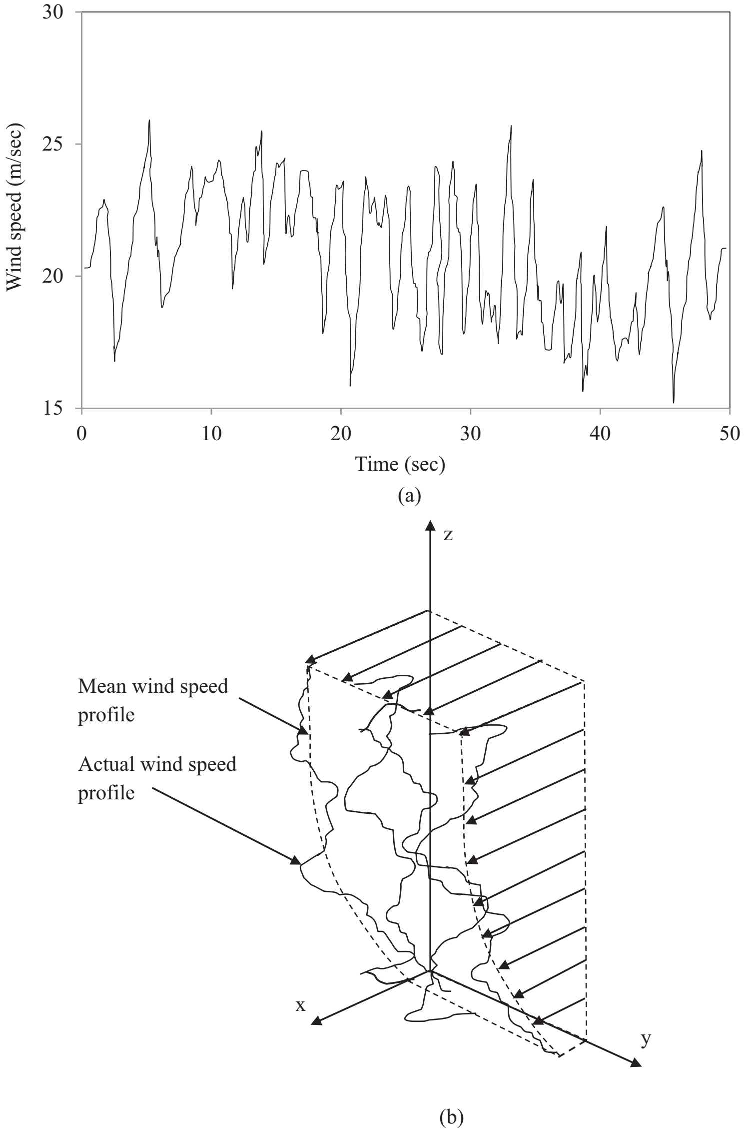


Figure 3. Fluctuation of wind speeds about the mean value: (a) in a time domain; (b) in three-dimensional space (Arshad and O'Kelly, 2016).

mean wind speed $\bar{U}_{Z,T}$with averaging period $T$ at height z above sea level:

$$\bar{U}_{Z,T} = \bar{U}_{1H}\left(1 + Cln\frac{z}{h}\right)\left(1 - 0.41I_{Z}ln\frac{T}{T_{1H}}\right) \tag{4}$$

where

$h$ = 10 m and $T_{1H}$ = 60 min and $T <\ T_{1H}$ and

$$C = \frac{5.73}{100}\left(1 + 0.15\bar{U}_{1H}\right)^{1/2} \tag{5}$$

$$I_{Z} = 0.06\left(1 + 0.043\bar{U}_{1H}\right)\left(\frac{Z}{h}\right)^{-1/4.55} \tag{6}$$

For the prediction of energy output of a wind turbine, among the most important of data is the wind speed frequency distribution (Siddique and Wazir 2016). Wentink (1976) concluded that Weibull distribution gave the best fit to the wind speed data as compared to the other distribution functions, such as Rayleigh distribution, Planck‘s frequency distribution and Gamma function. Similar recommendations have been reported by other investigators including Peterson et al. (1997) and Rehman, Halawani, and Husain (1994).

The probability density function ($f_{\text{wind}}$) of a Weibull random variable (wind speed in our case) $U$ can be given by:

$$f_{wind} = \frac{k_t}{A}\left(\frac{U}{A}\right)^{k_t - 1} exp\left(-\frac{U}{A}\right)^{k_t} \tag{7}$$

while the cumulative distribution function, which is the integral of$f_{wind}$, can be established as:

$$F_U = 1 - exp\left(-\frac{U}{A}\right)^{k_t} \tag{8}$$

Where $A$ is a scalar and $k_t$ is a shape factor that quantifies the width of the wind speed distribution.

The values of $A$ and $k_t$ are larger for offshore environments, indicating a higher probability of greater wind speeds compared with onshore environments (Fischer 2011; Tricklebank, 2008).

The wind climatology including wind speed profile along with wind power density is a vast area of research and dissuasion, especially when it is to be explored on a global scale. Different wind characterizing parameters in relation to wind energy development on the global scale can be found from many of the online data sets available such as https://globalwindatlas.info/; https://www.irena.org. Such types of wind atlas can be used for the preliminary assessment of wind power generation potential across the globe.

### 4.3. Turbulence effects and gust

The momentary deviations from the mean wind speed are defined as turbulence, hence the total wind speed can be written as the sum of mean wind speed and its fluctuating component (i.e. turbulence). In the lower layer of the atmosphere (i.e. to a height of 100 m), winds are modified by frictional forces and obstacles that not only alter their speed but also their direction. This is the origin of turbulence in the wind's flows. For offshore environments, turbulence is usually determined with reference to the mean wind speed $\bar{U}_{10}$ and is characterized by the standard deviation $\sigma_U$.

For a given value of $\bar{U}_{10}$, the standard deviation $\sigma_U$ of the wind speed shows a natural variability from one 10-min period to another (Kidmo et al. 2015; DNV(DetNorskeVeritas) 2014 ). The magnitude of the turbulence depends on meteorological and geographical conditions in terms of atmospheric layering and terrain. A measure used for turbulence is turbulence intensity, defined as the ratio of the standard deviation of wind speed to the mean wind speed for a given time period (Stival, Guetter, and Andrade 2017; Bardal *et al.*, 2015).

For a particular site, turbulence intensity correlates with wind speed and surface roughness; higher wind speed and lower surface roughness producing lower turbulence (Argyle et al. 2018; De Vries 2007). The spectral density of the wind speed, which explains how the energy of the wind turbulence is distributed between different frequencies (including wake effects from any upstream wind turbines), is of interest for the estimation of wind energy yield (Tobin et al., 2018). The spectral density of the wind speed may be represented by the Kaimal spectrum (Bandi 2017).

A gust is a discrete event within a turbulent wind field. As illustrated in Figure 4, one way to characterize a gust is to determine: amplitude, rise time, maximum gust variation, and lapse time. Wind turbine structural loads caused by gusts are affected by these four factors (Hansen 2006; Jamil, Parsa, and Majidi 1995; Zhou et al. 2018). The main contributors to extreme loading on the wind turbine structure are due to short-term fluctuations of wind speed, such as transient events like gusts (DNV, 2014).

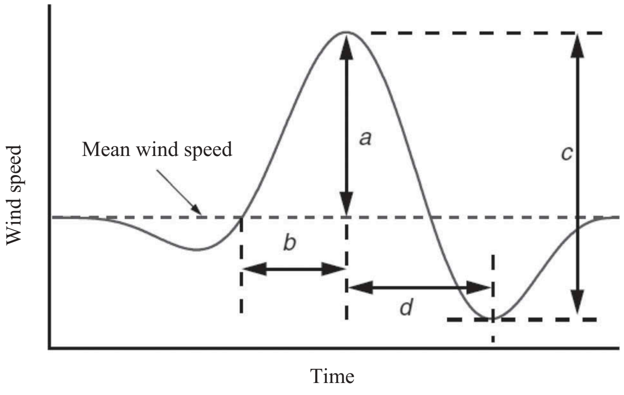


**Figure 4.** Illustration of a discrete gust event; (a), amplitude; (b), rise time; (c), maximum gust variation; (d), lapse time.

## 5. Capacity factor and the availability of wind power

The capacity factor (CF) of a wind turbine or a wind farm refers to the percentage of the nameplate capacity that a turbine (or wind farm) will deliver in terms of electricity generation per annum (Baloch, Kaloi, and Memon 2016). Average capacity factors vary widely from region to region; for instance, for onshore wind farms in Asia, Europe, and North America, CF values lies in the ranges of 20–30%, 25–35% and 30–45%, respectively (IRENA, 2016). CF values in the range of 40–50% have been reported for offshore wind farms in Europe (IRENA(International Renewable Energy Agency) 2012). For a typical 1.5 MW wind turbine, the capacity factor ranges from 30% to 35% (REN (Resolute Energy Corporation) 2017). Global average capacity factors grew from an estimated 20% in 2000 to 30% in 2017 (a 50% increase) (IRENA 2018) and may reach up to 32% in 2025 for onshore wind farms (IRENA(International Renewable Energy Agency) 2012). From the authors' perspective, similar trend in future in can also be expected for offshore wind farms.

The coefficient of power ($C_P$) of a wind turbine is defined as its efficiency of capturing the kinetic energy that exists in a unit area of intercepted wind (such as "*A*") at the given wind speed. The maximum extractable power from any wind machine is limited by the Betz's relation (1942), which assigns the power coefficient $C_P = 0.59$ for the maximum performance of a wind machine (Ahmed, Ahmed, and Akhtar 2006).

Theoretically, wind power depends upon the mass-flow rate ($dm/dt$) of the air through a rotor disc of area ($A$), as illustrated in Figure 5. From the continuity equation of fluid mechanics, the mass flow rate is a function of air density, ρ, and air velocity (U, assumed uniform) and is given by (Tong 2010):

$$\frac{dm}{dt} = \frac{1}{2}\rho A U \tag{8}$$

The kinetic energy per unit time, or power, of the flow, is given by:

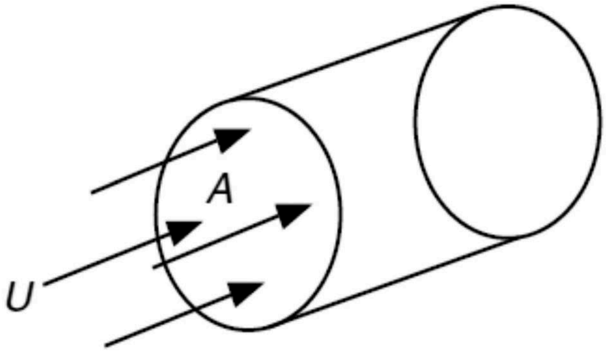


**Figure 5.** The flow of air through a rotor disc; A, area; U, wind velocity

$$P = \frac{1}{2}\frac{dm}{dt}U^2 = \frac{1}{2}\rho A U^3 \tag{9}$$

The wind power per unit area, P/A or wind power density is:

$$\frac{P}{A} = \frac{1}{2}\rho U^3 \tag{10}$$

For standard conditions (sea level, 15°C), the density of air is 1.225 kg/m$^3$.

Equation 10 implies that wind power density is proportional to the cube of the wind velocity. The actual power production potential of a wind turbine must take into account the fluid mechanics of the flow passing through a power-producing rotor, the aerodynamics and the efficiency of the rotor/generator combination. In practice, a maximum of about 45% of the available wind power is harvested by the best modern horizontal axis wind turbines.

NREL (National Renewable Energy Laboratory) has classified the wind power potential into seven categories on the basis of wind power density and wind speed, as given in Table 1.

In order to build the wind climatology necessary for a reasonable indication of wind potential, a minimum one-year period of wind measurements are required (Al-Yahyai, Charabi, and Gastli 2010; Ganesan and Ahmed 2008). A realistic assessments of the wind energy potential at a site requires statistical analysis of wind data, including: wind speed (preferably recorded at hub height); speed frequency distribution; wind shear; turbulence intensity; wind direction distribution, and; extreme wind gusts having return periods of up to 50y or 100y (Arshad and O'Kelly 2013; DNV, 2014). Additionally, a mutual interaction among such wind parameters is highly terrain specific. Figure 6(a) shows the typical effect of wind shear and the corresponding variation in theoretical wind power density at three different terrain locations including open sea (α = 0.11), grassland (α = 0.16) and urban area (α = 0.4). From this figure, it can be inferred that in open sea areas the mean wind velocity increases from 4 to 5 m/s (25% increase) when hub height is changed from 10 m to 100 m above the mean sea level. This 25% increase in mean wind velocity causes an increase of 110% in the wind power density. Similarly, the corresponding increase in wind power density for the grassy land and urban areas is 230% and 1872%, respectively, against the velocity increase of 50% and 170%, corresponding to these terrains. Figure 6(b) shows a representative (qualitative) variation in turbulence intensity and the wind power density with change in mean wind velocity. From this figure, it can be concluded that turbulence intensity sharply decreases with an increase in wind velocity, while, almost reverse is the situation for the change in wind power density with the increase in wind velocity. Further discussion on this topic is beyond the scope of this research.

**Table 1.** Wind power potential classification.

| Wind power class | Resource potential | Wind power density at 50 m height | Wind speed at 50 m height |
|---|---|---|---|
| | | Watt/m$^2$ | m/sec |
| 1 | Poor | 0–200 | 0.0–5.6 |
| 2 | Marginal | 200–300 | 5.6–6.4 |
| 3 | Fair | 300–400 | 6.4–7.0 |
| 4 | Good | 400–500 | 7.0–7.5 |
| 5 | Excellent | 500–600 | 7.5–8.0 |
| 6 | Outstanding | 600–800 | 8.0–8.5 |
| 7 | Superb | >800 | >8.5 |

## 6. Global prospects of wind-power generation

### 6.1. Total wind-power generation capacity

Wind-power generation is rapidly growing in popularity, especially in Europe, Asia, and the USA, over the last few years. Global installed wind power capacity of 540 GW achieved by the end of 2017 shows an increase of more than 20 fold compared with that of installed capacity of 24 GW in 2001 as shown in (Figure 7) (WWEA (World Wind Energy Association) 2016; GWEC 2017). A cumulative growth of more than 10.67% over the last year (2016) was also observed (GWEC, 2018).

The contribution of different regions of the world to the existing wind power capacity is shown in Figure 8. This figure depicts that contribution from Asia, with 228 GW (42% of 540 GW), is highest followed by Europe and North America with inputs of 178 and 105 GW, respectively. The leading countries for total wind power capacity per inhabitant are Denmark, Sweden, Germany (which moved up from sixth), Spain, and Ireland (WWEA 2012).

The outlook for Africa and the Middle East is particularly uncertain, but new capacity additions could increase twenty-fold from 0.2 GW in 2010 to 4 GW in 2018 (GWEC 2014). However, more encouragingly, 5 GW capacity was operational by the end of 2017 (GWEC (Global Wind Energy Council) 2018; REN (Resolute Energy Corporation) 2017).

Furthermore, China, the USA, Germany, India, and Spain being the top industry players during 2017, contributed more than 67% to the global increase in wind-power generation installed capacity, as shown in Figure 9 (WWEA (World Wind Energy Association) 2016; GWEC (Global Wind Energy Council) 2018; GWEC 2017). China is likely to continue dominating new capacity additions, as its government's ambitious plans and supportive policies align. Although new capacity additions may not grow as rapidly as they have done in recent years, China still has plans to reach 200, 400 and 1000 GW of installed capacity by 2020, 2030 and 2050, respectively (IEA, 2011).

The Global Wind Energy Council (GWEC 2017) has suggested four different scenarios to foresee the cumulative wind-power capacity till 2050. Figure 7 shows the two extreme scenarios: least ambitious (termed as New Policies Scenario (NPS), and most ambitious (termedas Advanced Scenario (AS), ) depicting that global acumulative wind power capacity may reach from 540 GW in 2016 up to 2870 GW (as per NPS) and to 5805 (as per AS) GW by the end of 2050. These figures correspond to 20–41% of the global electricity contribution in 2050, while the current share (year 2017) of wind energy is limited to approximately 4% of the global electricity demand. Figure 10 shows the gradual anticipated development of the wind power as per two extreme scenarios in six different regions of the globe. Asia, North America, and Europe will continue to drive new capacity additions in the foreseeable future with the contribution of up to 2614, 919 and 718 GW, respectively, in 2050 (GWEC 2017).

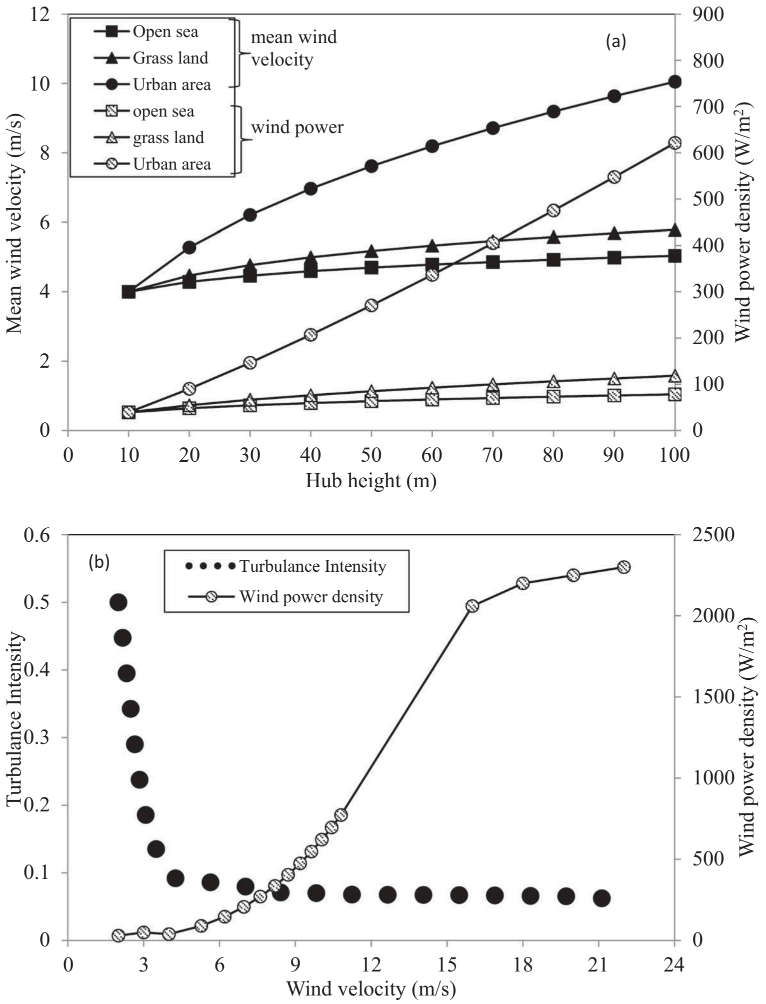


**Figure 6.** (a) Typical curve showing the effect of wind shear on wind velocity and wind-power density; (b) Typical curve showing variation in turbulence intensity and wind power density with wind velocity.

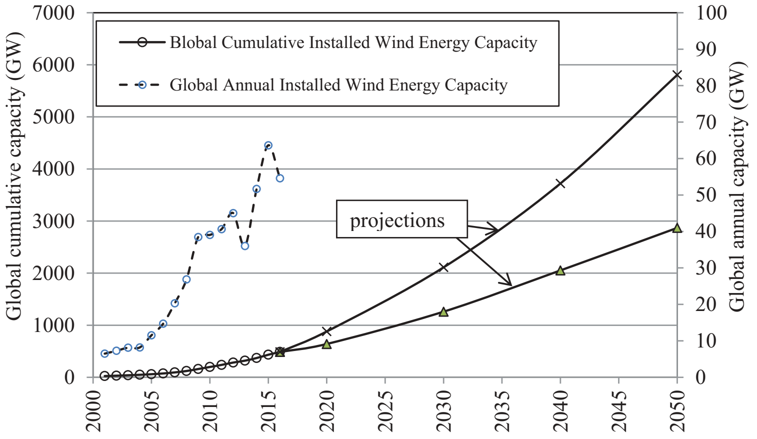


**Figure 7.** Annual and cumulative increase in global installed wind-power capacity till 2017 and projected for 2050 (GWEC (Global Wind Energy Council) 2018; IRENA (International Renewable Energy Agency) 2012; EWEA 2017).

### 6.2. *Offshore wind-power capacity*

Figure 11 shows the trend in the increase of acumulative offshore wind capacity from 2011–2017, while Figure 12 depicts that the offshore market is dominated by the United Kingdom, Germany and China, with installed capacities of 6836, 5355 and 2788MW, respectively, by the end of 2017 (GWEC 2017; GWEC (Global Wind Energy Council) 2018). During 2017, Germany, China, and the Netherlands jointly contributed by more than 94% to the global increase in the offshore wind-power generation installed capacity as shown in

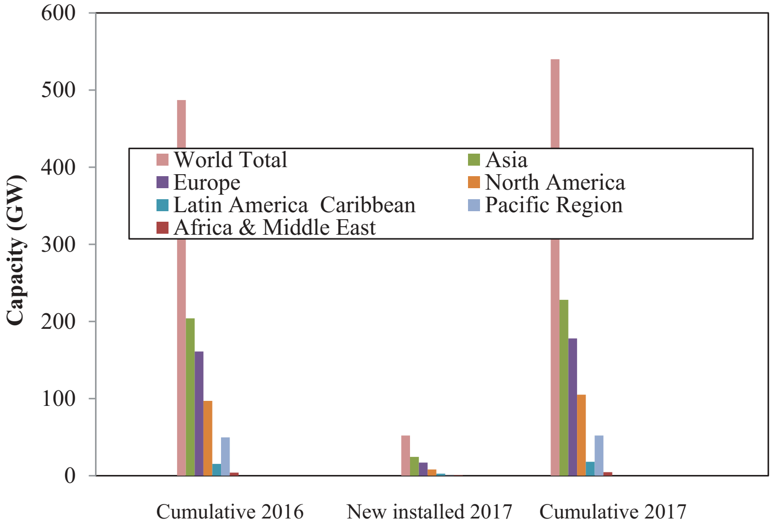


**Figure 8.** Increase and cumulative wind-power generation capacity in different regions during the year 2017 (GWEC (Global Wind Energy Council) 2018; REN (Resolute Energy Corporation) 2017; IRENA(International Renewable Energy Agency) 2012).

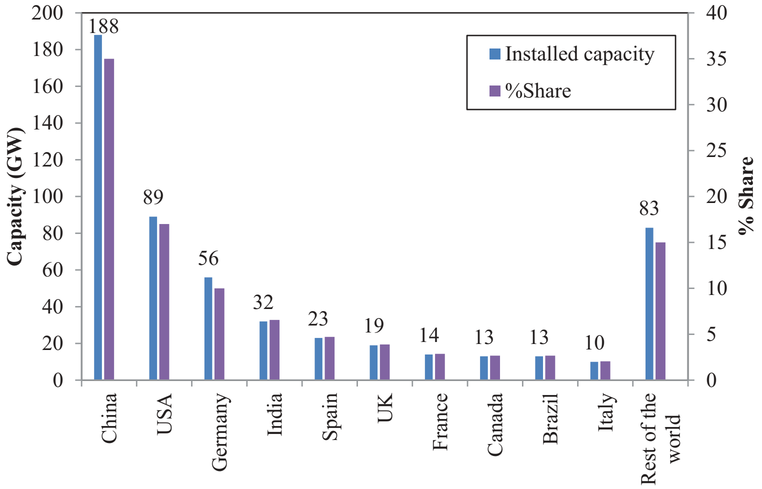


**Figure 9.** Shares of different countries in cumulative installed wind-power generation capacity by the end of 2017 (GWEC (Global Wind Energy Council) 2018; REN (Resolute Energy Corporation) 2017).

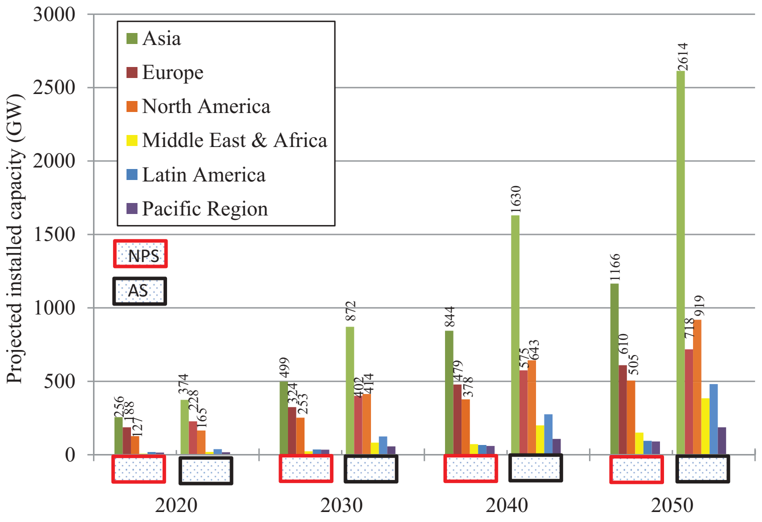


**Figure 10.** Gradual anticipated development of the wind power as per two extreme scenarios in six different regions of the globe (GWEC 2017).

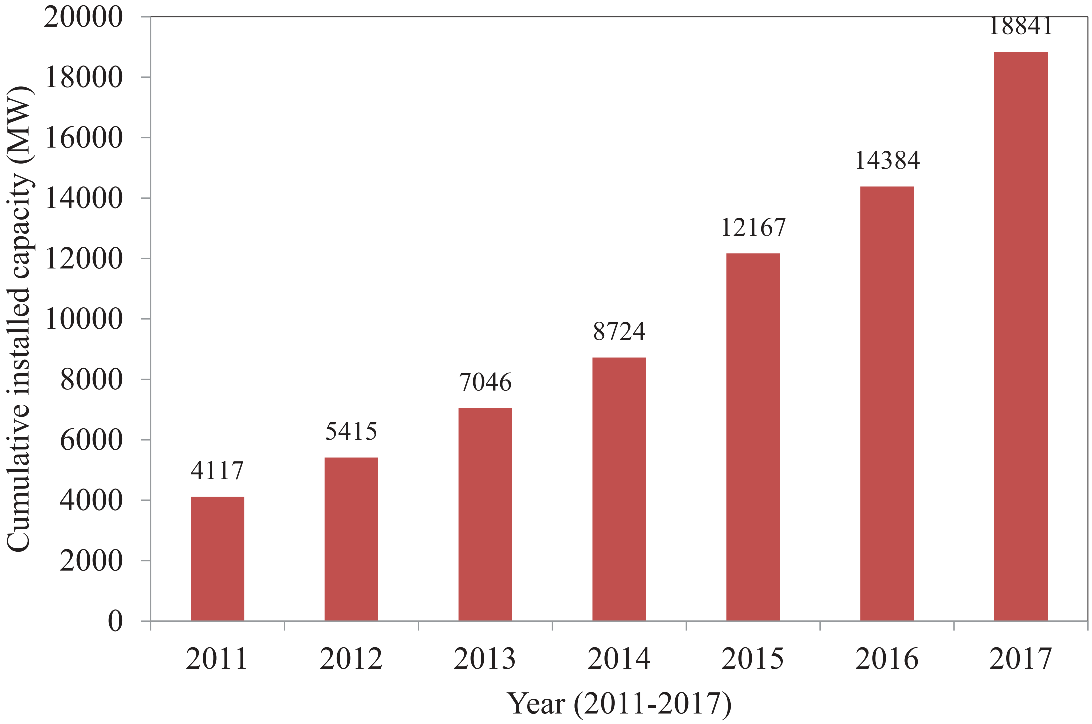


**Figure 11.** Increase and cumulative off-shore wind-power generation capacity from year 2011 to 2017 (GWEC 2017; GWEC (Global Wind Energy Council) 2018).

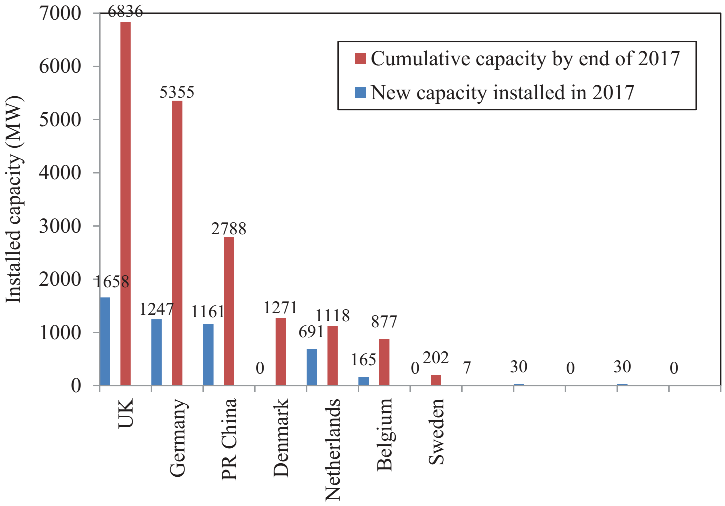


**Figure 12.** Increase and cumulative off-shore wind-power generation capacity by the end of 2017 in top seven countries (GWEC 2017; GWEC (Global Wind Energy Council) 2018).

Figure 12. Europe accounts for more than 87% for the installed global offshore wind-power generation capacity.

During 2017, Taiwan and France have made their first commercial offshore wind power project profitable with the capacity of 8 and 2 MW, respectively. India may be the next country to develop an offshore wind power pilot project of 100 MW during 2017–18. By the end of 2020, it is predicted that the installed capacities in the United Kingdom, Germany, France, and the Netherlands will reach up to 13, 10, 6, and 5 GW, respectively. Collectively the European Union (EU) has plans to generate approximately 40 GW from offshore wind by 2020 (E.ON Climate & Renewables, 2011; EWEA 2009). It is also estimated that the offshore wind energy in the European Union (EU) may reach up to 56 GW during 2020, as compared to 820 MW in 2005. According to the more ambitious projections, a total of 80 GW could be installed by 2020 worldwide, with three-quarters of this in Europe (GWEC, 2011).

### 6.3. *Wind energy penetration into world electricity mix*

Almost, 97% of wind farm installations in the world have taken place in the top and emerging markets namely – European Union, the USA, China, and India (WWEA 2015). Further, wind was the largest single source (nearly 50%) of all increase in electricity generation globally through renewable resources.

From 2011 to 2016, the share of wind energy to the global electricity demand increased from 2% to 4%, and by 2050 this share may reach up to 20% to 41% (GWEC 2017; WWEA, 2105). Another study conducted by WWEA foresees that by 2050, various technological advancements and adoption of strategies would enable high penetration levels of at least up to 40% in the power systems all over the world. The Intergovernmental Panel on Climate Change (IPCC) in its report has indicated that in two of its scenarios, Median and Ambitious, by 2050, wind energy could account for 13–14% and 21–25% of global electricity generation, respectively. In the European Union, the contribution of wind energy to the electricity mix may reach up to 20%, 33% and 50% by the end of 2020, 2030 and 2050, respectively (EWWA, 2017), while statistics show that by the end of 2013, the wind accounted for 13.3% of the total electricity generation capacity in the EU (WWEA 2015). By the end of 2014, the total accumulated capacity of wind turbines connected to the public grid in China was about 97.32 GW, constituting 6.2% of the total electricity generation capacity in the country. WWEA (2015) has projected that wind energy will be contributing up to 10%, 14% and 18% of the electricity demand in China by 2030, 2040 and 2050.

## 7. Cost analysis of wind energy and future trends

Three types of cost breakdown are associated with wind energy production, comprising: capital cost, operation and maintenance (O&M), and the levelized cost of energy (IRENA(International Renewable Energy Agency) 2012; Søren, Poul-Erik, and Shimon 2009; Mengal et al. 2014). Capital costs occur at the initial stage of the project and involve the initial expenses for planning & design, equipment, engineering system, and installation. The operating and maintenance costs include the regular repair, operation, inspection, and salaries of the regular staff/labor while additional costs may also occur due to the adverse environment impacts (Arshad and O'Kelly 2013; Mousavi, Ghanbarabadi, and Moghadam 2012). The levelized cost gives an overall depiction of the investments required over the life cycle of the wind power plant (Cambell 2008; Søren, 2009). A significant portion of the cost reductions is coming through technology improvements, which are generally evolutionary.

### 7.1. Capital investment costs

Wind energy projects are initial capital intensive due to the fact that the majority of the costs must be borne at the beginning of the project or even before any physical progress (IRENA (International Renewable Energy Agency) 2012). Globally, the installed costs of onshore wind have seen a significant decline since the early 1980s. Global weighted average installed costs declined from 4766 US$/kW in 1983 to 1477 US$/kW in 2017; that is, an overall reduction of 69% between 1983 and 2017 (IRENA 2017). Capital investment costs largely depend on the region where a wind energy farm is going to be developed; for example, onshore wind farms (for turbine size 1.5–3 MW and capacity factor 20–50%) were as low as 1044–1420 US$/kW in China and India, 1054–3702 US$/kW in the UK/Europe and 1481–2445 US$/kW for the North America (REN (Resolute Energy Corporation) 2017), but typically ranged between 1800–2200 US $/kW in most other major markets (IRENA 2017).

Table 2 shows comparisons between capital investment costs for different components of onshore and offshore wind-energy projects.

IRENA (2017) estimated that overall, global weighted average total installed cost for onshore wind could fall from around 1560 US$/kW in 2015 to 1370 US$/kW in 2025. GWEC (2017) foresees that capital investment costs for the onshore wind farms may decrease to 1690, 1586, 1527 and 1520 US$/kW, by 2020, 2030, 2040 and 2050 respectively, compared with capital investment cost of 1830 US$/kW in 2015. International Energy Agency (IEA) (2013) estimates that the capital investment costs of wind power are expected to reduce by almost 23% for onshore and 38% for offshore projects by 2050, when compared with costs occurring in 2010. The main drive for such reduction potentials would be technology development and economies of scale.

Capital investment costs for offshore are approximately double (Industry Update 2017) and may reach up to three times that for onshore wind-power projects having the similar power-generation capacity. This is primarily on account of increased investments in transporting materials/turbines, constructing and installing foundations, equipment and turbines at sea and laying offshore cables (IRENA(International Renewable Energy Agency) 2012; Junginger, Faaij, and Turkenburg 2004). However, modeling showed that the offshore wind turbines would produce 28% more energy as a result of the better wind resource (Fuglsang and Thomsen 1998). Kooijman et al. (2001) and Søren, Poul-Erik, and Shimon (2009) pointed out that approximately 70–75% of the total cost of offshore wind-power production is related to initial capital costs, including those of the turbine, foundation, electrical equipment/grid connection.

### 7.2. Operation and maintenance (O&M) costs

The operation costs can include a cost for insurance on the wind turbine, taxes, and land rental costs, while the

Table 2. Comparison between capital costs for offshore and onshore wind energy projects (IRENA(International Renewable Energy Agency) 2012; Kooijman et al. 2001; Junginger, Faaij, and Turkenburg 2004).

| Item | Offshore | Onshore |
|---|---|---|
| Capital investment cost (US$/kW) | 3300–5000 | 1700–2450 |
| Wind turbine cost, including production, transportation and installation (% of capital investment cost) | 30–50 | 65–84 |
| Cost of grid connection including cabling, substations and buildings (% of capital investment cost) | 15–30 | 9–14 |
| Construction cost including foundation, transportation and installation of tower and turbine and other infrastructure (e.g. access roads) necessary for turbine installation (% of capital investment cost) | 15–25 | 4–16 |
| Other capital costs including development and engineering costs, licensing procedures, consultancy, permits, supervision, control and data acquisition, monitoring systems (% of capital investment cost) | 8–30 | 4–10 |

maintenance costs can include the following typical components (Manwell, McGowan, and Rogers 2010):

- routine checks;
- periodic maintenance;
- periodic testing;
- blade cleaning;
- electrical equipment maintenance;
- unscheduled maintenance costs.

For wind-power generation, the overall contribution of operation and maintenance (O&M) costs to LCOE may be significant and are site-specific along with capacity factor dependent. Data from different countries including the USA, China, and many European countries show that O&M costs for onshore wind power account for between 11% and 30% of total LCOE (IRENA(International Renewable Energy Agency) 2012). The lowest contribution of 0.005 US$/kWh was documented for the USA (IRENA(International Renewable Energy Agency) 2012) and the highest of 0.043 US$/kWh for the Netherlands (IEA, 2008), while in major wind markets averages between 0.01 US$/kWh and 0.025 US$/kWh. The Danish Wind Industry Association states that annual operation and maintenance (O&M) costs for wind turbines generally range from 1.5% to 3% of the original turbine cost and that the newer generation of wind turbines have the estimated annual O&M costs ranging from 1.5% to 2% of the original price of the turbine, or approximately 0.01 US$/kWh (Manwell, McGowan, and Rogers 2010).

O&M costs for offshore wind power are significantly greater on account of higher costs due to logistical complexity including accessing/maintenance of the wind turbines, towers and cabling and higher expected failure rates for some mechanical and electrical components. In the United Kingdom, for example, Feng, Tavner, and Long (2010) reported that O&M costs for offshore wind-power projects located in shallow water depth were approximately 1.5 times that for onshore.

Overall, O&M costs for offshore wind power are typically in the range of 0.027 to 0.054 US$/kWh (ECN 2011). In Europe, reductions in capital investment costs of 10% are expected for offshore wind-power projects between 2020 and 2050 (CEC, 2007; Søren, Poul-Erik, and Shimon 2009). On the basis of global data available in 2010, IEA (2013) foresees a 20% reduction of onshore O&M costs by 2030, rising to 23% by 2050. Larger reductions of 35% in 2030 and 43% in 2050 are probable for offshore O&M costs.

### 7.3. Levelized cost of energy (LCOE)

The LCOE cost is often cited as a convenient summary measure of the overall competitiveness of different energy generating technologies. For wind power systems, LCOE represents the sum of all costs including capital costs, operation and maintenance costs for a fully operational wind power system over the project‘s lifetime, with financial flows, discounted to a common year (Cambell 2008; Søren, Poul-Erik, and Shimon 2009). Given the capital-intensive nature of most renewable power generation technologies and the fact that fuel costs are low-to-zero, the discount rate used to evaluate the project has a critical impact on the LCOE (IRENA 2017). Theoretical/empirical methods that use more extensive databases available for onshore wind-power projects in estimating LCOE for new offshore projects are not reliable (IRENA(International Renewable Energy Agency) 2012). Similar to capital investment costs, LCOE is also highly region/country specific, however, globally for onshore wind power LCOE ranges from 0.04 to 0.16 US$/kWh (REN (Resolute Energy Corporation) 2017).

The Levelized cost is calculated using the following equations (Mousavi, 2012):

$$LCOE = C_k + \left[\sum_{t=0}^{PL}\left(\frac{C_O(1+e_O)^t}{(1+r)^t} + \frac{C_{Fud}(1+e_{Fuel})^t}{(1+r)^t}\right)\right] \times \frac{r(1+r)^{PL}}{(1+r)^{PL}-1} + C_{EC} \tag{11}$$

$$C_k \frac{DR \times TPC(1+r)^{CL}}{HY \times CF} \tag{12}$$

$$C_O \frac{FOM}{HY \times CF} + VOM \tag{13}$$

$$C_{Fuel} = FC \times HR \tag{14}$$

where $C_k$ is the sum of capital costs of plant; $C_O$are the operating and maintenance costs of plant; $C_{Fuel}$is the fuel cost; $C_{EC}$external costs; TPC total plant cost ($/KW); $r$ is the discount rate (%); $t$ = time in year; CL = construction life (year); HY = hours per year; CF = capacity factor (%); FOM = fixed O&M cost ($/KW/year); VOM = variable O&M cost ($/KWh); FC = fuel cost ($/MMBTU); $e_{O\&M}$ = escalation rate of O&M cost (%); $e_{Fuel}$ = escalation rate of fuel cost (%); PL = plant life (years); DR = depreciation rate (%).

REN21 (2017) estimated that for Europe, onshore LCOEs were between 0.05 and 0.16 US$/kWh for 2017; assuming a typical capacity factor (ratio of average power delivered to theoretical maximum power) value for new onshore projects of between 25% and 35%. For China and India, this figure ranges from 0.05 to 0.08 US$/kWh for a capacity factor of 20% to 30%. In North America, the LCOE for onshore wind having a capacity factor of 30–45% was estimated between 0.04 and 0.10 US$/kWh for 2017.

Central and South America, Oceania and Africa had weighted average LCOEs of between 0.08 and 0.10 US$/kWh. In 2014 and 2015, the best wind projects delivered electricity at between 0.04 and 0.05 US$/kWh (IRENA 2017).

A study documented by IRENA (2017) on the basis of global weighted average onshore wind energy shows that LCOE may reduce to 0.05 US$/kWh by 2025, yielding a 26% decrease when compared with the corresponding cost in 2015. Wiser et al. (2016) anticipated that LCOE for onshore wind energy will decrease by 24% and 35% by 2030 and 2050, respectively, when compared with the corresponding value of cost in 2015. Such reductions may be due to advancements in design and size rotor and towers, reduction in financing costs and overall improvement of technology.

As a general trend, the LCOE for offshore wind-power generation around the globe is typically almost double that of onshore having a similar capacity factor (Roddy et al. 2009).

LCOE reductions for the offshore wind energy may be up to 35% in 2025 when compared with the corresponding value in 2015 (IRENA 2017). Wiser et al. (2016) projected that LCOE for offshore wind energy will decrease by 30% and 41% by 2030 and 2050, respectively, when compared with the corresponding value of cost in 2015. Another study documented by BNEF (2018) predicts that onshore wind LCOE will fall 47% by 2040 and compared to 71% for the offshore wind. A more recent study documented by Kost et al. (2018) predicts that LOCE for the onshore wind energy in Germany may drop by 14% between year 2018 and 2035. Similarly, Banja and Jégard (2017) have estimated a 27% reduction in the LOCE for the onshore wind energy between 2020 and 2050. On the same, NREL annual technology baseline 2017 data projects a 30% decline in onshore LCOE in the USA between 2020 and 2050 (https://energyinnovation.org). Likewise, according to www.bnef.com (2019) cost of wind energy is expected to drop 58% by 2050 and will become more cheaper the electricity generated from fossil fuels.

### 7.4. Jobs and investment trend in wind-power generation industry

The number of jobs available in the wind-power generation industry for 2012–2016 is shown in Figure 13 in conjunction with the overall number of jobs in the entire renewable energy sector. This figure demonstrates an increasing trend in the number of jobs in the wind-power industry. Jobs increased by 7% in 2016, and in total 55% more jobs were available in 2016 than in 2012. It is also interesting to note that the share of the jobs in the wind-power sector remained proportional for the years 2012–2016, staying at the rate of 13–14% of total of jobs in the entire renewable energy sector (IRENA, 2017a). In 2016 almost half a million jobs were available in the wind-power industry in China, which is nearly 50% of the overall number of global jobs in that sector. Germany and the USA remained in 2nd and 3rd position behind China with 0.14 and 0.1 million job opportunities in the wind-power sector (Figure 14). Obviously,

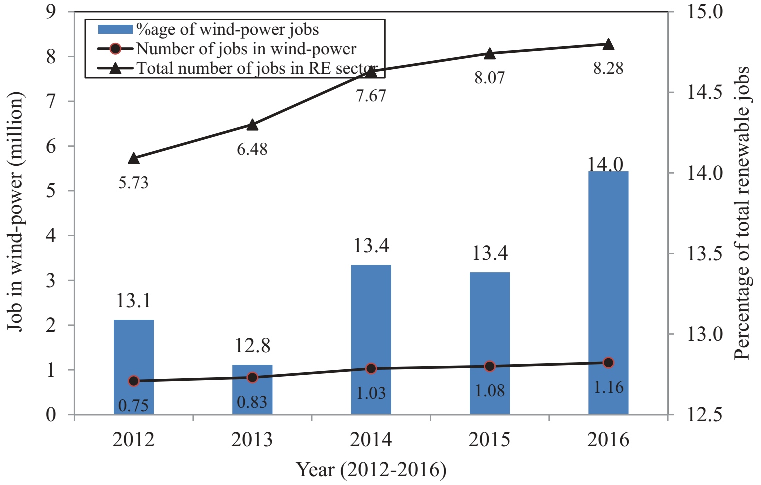


**Figure 13.** Number of jobs in renewable energy sector for year 2012–2016 (REN (Resolute Energy Corporation) 2017; IRENA 2017).

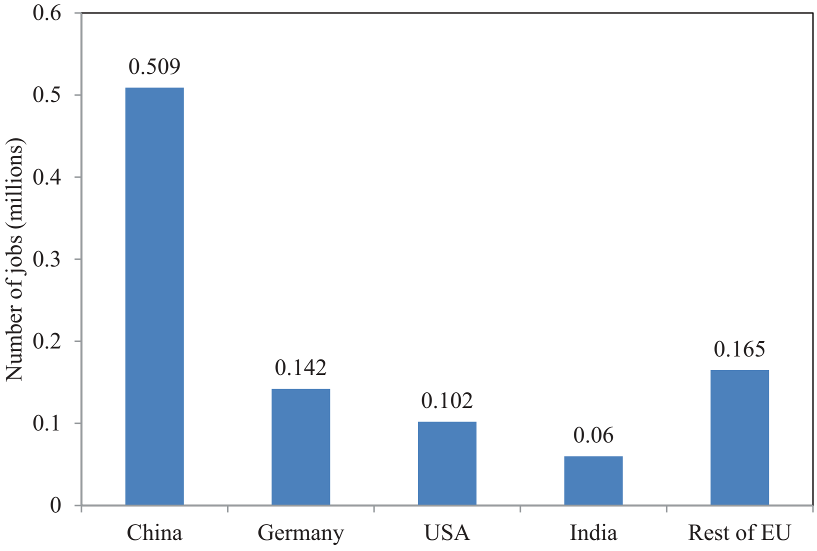


**Figure 14.** Number of jobs in wind-power sector during year 2016 in different countries (REN (Resolute Energy Corporation) 2017; IRENA 2017; AWEA (American Wind Energy Association) 2017).

employment opportunities in the wind energy sector are likely to increase in line with continuous deployment. An accelerated ramp up in wind energy resource deployment, in line with global climate imperatives, could lead to a total of 3 million jobs in the sector by 2030 (compared with the current level of 1.2 million) and 4 million by 2050 (AWEA, 2017; IRENA, 2017a). The Global Wind Energy Council projects that by 2030, in its most favorable policy scenario, employment could double to 2.4 million (GWEC 2017).

Figure 15 presents data in relation to global investment in renewable energy and wind-power development from 2004 to 2016. This shows that total investment in renewable energy increased from US$47 billion to US$242 billion during these 13 years. However, investment in wind-power fluctuated from between 30% and 47% of total investment in renewable energy for the same period (REN (Resolute Energy Corporation) 2017; IRENA 2018). Figure 16 demonstrates that the percentage share of investment in renewable energies is constantly increasing in developing countries. Developing countries' share of investment increased from 21% in 2004 to 48% in 2016; developed countries' share decreased to 52% in 2016 from 79% in 2004 (REN (Resolute Energy Corporation) 2017; IRENA 2018). In Figure 17, China, the USA, and the EU emerge as the major players in investments in renewable energy over the past 13 years. According to a study by BNEF (Bloomberg New Energy Finance) in 2017, approximately US$7 trillion will be spent on solar and wind power generation worldwide by 2040. For the EU to reach a 34% share in renewables development by 2030, an estimated average investment of US$ 73 billion per year is required.

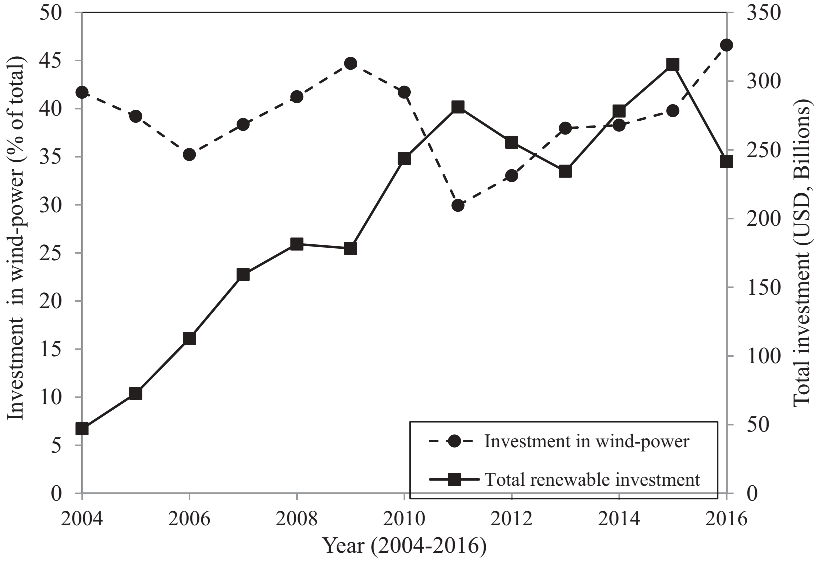


Figure 15. Investment trend in renewable and wind-power sector during 2014–2016 (REN (Resolute Energy Corporation) 2017; BNEF, 2017).

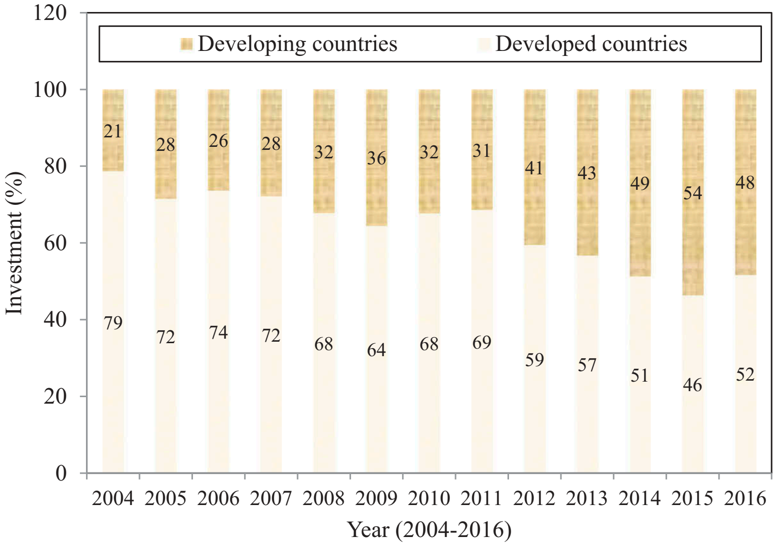


Figure 16. A comparison of investment in renewable energy sector in developed and developing countries (BNEF (Bloomberg New Energy Finance) 2017; IRENA 2018).

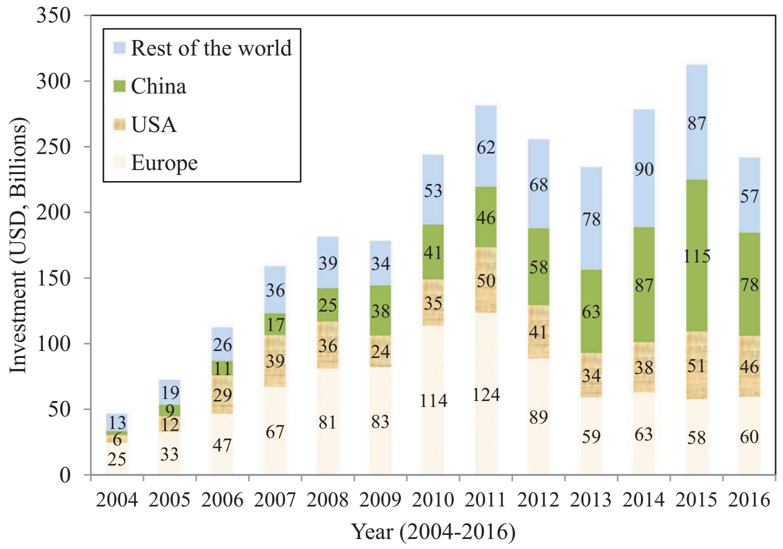


**Figure 17.** Investment trend in renewable energy sector in different regions of the world (REN (Resolute Energy Corporation) 2017; IRENA 2018).

## 8. Key challenges for wind energy development

The existing literature shows that there are significant obstacles preventing the quick penetration of renewable energy resources in general, and wind energy in particular, into the energy generation mix. These obstacles include policy, institutional, regulatory, financial, and information and technological barriers (Arshad and O'Kelly 2018; Qazi et al. 2017; GWEC 2016; ; Singh et al., 2016; Ghafoor et al. 2016; Rauf et al. 2015; Kessides 2013; Victor 2005; Jamasb 2006). From the authors' perspective, these barriers can be documented separately for developing and developed countries.

### 8.1. For developed countries

The key barriers for the development of wind energy resources in developed countries include the following factors:

- Geographical considerations, as sites with the most wind-energy potential, are quite far away from the load centers. The construction of suitable transmission line networks require considerable capital investments;
- There is little incentive to move from fossil-fuel based resources as they already meet the countries' electricity generation needs;
- Investors and developers are subject to sudden changes in legislation related to wind energy, which makes it difficult for them to plan new investments in wind energy assets as well as retrofit existing assets;
- Environmental issues, including radar coverage, rare species endangerment, height restrictions, and the distance of turbine developments from housing areas can cause public opposition to wind-energy developments. Projects have been significantly delayed or even halted due to these issues;
- Transport and logistical issues are becoming much more prevalent as barriers to onshore wind-energy developments due to a lack of sufficient infrastructure, investments, and human resources;
- Offshore developments are impacted by communities concerned about impacts on tourism and nature, causing project delays and cancellations.

### 8.2. For developing countries

Developing countries face principally different barriers than developed countries. These include:

- The lack of public or official awareness and technological knowledge on the potential of renewable energy resources and markets badly hinder the consideration of wind energy options in the decision-making process, at both the national policy-making and investor-planning levels;
- Complex administrative procedures, with the involvement of numerous central and local authorities, dampen investor enthusiasm for such projects;
- In many developing countries, such as Pakistan, electricity transmission networks are outdated and are not capable of supporting additional loads;
- It is difficult for many developing countries to attract workers qualified in the field of renewable energy due to personal security issues;
- Some times corrupt political leadership and lawmakers lead to the absence of transparent and fair policies; therefore, investors are discouraged from the beginning or contributing to projects;
- These countries (developing) can also potentially suffer from a lack of infrastructural and logistical support networks in terms of technical staff, reliable data, transmission lines, dependable grid connection capacity, manufacturing facilities, and transport services. These factors demand large capital investments to correct, thus the cost-effectiveness and economic viability of wind energy projects are undermined;
- Dependence on fossil fuel and the subsidies applied to them are major obstacles to realizing their renewable energy goals;

- Uncertainties in the continuity of government policies are also contributory factors.

## 9. Recommendations for future development and practice

A multidisciplinary approach is suggested as the best solution for making the wind-power industry more cost-effective and practicable:

- Primary legislation may be helpful in order to facilitate multiple governmental stakeholders working amicably with investors and developers on wind-energy projects. This could be facilitated by governments easing current requirements to obtain obligation certificates;
- Financial and fiscal incentives, or lack thereof, can play a vital role in attracting or discouraging private investment in new technologies (such as wind power). Granting soft loans or subsidies for the wind energy sector may prove advantageous;
- The development of wind-energy is, of course, closely linked with the development of the underlying power system, which delivers energy through the grid to the end users. In many developing countries, existing power grid infrastructures and transmission and distribution systems are not capable of performing their functions and should be improved upon to reduce energy losses that lead to reductions in the LCOE;
- The development of innovative fabrication materials (with appropriate characteristics of strength, durability, and light-weight) for wind turbines may contribute to considerable reductions in the LCOE;
- Some regions and countries experience fluctuations in power supply due to a combination of low peak power demand and high wind-energy yields. In these cases, wind power could not only fully cover the national consumption of electricity, but it could also produce surplus wind energy. Given this, investment in electricity storage facilities would be an essential component of an integrated-systems approach to manage demand-supply equations affordably, sustainably and efficiently;
- The use of more sophisticated electromechanical components in wind turbines (e.g. direct-drive units that eliminate the requirement for a gearbox, thereby removing one of the key components prone to failure) will increase the efficiency and hence energy yield, whilst also reducing operation and maintenance costs for the project;
- In-depth experimental and numerical studies should be carried out to bridge the knowledge gap between the existing design codes/guidelines developed for the offshore oil and gas industry, and the more onerous applied loading and larger support structures/foundations required for the offshore wind industry;
- The development of more advanced software tools for modeling wind energy system integration with the power-grid would be very helpful for analysis, testing and evaluation of the accuracy of wind energy generation systems;
- In developing countries, special concerns and objective for further research and analysis should focus on increasing safety, cybersecurity, feasibility, compliance, monitoring and evaluation, and decreasing costs, of such renewable energy projects.

## 10. Summary and conclusions

Wind power appears to be a useful and efficient source of energy to meet the universal goal for clean and cost-effective energy production. Individual wind turbine and wind farm rated power-generation capacity have increased many-fold over the past two decades. This strong growth is projected to continue for the near-to-medium future, particularly in Asia, Europe, and North America. Initial capital investment costs and LCOE for onshore wind-power generation are comparable with conventional fossil-fuel-fired and other renewable technologies; however, these costs have the potential to be reduced even further. Offshore wind-power generation projects attract higher costs on account of the challenges associated with a harsher marine environment and existing deficiencies in design and construction technologies.

The development and improvement of design criteria/methods for wind turbine foundations, support structures and the turbines themselves, along with the use of innovative materials in their fabrication, can be lead to reductions in the LCOE and increases in the lifespan of offshore wind turbines. The introduction of legislation can lead to the reformation of the rules and regulations imposed on the wind-power generation industry. Cost reductions achieved for other offshore industries (e.g. oil/gas sector and offshore cable laying) can also be achieved for the wind-power generation industry through a multidisciplinary and integrated approach. Developments in commodity costs, in particular steel, copper, and cement, will also impact on potential costs for wind-power development projects.

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