Arabian Journal for Science and Engineering (2022) 47:7891–7909
https://doi.org/10.1007/s13369-021-06357-1

REVIEW ARTICLE-MECHANICAL ENGINEERING

Principle Parameters and Environmental Impacts that Affect the Performance of Wind Turbine: An Overview

Mohamed Bashir Ali Bashir[1,2]

Received: 15 August 2021 / Accepted: 28 October 2021 / Published online: 18 November 2021

Abstract

The share of wind-based electricity generation is gradually increasing in the world energy market. Wind energy can reduce dependency on fossil fuels, as the result being attributed to a decrease in global warming. This paper discusses and reviews the basic principle parameters that affect the performance of wind turbines. An overview presents the introduction and the background of energy consumption, following the order of the elaboration of wind turbines, including mathematical models, categories of wind turbines were critically discussed. Moreover, it also focuses on materials that are commonly considered for wind turbine manufacturing, and the process used to recycle them. The scale of recycling methods for fiberglass and thermoplastic is presented in the respective section. Various parameters that reduce the function of wind turbines are explained in depth. This review also discusses various environmental impacts of wind turbines. Future research studies are suggested in the conclusion section.

Keywords Renewable energy · Wind turbine · Impact of wind turbine · Emission reduction

Abbreviations

CO_2	Carbon dioxide
CO	Carbon monoxide
IEA	International energy agency
TCE	Tons of standard coal equivalent
GHG	Greenhouse gases
GDP	Gross domestic product
TEC	Tidal energy converters
GWEC	Global wind energy council
CF	Capacity factor
VAWT	Vertical axis wind turbine
HAWT	Horizontal axis wind turbine
AEP	Annual energy production
NREL	National renewable energy laboratory
ICC	Initial capital cost
FCR	Fixed charge rate
AOE	Annual operating expenses
AC	Alternating current
DC	Direct current
GRP	Glass-reinforced plastic
FRP	Fiber-reinforced polypropylene
PEI	Polyetherimide
PEEK	Polyetheretherketone
PPS	Polyphenylene sulfide
AR	Aspect ratio
TSR	Tip speed ratio

1 Introduction

For decades, utilization of energy has increased remarkably all over the world. Significant efforts were carried out by most of the developing countries to mitigate and minimize the impact of climate change through the optimization of energy use [1]. Moreover, owing to the large combustion of fossil fuels, large quantities of greenhouse gases, carbon dioxide (CO_2), and carbon monoxide (CO) are being released into the atmosphere, which increases the risks of global warming and climate change. Whereas the energy generation of fossil fuels is obtained with only 30–40% of efficiency [2], thus, more than half of the energy is lost as waste heat, which has a detrimental impact on the economy and environment.

✉ Mohamed Bashir Ali Bashir
mbabashir3@gmail.com; mbashir@ju.edu.sa

[1] Department of Mechanical Engineering, College of Engineering, Jouf University, Sakaka 42421, Saudi Arabia

[2] Department of Mechanical Engineering, Faculty of Engineering, Eldaein University, 63312 Eldaein, Sudan

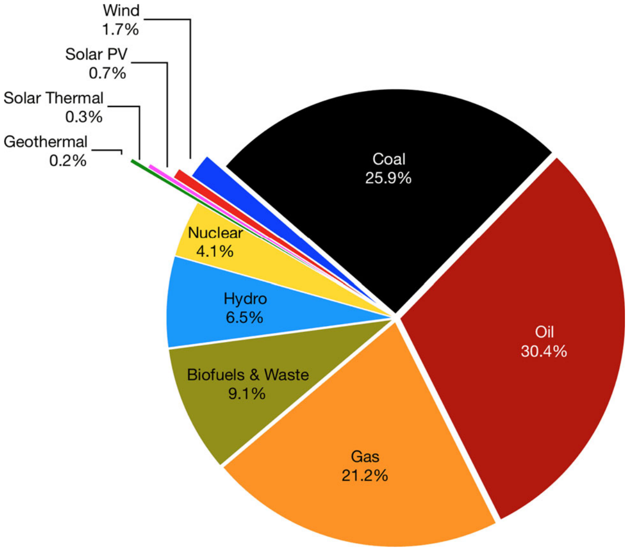


Fig. 1 Global energy consumed from the primary sources in 2017 [6]

Nowadays, the urgent need for alternative energy sources is to cut down the total energy consumption of fossil fuels and greenhouse gas emissions as a result of increasing energy demand. However, global total energy demand increased by about 160% from 1990 to 2017, increasing 1.6 times in 27 years [3]. Thus, continuous efforts and studies focus on a more attractive energy technology that enhances the performance, economic aspect, and climate change with a common strategy adopted by several countries [4]. Moreover, renewable energy sources are crucial and important for the industrial and commercial sectors to run appliances at homes or offices and to run factories [5]. Figure 1 shows the consumption energy rate of fossil fuels and renewable energies in 2017 [6].

Sustainable energy sources, including solar energy, geothermal, tidal energy, hydropower, biomass, and wind power, generated approximately 12–14% of the world's energy demand [7–11]. Among the families of these renewable energy sources, wind power is the most advantageous and effective alternative energy source, which has grown rapidly over the past decades in most developing countries [12–15]. Moreover, wind energy is a hot topic that has been actively discussed in academic and political sectors to explore its potential mitigation of climate change problems [1]. Wind energy offers several benefits, such as being inexpensive, uninterrupted, environmentally friendly, and globally abundant. The energy generated in any form contributes to environmental impacts to some extent, besides, wind energy has negligible environmental impacts compared to conventional energy sources [5].

The growth in wind energy harnessing mainly depends on the energy policy, geographical location, local wind characteristics, and the wind turbine. Among them, the performance of wind turbines has a major influence on wind energy generation. Several factors affect the performance of a wind turbine, including operating wind speed, blade length, tower height, casing design, and surrounding environmental factors such as weathering, icing, and birds and insect collisions [16]. The performance of a wind turbine is prone to the aerodynamics of the blade. Furthermore, a collision of birds and insects alters the aerodynamic shape of the blade, and this leads to an increase in aerodynamic drag, as a result, power generation is decreased by up to 50% [17]. On top of that, the surface is also altered due to ice accumulation; as a result, power generation can be decreased by 20% to 50% [17]. In normal conditions, the performance of wind turbine is directly associated with the profile wind speed at a particular location. The variations occurring in wind speed profiles significantly affect turbine performance.

The reliability of a wind turbine needs to be maximized, as it also determines the other challenges such as maintenance. Referring to statistics on malfunctioning of the turbine, more than 20% of failures in large wind turbines occur due to malfunctioning of the gearbox [18]. Among the other elements, the drivetrain gearbox is the most crucial element associated with failure in large wind turbines. In direct drive type of wind generators, the multistage gearbox is not installed to control the complexity of the shaft speed; this also results in increased failures and excessive wear [19, 20]. The parameters that affect the performance of vertical axis wind turbines include the airfoil shape of the blade, structural design, and Reynolds number, orientation of each blade, number of blades, aspect ratio, chord-to-rotor radius ratio, the blade coning angle, blade pitch angle, height-to-radius ratio, and tower design [21]. All of these parameters have a significant contribution to the turbine's overall efficiency. The decrease in the angle of attack at the blade tip creates turbulence in the wind flow behind the blade tip vortex. This circulation can increase vortex shedding, ultimately increasing the fatigue load and resulting in structural damage. Furthermore, the number of blades for a vertical axis wind turbine is case-dependent, and it determines the efficiency and structural stiffness of the turbine [22].

Therefore, it is crucial to study all the parameters that affect wind turbine performance and to discuss their remedies. Wind turbines are a promising remedy to meet future sustainable energy demands, among which the vertical axis wind turbine is an attractive technology for converting wind into some useful form of energy such as electricity. The latest offshore vertical axis turbine has a 20% less cost of energy than the horizontal axis wind turbine [23]. However, vertical axis wind turbine technology is still not mature to fully replace commercial offshore HAWT installed in shallow waters. The parameters related to aerodynamics and the study on VAWTs have obtained limited attention and referring to a study by Sutherland et al. [22] the best optimal

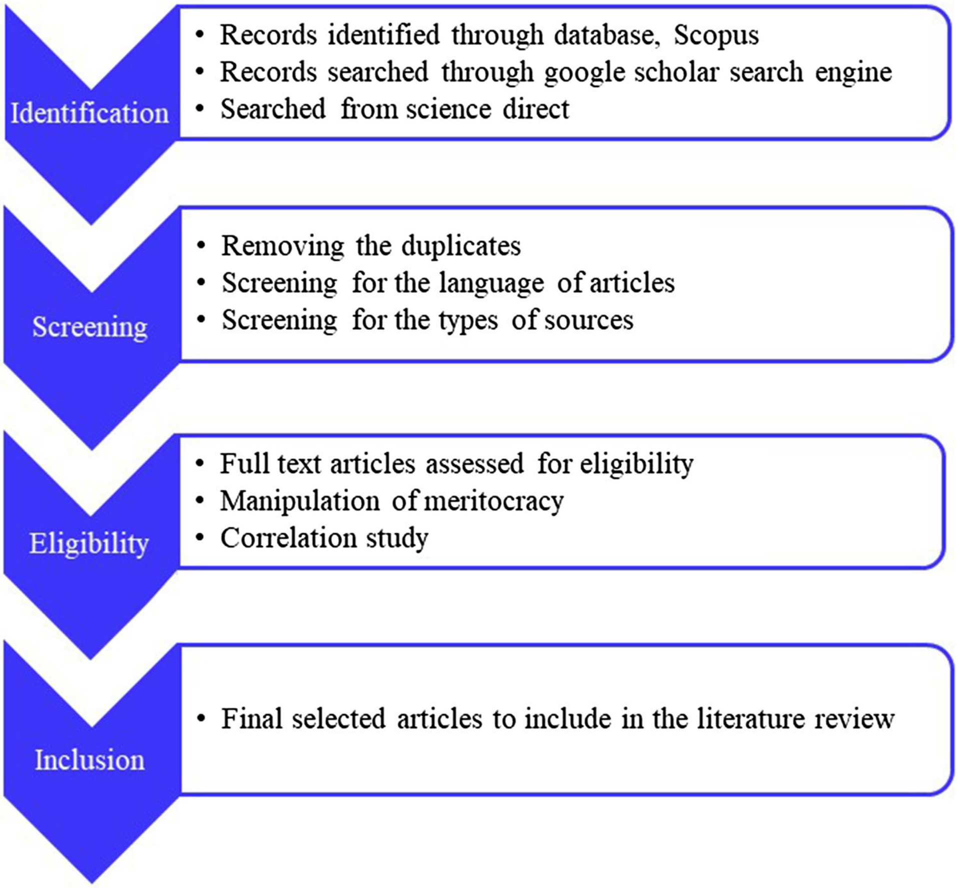


Fig. 2 Flowchart of review process

design is yet an open debate. The current review study provides an understanding of the important parameters that need to be considered for designing the wind turbine, and the recommendation on the areas of future study. This can be a great motivation for researchers working on the optimization of the wind turbine, and especially on aerodynamic performance improvement for VAWT. Furthermore, the process of the current review is explained in Fig. 2.

This paper is structured as follows, after this introduction. Section 2 deliberates the energy consumption. In Sect. 3, the wind turbine is discussed. The parameters involved in the performance of wind turbines are discussed in Sect. 4. In Sect. 5, the environmental impacts of wind turbines are illustrated. We finish in Sect. 6 with the conclusions. The aim of this paper is to illustrate and elaborate on the principle parameters affecting wind turbines, and the environmental impacts of wind energy harnessing.

2 Energy Consumption

World energy consumption has increased rapidly in recent years as a result of population growth, urbanization, and development. Researchers have been focusing on the environmental impacts of the huge utilization of energy, while reducing greenhouse gas emissions. Due to current economic growth and industrial development, experts predict that the global energy requirement by 2050 will be about ~30 TW [24], while at the end of the twenty-first century, it could increase up to ~46 TW [25]. As mentioned in International Energy Agency (IEA) report, global electricity is generated primarily from coal (41.5%), natural gas (20.9%), hydraulic power (15.6%), nuclear energy (13.8%), petroleum products (5.6%), and from other resources is 2.6% [7]. Among the other countries, China was observed to be the country

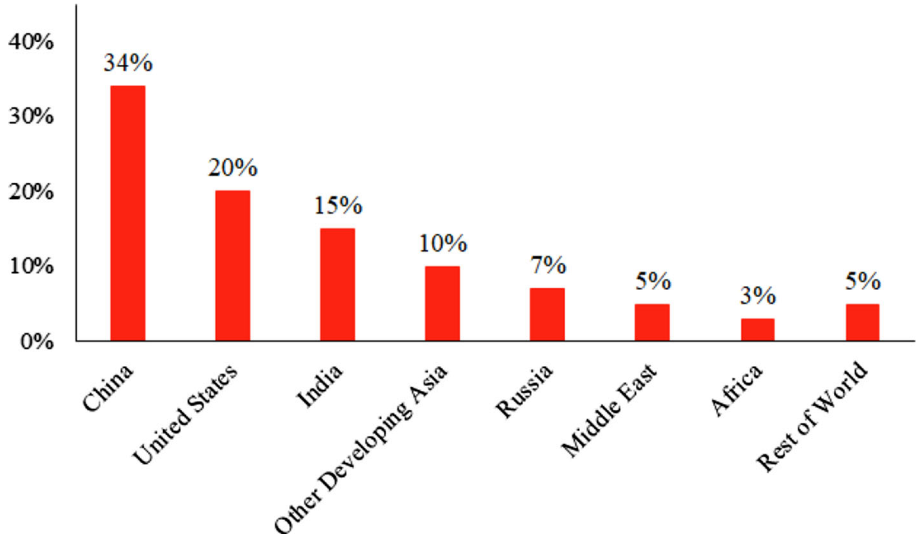


Fig. 3 World's primary energy growth in 2018 [28]

having the largest economy and energy consumption rate in global energy [26, 27]. The energy consumption of China was 571.44 MTCE in the year 1978, which was then increased by 7.9 times by the year 2017, consuming 4490 MTCE, due to rapid industrialization and urbanization [26]. Considering the rapid growth rate in the energy consumption of China, it is predicted to increase to 4957.343 MTCE in the year 2021. As shown in Fig. 3, China had the largest primary energy growth in the world in 2018, followed by the USA [28], whereas Fig. 4 highlights the world's primary energy consumption increased by 2.9% in the same year [28]. The largest amount of energy consumption was based on fossil fuels, which were more than 80% of global energy utilization [29]. The utilization of coal, natural gas, and petroleum as sources of energy leads to an increase in global greenhouse gases (GHG) emissions. Since China is leading in global primary energy consumption, it has become one of the largest CO_2 emitter countries, thereby contributing 27.6% of global emissions in 2017 [27]. However, to reduce its share in the world's GHG emissions, China has established the goal to increase its energy consumption to 20% of renewable energy sources by the year 2030 [30]. This can significantly reduce CO_2 emissions per unit GDP (Gross Domestic Product) by 60 to 65% [30, 31].

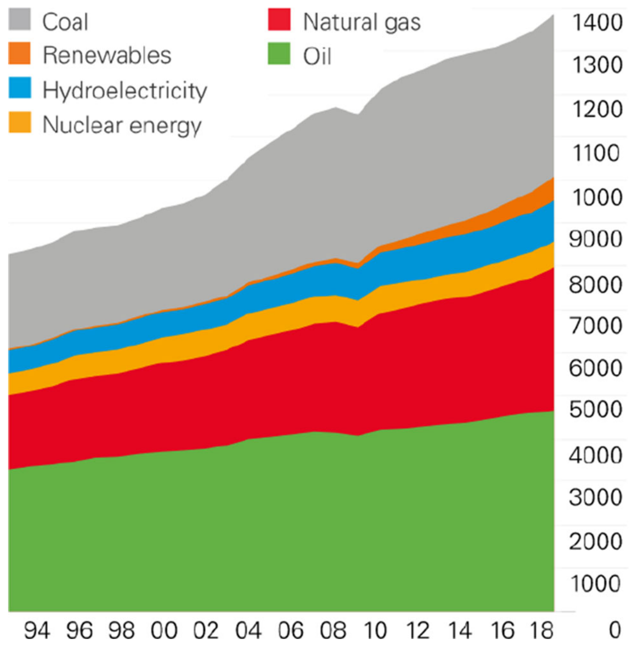


Fig. 4 World's primary energy consumption (million tons oil equivalent) [28]

Additionally, due to the increase in global energy consumption, wind energy has been noted as the most promising green energy source, among other sources of electricity generation [32]. It is a large-scale power generation source, relatively cheap, and can mitigate environmental pollution. Over several decades, many researchers and engineers have suggested the installation of wind turbines for electricity generation in high wind energy density areas such as coastal and plateau regions. This is due to the lower installation cost, higher efficiency of a wind turbine, higher reliability, handiness to the powerhouse, cost-effective operation, and the increased prices of oil production [33]. Apart from this, the worldwide perspective of wind power density is enormous, which is estimated to be 630,720 to 1,489,200 TWh/year [34]. Considering this, the US Department of Energy has set a goal for the country to generate 20% of its total energy consumption from wind by 2030 [35]. While the total wind-based energy generation rate in the country was 5.5% in the year 2016, in which Iowa had the highest share of 36.6% [35]. Such a policy to encourage wind energy harnessing can be a great support for the stakeholders to invest in the installation of the wind turbine. The early-stage development in wind energy was much lower compared to solar energy generation. The main reason for this was poor aggregate policy support, both in terms of wind energy development and wind energy usage. Wind energy development and installed capacity are only higher in developing countries such as China and the USA. It is therefore important to ensure that wind energy is harnessed to its maximum from the installed wind turbines, as this helps to gain the attention of policymakers for wind energy development.

3 Wind Energy Generation

The utilization of the energy generated from greener sources of wind, solar, and ocean energies mitigates CO_2 emissions to the environment. Among them, wind energy technology is the most promising, popular, cheapest, and most attractive renewable energy source [35]. Furthermore, numerous countries have been rapidly investigating the feasibility of installing wind turbines for electrical power generation over the last two decades, because of the higher costs of fossil fuels and unpredictable petroleum supplies from OPEC countries. Studies carried out by research scholars in the field of energy industry have concluded that wind and solar energy sources offer the cleanest and most cost-effective electricity generation [33, 36–38]. Wind turbines are the fastest growing energy generation technologies that offer zero greenhouse effects compared to other renewable energy technologies, including solar cells, tidal energy converters (TEC), hydrogen fuel cells, and the technology involved in power generation biodiesel, and biomass [33].

Wind turbine installation has increased rapidly in most developing countries due to significant reductions in installation costs, which are much lower compared to fossil fuel-based power generation [39]. Moreover, the total installed wind power in the year 1998 was 7600 MW, which was then increased to 364,270 MW by the year 2014 [40]. Afterward, 167 GW of power generated from renewable energy sources was included worldwide in the year 2017 [41]. The installed capacity of 167 GW has a wind power share of 47 GW, including 4 GW generated from offshore wind sources [42]. According to the Global Wind Energy Council (GWEC), worldwide wind energy installations accomplished 591 GW in 2018, and it appears to add 330 GW of wind power to the global energy market from 2019 to 2023, bringing total capacity to over 900 GW [43]. In the year 2019, 59.7 GW of power generated from the newly installed turbines was added to achieve the worldwide capacity of 650.8 GW as shown in Fig. 5 [44]. The major contribution to this addition from the USA and China by generating 9.1 and 27.5 GW, respectively [44]. However, in 2020, markets were slowing down due to Coronavirus crisis.

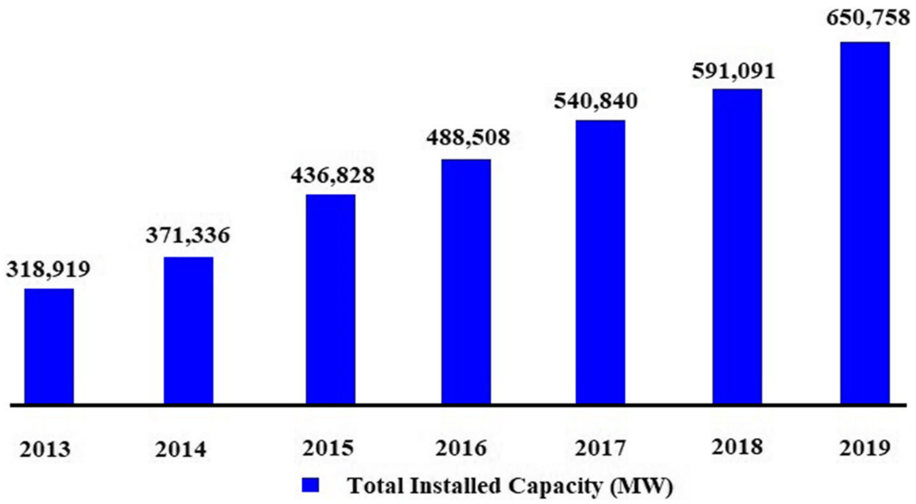
Energy consumption based on renewable energy generation is estimated to increase by 32% in the European Union (EU) by the year 2030. However, it is also estimated that utilization of renewable energy will be increased to 55% to 75% by the year 2050 [45]. In this regard, the IEA report predicted that worldwide energy generation by wind sources will be increased by up to 18% by the year 2050 [40]. Another study expected that over 20% of global electrical energy demands will be from wind energy by 2050 [46, 47]. China is the biggest producer of electricity from wind turbines; it is projected to generate 20% or more of its energy desires from wind energy [47]. If the support of stakeholders continues, wind-based renewable energy generation in the EU could be raised to 965 TWh by 2030, compared to 83 TWh in 2005, supplying 23% of European electricity [48]. In this regard, offshore wind energy generation is likely to increase by 21% each year [49]. In recent years, China has served as the leading country for wind energy installation, and holding 34.03% of global wind energy installation as seen in Fig. 6 [50]. The popularity in the utilization of wind energy technologies worldwide attributes to lower costs per unit of electricity consumption for end users. The exploration of wind energy sources has begun mainly due to the interest to mitigate the environmental pollution that was increased because nonrenewable energy sources were utilized for energy generation. While increasing energy demand and costs are the added motivation to explore further in the wind energy generation industry. Wind energy generation and installation are rapidly increasing in developing countries as well as developing countries. Wind energy generation has several advantages, such as being inexpensive, endless, and minimizes negative impacts on the environment; it is crucial to take advantage of potential sites for wind energy generation.

3.1 Mathematical Models for a Wind Turbine

A wind turbine consists of blades that are linked to the shaft of the rotor. The blades capture the kinetic energy of the upstream wind and transform it into the mechanical energy of the shaft. It is linked to the electrical generator to generate electricity. The amount of power output from a wind turbine depends on the speed of the upstream wind, wind turbine size, and the swept area. The maximum extractable kinetic energy from a wind turbine is limited to $16/27 \approx 59.3\%$ of the available wind power [51]. This is commonly known as Betz limit, referring to Albert Betz in 1919, and it yields the maximum limit of aerodynamic efficiency that a turbine can achieve. The energy yield of a wind turbine is directly related to the air density ρ and the cube of wind velocity v (air density at standard temperature and altitude above sea level is equal to 1.225 kg/m^3), as follows [42]:

$$P_v = \frac{1}{2}\rho A v^3 \tag{1}$$

Fig. 5 Worldwide cumulative wind installed capacity [44]



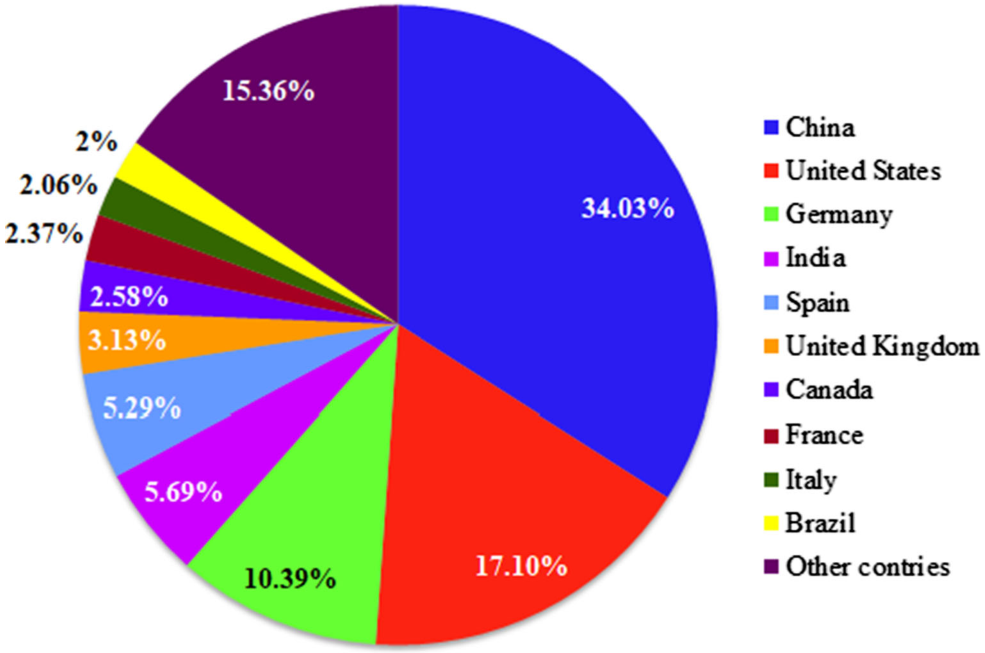


Fig. 6 The share of top ten countries in the global wind energy [50]

where P_v is power (W), $A = \pi R^2$ denotes swept area, and v stands for wind speed. The cut-in and cutoff speed limits of a turbine are set at 3 m/s and 25 m/s, respectively [52]. The mathematical model of the mechanical power (P_m) output or rotor shaft power is computed by the following relation [53, 54]:

$$P_m = C_p P_v \tag{2}$$

$$P_m = \frac{1}{2}\rho A v^3 C_p(\lambda, \beta) \tag{3}$$

where C_p is the coefficient of performance or the turbine efficiency, which is a nonlinear function of tip speed ratio λ and the blade pitch angle β $(0 \le CP \le 1)$. The relationship between the power coefficient (C_p) and the torque coefficient (C_T) is given by Eq. (4) [55]:

$$C_p = C_T \lambda \tag{4}$$

The tip speed ratio, λ, can be computed by Eq. (5) as:

$$\lambda = \frac{R.\omega_m}{v} \tag{5}$$

In the Eq. (5), R stands for blade length (i.e., radius of swept area) and ω_m denotes angular speed. Since the mechanical power of the rotor shaft is transferred to the electrical generator via a gearbox, the resultant power relies on the efficiency of the gearbox (η_m) and generator (η_g). The resultant output power (P) can be computed using Eq. (6) [33]:

$$P = \frac{1}{2}\rho A v^3 C_p \eta_m \eta_g \tag{6}$$

Because wind speed is variable with time, wind turbines operating at its rated speed are very rare [56]. In this case, the capacity factor is useful to estimate the average power generated by the turbine. The dimensionless CF is expressed as [57]:

$$\mathrm{CF} = \frac{P_{e,\mathrm{avg}}}{P_r} = \int_{V_i}^{V_R} P_n f(V)\mathrm{d}V + \int_{V_R}^{V_0} f(V)\mathrm{d}V \tag{7}$$

The performance of VAWT is mainly exhibited by the coefficient of torque (C_t) and power (C_p). Following Eqs. (8) and (9) are useful to compute C_t and C_p of the Darrieus-type VAWT [43]:

$$C_t = \frac{T(t)}{0.5\rho A {v_\infty}^2 R} \tag{8}$$

$$C_p = \frac{P(t)}{0.5\rho A {v_\infty}^3} \tag{9}$$

where *T(t)* shows the instantaneous torque, *P(t)* stands for the power produced by the turbine. Further, ρ denotes air density, V_∞ denotes the free-stream velocity, and swept area is computed by A = DH [11, 43, 57].

The manufacturers in the wind energy industry always focus to design the turbine that performs with better efficiency for a longer period. To help manufacturers with this aim, researchers always investigate the characteristics that are associated with wind turbine performance during shorter and longer periods [58]. One of the methods to improve its performance is the maximizing annual energy production, generally expressed as [59]

$$\mathrm{AEP(KWh)} = P_{e,\mathrm{avg}} \times \mathrm{time} = P_{e,\mathrm{avg}}(\mathrm{KW}) \times 8760(\mathrm{h}) \tag{10}$$

The AEP can be normalized to compute from the mean yearly produced wind, given as:

$$W_M = \frac{1}{2}\rho A V_M^3 \tag{11}$$

The total cost of the wind turbine can be computed using the NREL model, given as:

$$\mathrm{Cost} = \mathrm{FCR} \times \mathrm{ICC} + \mathrm{AOE} \tag{12}$$

In Eq. (12), “Cost” means the total turbine cost, “ICC” stands for an initial capital cost of the turbine, “FCR” means fixed charge rate, and “AOE” means the annual operating expenses of the turbine [60].

3.2 Categories of Wind Turbine

Wind turbines generate electricity by using the kinetic energy of the wind speed to drive the rotor shaft linked to a generator. The size of turbines varies from small, having generating capacities up to 10 kW, to large, having generating capacities up to 10,000 kW. The blade length is the key factor in assessing the electrical power generation capability of the turbine, as shown in Fig. 7. The main classification of wind turbines is (a) horizontal axis wind turbine (HAWT) and (b) vertical axis wind turbine (VAWT) [61, 62]. There are several types of VAWT, such as (i) Darrieus, (ii) Savonius, (iii) Straight-bladed, (iv) Troposkien, and (v) Helical-type as displayed in Fig. 8 [64]. Additionally, the classification of wind turbines can be based on the driving force, *i.e.,* lift-type and drag-type wind turbines. An example of lift-type is a horizontal axis wind turbine and an example of drag type is Darrieus turbine [63].

Choosing the type of wind turbine depends upon the intended scale of energy generation, for large-scale wind power harnessing, HAWTs are installed, while VAWTs are preferred for stand-alone or small-scale wind power. Preferring VAWT has several merits over a HAWT, such as minimum complexity due to smaller size, effortless installation, and independence of wind direction. The maintenance of VAWt is also much easier as it operates at comparatively lower heights, with an efficiency of above 70% [61]. The absence of a yaw mechanism makes VAWTs more suitable in terms of reduced structural complexity and easier power production. However, the main drawback of VAWT includes the absence of self-start-up ability and smaller aerodynamic performance [65–68]. The merits that attract interest in installing VAWT are summarized as [69–73]:

- Absence of yaw mechanism: it does not depend on the direction of the wind when generating the power.
- Minimum noise: as it operates at a low tip speed ratio.
- Minimum cost of manufacturing: the smaller size, absence of yaw mechanism, and ordinary profile of the blade reduce the cost of manufacturing.
- Minimum installation cost: the smaller height of the tower reduces installation and maintenance costs.
- Scalability: there is a lower effect of tower height on turbine performance.
- Minimum shadow flickering.
- Environmental safety: environmental safety in terms of minimum bird death rates.
- Visually appealing.

A typical horizontal axis is paramount in the wind power industry, having the design identical to the windmill. It can be classified based on several parameters. One of the classifications considering the power rating and the diameter of

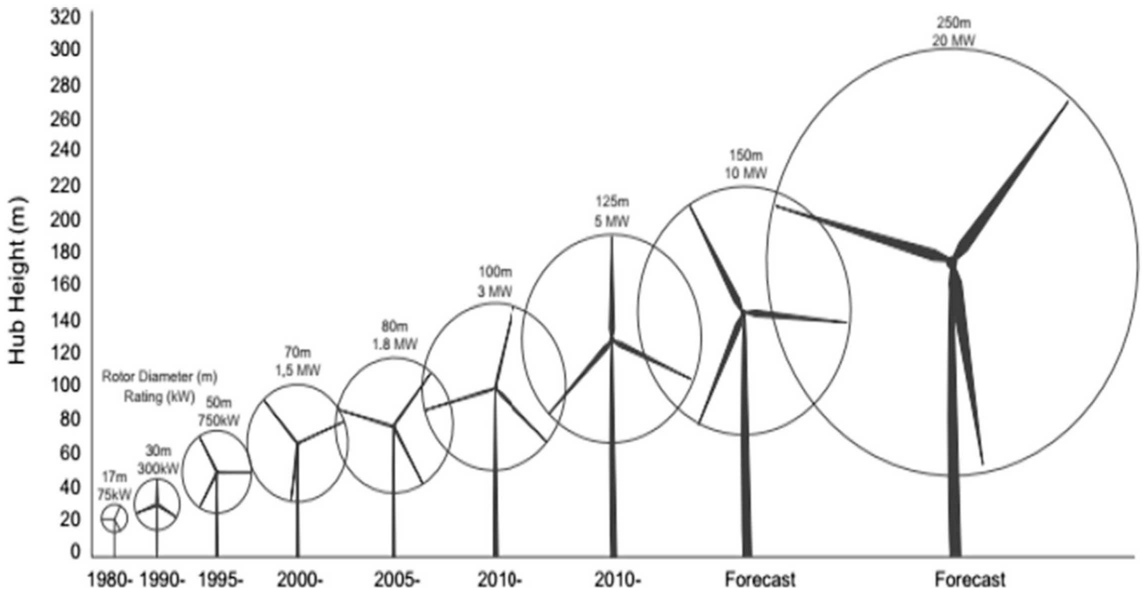


Fig. 7 Growth in the size of commercial wind turbines [63]

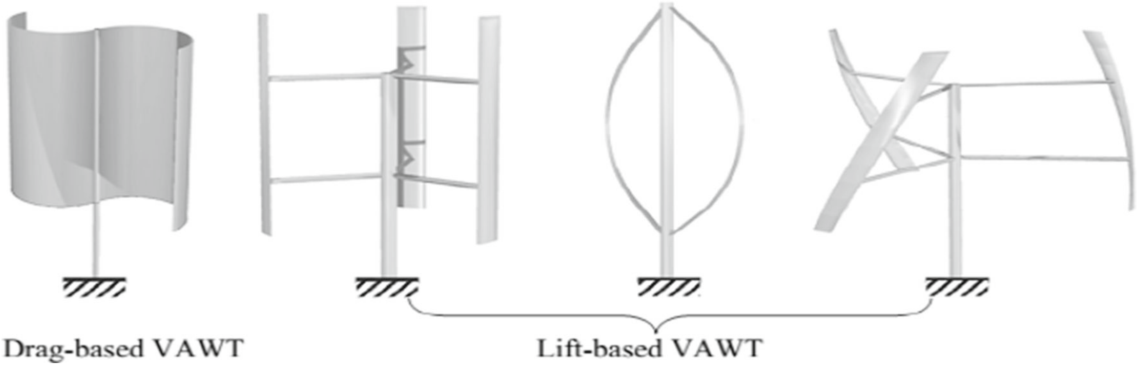


Fig. 8 Types of vertical wind turbines based on driving force **a** S-Shaped Savonius, **b** Straight-Bladed, **c** Troposkien, and **d** Helical-Shaped Darrieus wind turbine [64]

the turbine swept area is shown in Table 1 [61]. The generator is located inside the casing at the top of the tower; it is linked to a rotor shaft. The rotor of the wind turbine needs to face the direction of the wind for better performance; therefore, a yaw mechanism is installed in the HAWTs and a vane in the small HAWTs to direct them in line with the wind direction [74]. Inside the casing, there is also a gearbox to speed up shaft rotations so that the electric generator receives enough rpm required for power generation. The gearbox can be auto-controlled employing a servomotor, which is linked to a wind sensor. In this way, the turbine is capable of generating electricity from high wind speeds [39]. During high wind speed, turbulence can occur due to the turbine tower; therefore, the rotor is placed in front of the tower. The blades of wind turbines are also made rigid to withstand the load caused by high winds [74]. Although the tower creates turbulence during high winds, some turbines are still made by installing the rotor behind the tower, as it does not require an extra mechanism to change the direction. Moreover, the blades of the turbine bend during high winds, so the swept area is decreased and hence the wind load during high winds is also decreased.

There are several advantages of HAWTs such as:

3.2.1 High Operating Wind Speed

A horizontal axis wind turbine is most suitable to install on sites that are observed to have high wind speeds. Since the amount of energy generated by a turbine is related to its swept area and upstream wind speed, large-scale wind turbines are installed at those sites. Many of the offshore wind sites experience wind speed up to 20 m/s [75]. At such wind speed, VAWT is not suitable to install, whereas the HAWT can generate appreciable power. Furthermore, increasing the height of the tower will enable the turbine to receive high wind speed. Moreover, wind speed and power can increase

Table 1 Classification of horizontal axis wind turbine based on turbine swept area and power rating [61]

Types of HAWT	Rotor diameter (m)		Swept area (m^2)		Standard power rating (kW)	
Small scale						
Micro	0.5	1.25	0.2	1.2	0.004	0.25
Mini	1.25	3	1.2	7.1	0.25	1.4
Household	3	10	7	79	1.4	16
Small commercial	10	20	79	314	25	100
Medium commercial	20	50	314	1963	100	1000
Large commercial	50	100	1963	7854	1000	3000

by 20% and 30%, respectively, with increasing the tower height of 10 m. Under extreme wind conditions, the wind turbine rotates extremely fast, which can damage the turbine [76, 77]. Therefore, the wind turbine is designed at certain cut-in and cutoff speed. The cutoff velocity for the HAWT is always higher than the VAWT, thus indicating a higher energy yield. Depending on the wind profile at a particular location, the HAWT can be designed as a variable and a fixed-speed generator. Fixed-speed generators have higher efficiency if the turbine operates at its rated wind speed. While variable wind speed generators can operate at different upstream wind velocities and hence capture more energy, as the wind speed is variable in a real-life scenario [78].

3.2.2 High Efficiency

The blades of HAWT rotate perpendicular to the direction of the upstream wind; it allows extracting maximum energy from wind, along with whole rotation. HAWTs have the highest efficiency; they can convert 40% to 50% of receiving wind power into electricity [79]. The theoretical efficiency for HAWT is about 60% [39]. Despite the fact that the efficiency of HAWT is higher, they need high maintenance because of the additional parts installed on the turbines.

3.2.3 High Power Production

HAWT works in the same of a windmill; however, it is modernized. The modern HAWT is equipped with sensors to record real-time wind speed and direction, and a special yaw mechanism to direct it in the correct direction. The pitch of the blades is also variable; hence, the maximum power can be produced from wind [80].

3.2.4 High Reliability

The HAWT has been paramount in the wind power industry for decades. A lot of research has already been carried out on different aspects of the manufacturing, installation, and operation of a HAWT. Hence, the HAWT is more mature compared to other types of wind turbines [77].

The drawbacks of HAWTs are:

- The HAWTs have higher construction costs; a strong foundation is required to withstand the weight of the turbine rotor and casing
- Wind turbines are unappealing and disrupting the appearance of the landscape.
- Heavy machinery is needed to lift the turbine components
- HAWTs require an additional yaw control mechanism
- Cyclic stresses and vibration

3.3 Materials Used in the Manufacturing of Wind Turbine

Generally, composite materials are used in the blades; nacelles are made mostly from steel and copper, and the towers are manufactured from steel and concrete [40]. The blades are the most important part of a turbine. Historically, in 1941, wind turbine blades were made from steel in Vermont in the USA; however, a few hundred hours later, one of the blades failed [49]. The next, three composite blade wind turbine was installed in Denmark in 1956–1957. The turbine produced power for eleven years, and its blades were manufactured with steel spars, containing aluminum shells fitted on the wooden ribs. Following the 1970s, wind turbine manufacturing began production containing composite blades [49].

Nowadays, research has been focused on improving the individual wind turbine components. The materials of wind turbines are being recycled by conventional methods; however, the recycling of composite materials is still a challenge to researchers [39]. The main advantages of using composite materials are having the best mechanical properties and being light in weight. Wind turbine blades have the highest cost component of a turbine [40, 49], and an average of ten kg of blade material is needed per one kW of power generation [81]. The performance of the blade mainly depends upon its geometry and the type of airfoil [82]. Several research studies mainly focus on investigating the type of material to be used in the manufacturing of blades. The proper physical and mechanical properties of materials are studied thoroughly while manufacturing a wind turbine blade. These properties include lightweight, high strength, greater fatigue resistance, and greater stiffness [83]. The main focus for blade manufacturers remains to get a better material that will be beneficial in terms of performance, weight, and cost. The paramount challenge to enhance the manufacturing and performance of wind turbine blades is to get the material that has a higher recycling ability, simple processing, cost-effective, and it can last longer. Moreover, several types of materials employed during the manufacturing of blades are as follows:

3.3.1 Glass Fiber

The glass fibers are prepared from the mixture of silicon dioxide and aluminum oxide, which also contain some impurities in trace quantities to improve its strength. The diameter of fibers is kept at 5–10 μm while the desired strength is ensured by setting up the suitable density and stiffness. Apart from glass fibers, the blade of a wind turbine is also made from aramid and basalt fibers, natural fibers, polyester, or hybrid composites [84]. Numerous studies focus on the manufacturing of fibers that have higher strength compared to E-glass fiber, such as modified glass fiber compositions (*i.e.,* S and R types of glass fiber), carbon, basalt, and aramid types of fibers. The S-type of glass fiber was first introduced in the 1960s, having greater tensile (40%) and compressive (20%) strengths when compared to the E-type of glass fiber [85]. However, the price of S2-type glass fiber is around 10 times higher than that of E-glass.

Apart from high strength glass fibers, natural fibers are becoming popular due to their benefits like low cost, fairly mechanical properties, high specific strength, nonabrasive, biodegradable, and eco-friendly characteristics [83]. However, some disadvantages of these fibers include the flexible quality, increased moisture, and lower thermal stability [49].

Glass-reinforced plastic (GRP) is widely used in Chinese-made D61250 models. Such turbines are three-bladed, having blade length and pole height of 32 m and 68 m, respectively [86]. Moreover, the most suitable type of composites to manufacture the blades of a wind turbine are hybrid composites. Hybrid reinforcements like E-glass and carbon, and e-glass and aramid are promising substitutes for pure carbon and glass reinforcements. The research focus on these types of composites is predominant when considering the lightweight demand for wind turbine blades. To this end, Westphal et al. [87] analyzed the properties of hybrid composites consisting of glass and carbon in the application of the blade manufacturing scope of carbon glass hybrid composites in wind turbine blade applications by comparing the properties of carbon and glass laminates with hybrid laminates. It was concluded that the hybrid laminates showed favorable behavior in static tensile and fatigue loading conditions. However, their main concern is the compromise on the properties of high carbon fibers such as stiffness, fatigue, and stiffness. Furthermore, Thomas and Ramachandra [83] demonstrated that the full replacement of the pure glass reinforcements to hybrid composites will result in an 80% weight saving and a 150% expenditure increment, whereas a partial (*i.e.,* 30%) replacement in a turbine with 8 m blades would benefit from a 90% increased expenditure and 50% reduction in weight [9]. The wind turbine manufactured by LM wind power is an example of a hybrid composite consisting of carbon and glass, the turbine having the largest rotor (i.e., 80.4 m long) [49].

3.3.2 Carbon Fiber

An optimistic substitute for glass fiber is carbon fiber (CFs), having favorable mechanical characteristics in terms of strength and quality. Carbon fibers have greater anisotropy in higher stiffness and thermal expansion [84]. Compared to glass fibers, CFs have advantageous attributes in terms of maximum stiffness and minimum density. Despite that, blades manufactured from CFs possess very minimum damage tolerance, compression strength, and higher strain. Besides, the cost of CFs is also very high, compared to E-glass fibers [49]. The recycling of carbon fibers depends upon economic as well as environmental factors. Both the materials, *i.e.,* CFs and GFs, possess a higher ability to recycle in terms of environmental and economic perspective, which makes them energy-intensive when manufacturing. There exist different methods to recycle the CFs; they can be classified as mechanical, chemical, and thermal recycling. Adopting any of these methods depends upon the feasibility at the industrial and laboratory scale, setup costs, and more importantly, on the quality of the composites. Considering these limitations, researchers are more attracted to the hybrid method. The current hot topic in hybrid recycling research is microwave-supported chemical recycling [88].

3.3.3 Thermoplastic Composite

Nowadays, thermoset polymers are widely employed in the manufacturing of wind blades due to the beneficial properties of stiffness and strength, and easiness in the manufacturing process. However, the emission of styrene during the manufacturing process and the dumping of the blade are promising challenges. The important feature of thermoplastic polymers is the phase change property due to an increase in temperature; that is why they are easy to recycle and repair. The comparative analysis on the mechanical characteristics of fiber-reinforced polypropylene (FRP) and fiber-reinforced epoxy was conducted by [6]; the final results showed the higher strength (7 to 8 times) of thermoplastic FRP compared to thermoset FPR. Whereas the strength of alternative thermoplastic FRP is even higher, these alternative materials include polyetherimide (PEI), polyetheretherketone (PEEK), and polyphenylene sulfide (PPS). Apart from this, the widely required to manufacture a turbine blade is anionic polyamide-6 (APA-6), and it has enhanced static and fatigue characteristics. Moreover, it is also economically efficient to use in wind turbine blades as the expenses of resin and recycling processes are comparatively lower [83].

The wind turbine blades are manufactured from fiber-reinforced polymer composites to provide resistance to physical loads such as gravity. The current composites used for manufacturing are able to give partial support against such physical loads. Therefore, the scientists are researching alternative composites that are environmentally friendly, easy to recycle, stronger, and have the greatest damage resistance. One such example is the advancement of epoxy resins, which give a maximum wetting of the fibers. After the wind blade is manufactured, the composite fibers are applied as surface sizing, for the protection of fibers and to increase the bonding strength. Sizing comprises the aqueous suspension having 3 to 10% solid material [89]. There are several advantages of sizing such as making the fibers homogenous, an increase in fiber-matrix interaction, reduced void content, and decreasing the fuzzy behavior. Furthermore, the desired materials chosen for manufacturing of blades should be selected based on features such as lower cost, fair mechanical properties, high specific strength, nonabrasive, biodegradable, eco-friendly features, moderate density, high stiffness to ensure stability, longer life, higher performance, easiness in processing, and the ability to recycle [88].

Wind energy installations are growing dramatically and becoming globalized. The growth of wind energy installations creates tough competition for manufacturers to become dominant. In the previous year 2020, 24.6 billion USD was invested in the USA for the installation of new wind projects [90]. Due to a significant increase in investment for the installation of the wind turbine, Denmark-based company Vestas was the biggest manufacturer of wind turbines in 2020, installing a total wind power capacity of 9.6 GW [91]. However, other companies are shown in Fig. 9 [90].

4 Parameters Affecting the Performance of Wind Turbine

Renewable energy resources have enormous potential to produce power, not only because of the abundant resources, but also because of the greenhouse gas, and other pollutant emission reduction opportunities. With the increasing shortage of energy supply worldwide, wind energy is receiving, and wind turbines are the best tool for wind energy utilization. Moreover, designing an efficient wind turbine contributes to reducing dependency on nonrenewable resources, natural environmental restoration, and removing or reducing the utilization of toxins [74]. Hence, the performance of wind turbines is crucial in wind energy generation. It can be affected by several parameters like sweeping area, air density, wind speed, and power coefficient as a function of pitch angle and blade tip speed. Parameters affecting wind turbine performance are discussed below:

4.1 Effect of Blade Length

The wind is a natural occurrence of airflow at a particular speed and direction, thus possessing a high density of kinetic power. The kinetic power is harnessed by the wind turbine blades to create mechanical power, which is then converted to electrical energy by the generator. Design and manufacturing of the wind turbine blades are critical to achieving better performance through high strength and fatigue while minimizing the cost and weight. The blade is one of the most important components of a wind turbine that is in direct contact with the wind. To improve wind utilization, the aerodynamic performance of the airfoil needs to be enhanced. The performance of the airfoil affects the blade performance, thus affecting the power output of the wind turbine. Furthermore, the wind turbine is also affected by the number of blades. In large-scale HAWT, three blades are installed, whereas, in small-scale wind turbines such as the Savonius turbine, the optimum number of blades is two [50].

While considering blade design parameters, blade length is equally important as it has a significant effect on wind power harvesting. The relationship between rotor diameter and the power rating for HAWT is presented in Table 1 [61]. The larger the blade length of a wind turbine, the more power can be extracted from the wind. For example, the Whisper-500 wind machine has a 1.8 m blade length, and the mechanical power and electrical power output are rated at 3550 W and 3200 W, respectively. In the same way, the NY-WSR1204 wind turbine has a blade length of 0.8 m, which has 700 W mechanical power and 600 W electrical power output [47].

A typical horizontal axis wind turbine blade can be divided into three sections, namely the root, mid-span, and tip as shown in Fig. 10 [79]. The aerodynamic efficiency of the blade is higher at the tip; it decreases along the blade length, and becomes minimal at the root. The root of the blade should withstand the structural load, and hence, it is made thicker compared to other sections of the blade.

4.2 Effect of Wind Speed

Wind turbines depend on meteorological conditions, particularly the magnitude of the wind speed [93]. This subsection is concerned with the influence of one of the weather components on the wind turbines; that is, wind speed [8]. Wind speed and turbulence have a significant influence on wind turbine performance at a height of up to 160 m. According to [93], the relation of wind speed with height is computed by the following equation:

$$\overline{v}_H = \overline{v}_{\text{ref}} \cdot \left(\frac{H}{H_{\text{ref}}}\right)^{\alpha} \tag{13}$$

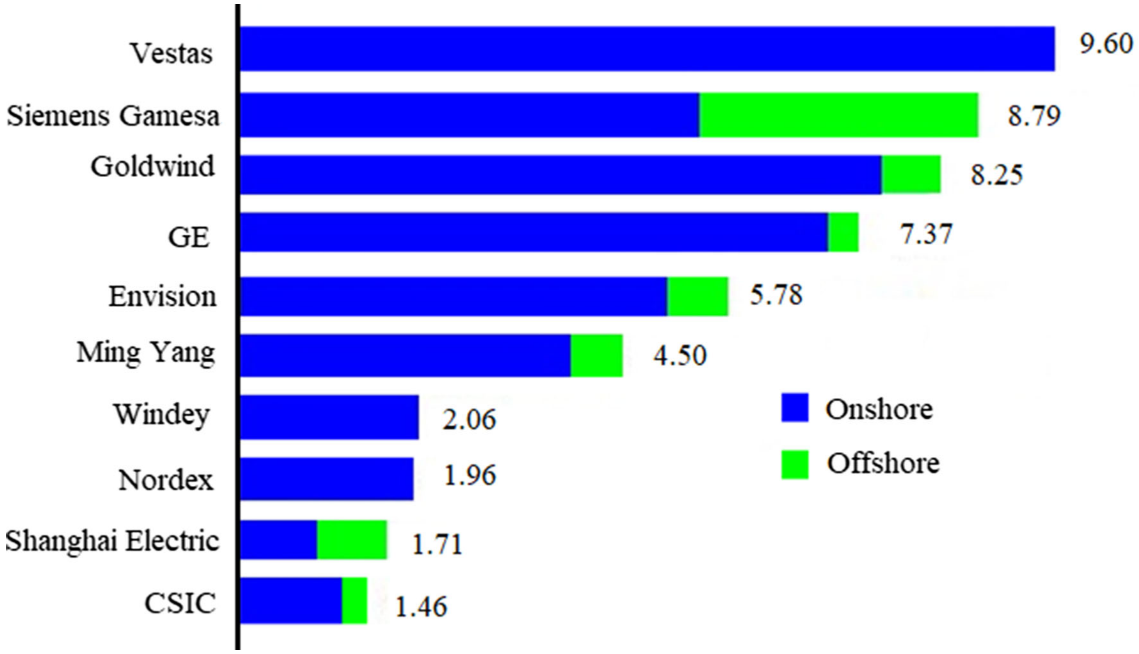


Fig. 9 Top ten wind turbine manufacturers by installations in the year 2020 [90, 92]

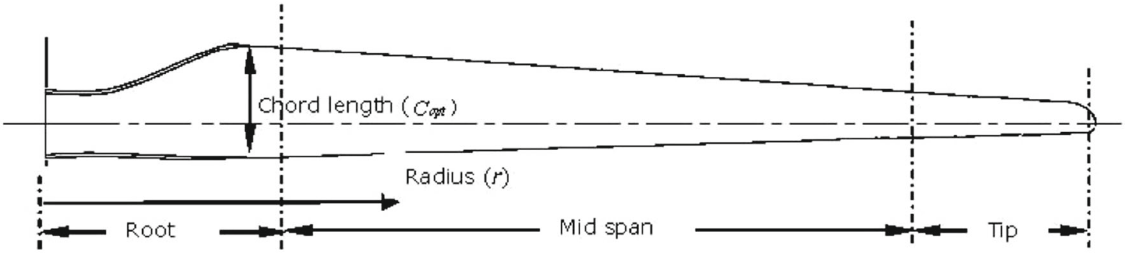


Fig. 10 Sections of a typical horizontal axis wind turbine blade [79]

where $\overline{v}_H$ stands for wind speed at elevation H (m/s), $\overline{v}_{\text{ref}}$ is the mean wind speed at reference elevation H_{ref}, H is the height (m), H_{ref} is the reference height (m), and α is Hellman's exponent or shear exponent. Many research studies illustrate the influence of wind speed on the turbine at a flat terrain site. The results show that wind turbines heavily depend upon atmospheric conditions, and consequently, power generation increases with the increase in the wind speed at the hub height [62]. However, wind turbines have to be designed to cope with various types of loads due to these effects, such as [8];

- Large instantaneous wind loads causing stress above the ultimate tensile strength of subassembly components
- Long-term wind load fluctuations, in time and magnitude that exceed the fatigue strength of subassembly components.

4.3 Effect of Air Density

Wind is a form of solar energy, thus the result of the uneven heating of the atmosphere through the sun, the irregularities of the earth's surface, and the rotation of the earth [81]. The kinetic energy in the wind, thus, depends on the density of the air. In other words, the denser the air, the more energy obtained by the wind turbine. A very high humidity combined with foggy, rainy weather, and icing in winter often reduces turbine performance [81]. At normal atmospheric pressure and 15° Celsius, air density is 1.225 kg/m^3, but it decreases slightly with increasing humidity. The relation between air density and wind speed can be expressed as follows [61];

$$U_n = U_t \left(\frac{\rho_t}{\rho_o} \right)^{1/3} \tag{14}$$

where $\rho_o = 1.225$ kg/m^3 is the standard density for which the power curve is given by the wind turbine manufacturer.

The density of air varies according to the location and the season of the year. Thus, air density plays an important role while doing wind energy assessment. The errors can be reduced when the seasonal variation of the air density at a particular location is considered instead of the constant air density. The variation of ± 6% can be observed due to change of season, i.e., winter to summer [94]. In the Northern Hemisphere, although changes in air density and wind speed are smaller, the variation in wind power density can be higher, mainly due to air density instead of wind speed. However, this effect is low in tropical locations.

4.4 Effect of Aspect Ratio

The aspect ratio is more important in the power yield of the turbine. It can be defined as the ratio between the blade length and the rotor radius. The aerodynamic performance of the Savonius rotor depends strongly on the aspect ratio (AR). Several research studies on Savonius tested different configurations for aspect ratios (noted α in the range of 0.5 to 5) by keeping other parameters constant; the results display that the power coefficient increases with the rise in the aspect ratio [95]. Various designs of change Savonius rotors having low AR have been reported in recent years. The study conducted by Yirtici et al. [45] concluded that the aspect ratio of 0.7 can achieve a maximum C_p of 0.21, and [96] confirmed that an AR of 0.77 achieved a maximum C_p of 0.24. Generally, the utilization of AR within the range of 1.5 to 2.0 set good results on the performance of the Savonius rotor [50]. The AR of a wind turbine changes Reynold's number, and hence, the performance of the turbine is also affected. The lower AR turbines are noted to have a higher coefficient of power as compared to turbines with higher AR, in the case of vertical axis wind turbines. Furthermore, a turbine with a low AR has less blade length and high cord length; as a result, the turbine can withstand a higher structural load. It also gives higher inertia moments, which means it has greater in-service stability [95].

4.5 Effect of Overlap Ratio

The overlap ratio is a major parameter that influences the structure of the flow around the rotor and consequently its aerodynamic performance. Most of the research studies show that the optimal value of the overlap ratio is in the range between 0.1 and 0.3 [27, 50, 97]. Additionally, [48] illustrated that the overlap ratio equal to 0.15 shows the best performance and gives an averaged power coefficient equal to 0.3161 for the TSR of 1.25 for Savonius rotor. The overlap in the Savonius blade allows a passage for air to pass between the turbine blades. This passage helps the air coming from the advancing blade to pass freely, leaving less thrust on the returning blade. Hence, the moment of the Savonius rotor is also increased. When the air from the advancing blade passes through this passage, the pressure behind the returning blade (i.e., concave side) is increased. In this way, the performance of Savonius turbine with a certain overlap is increased compared to the turbine with zero overlap ratio, because the drag on the Savonius rotor is also reduced [98].

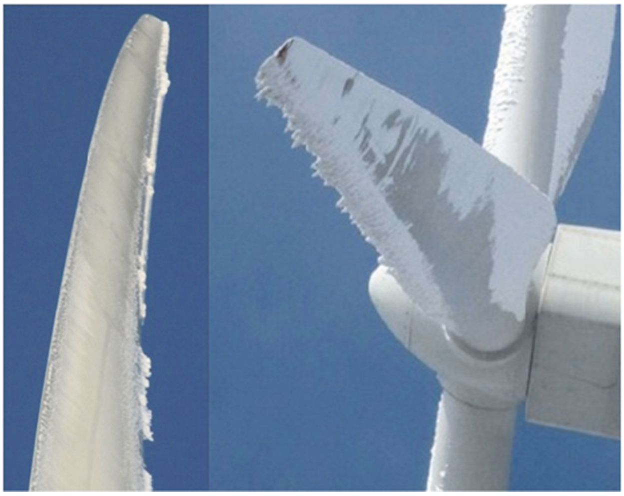


Fig. 11 The ice accumulation on the surface of the wind turbine blade [84]

4.6 Icing Effect

Icing is a physical phenomenon in cold climate regions; it has greater negative effects on wind turbine performance. The ice accumulation on the blade surfaces disturbs aerodynamic performance and safety, as shown in Fig. 11 [81, 84]. The major concerns due to icing can be the increase in mass on the blade, changes in the aerodynamic profile shape, unusual tower vibrations, decreasing the torque, and induced power output losses, etc. [26, 28]. Turbine blades are highly susceptible to ambient atmospheric environments such as icing. The small icing roughness on the surface of the turbine blade decreases the power output, whereas the heavy icing event can cause a complete turbine shutdown [99].

The icing effect results in the loss of Annual Energy Production (AEP) up to 17% and reduces the power coefficient in the range of 20–50% [30]. From a research project analysis by [100], the 517 wind turbines producing the 682 MW of electrical power decreased their production due to the blade's icing and had a cumulative loss of 18,966 MWh within 29 months. Conversely, ice accretion can cause overproduction of power output by changing the blade profile [99].

There are two techniques of ice measurement for wind turbines; (1) nacelle-based and (2) blade-based [99]. Additionally, numerous techniques have been used to avoid, reduce, and remove the ice from the blade surface. Moreover, techniques for icing mitigation can be either passive techniques which typically employ hydrophobic or icephobic paint on the surface, or active techniques that are used for removing ice from turbine blades and are either anti-icing or de-icing [99].

4.7 Rain Effect

The performance of wind turbines can be affected by different meteorological conditions during the operation. Rainfall is a physical phenomenon and one of the most common meteorological conditions. The performance of wind turbines can be influenced by the ambient atmospheric environment like rain; however, rain can induce a decrease in the aerodynamic lift and increase the drag [10, 35]. Rainwater can cause erosion on the surfaces of wind turbine blades [9, 35]. The erosion of the blades increases the surface roughness as the results increase the aerodynamic drag coefficient of the blades, ultimately resulting in undesirably lower performance and energy loss [9]. The annual energy production losses could be as high as 25% due to erosion on wind turbine blades [97].

Furthermore, water vapor condensation occurs extensively in the low-pressure region above the airfoil and releases the latent heat of water drops [10]. The rest of the incident rain drops form a thin water film upon the airfoil surface. The film is impacted by subsequent raindrops, which cause many craters and result in an uneven film that effectively roughens the airfoil surface and increases drag [35]. Several studies have shown that the performance of wind turbines decreases by up to 27% in power output due to the effects of rain [6, 97]. Additionally, there are still many other uncertain rain effects on wind turbine performance.

4.8 Effect of Diffuser Efficiency

A diffuser surrounding a rotor is a promising technique to enhance the performance of wind turbines above the Betz–Joukowsky limit (16/27) by accelerating and directing the airflow through the rotor disc. Moreover, placing a diffuser around the rotor would induce a velocity vector to increase the mass flow through the wind turbine rotor; in this way the theoretical Betz limit can be exceeded. Diffuser types vary according to the cross-sectional profile, as shown in Fig. 12 [48]. Many research studies show that utilizing diffusers on wind turbine rotors has attracted great attention for many years. The report carried out by Lilley and Rainbird [96] had estimated that a 65% increase in maximum power could be attained using a duct with a 3.5 m^2 area ratio and 15% pressure loss compared to a conventional system. Diffuser-augmented wind turbines (DAWTs) produce power more efficiently than other flow augmented turbines such as flat plate deflectors. The new model was validated by comparison with experimental data matches and shows good agreement when a diffuser efficiency of 80% [48]. The impact of the diffuser is assessed by the augmentation factor, the ratio of turbine efficiency to the Joukowsky limit. It is shown, for example, that the augmentation factor exceeds unity only for efficiency greater than 74% when the diffuser thrust is 0.2 of the total thrust and the ratio of the rotor area to diffuser exit area is 0.54. Diffuser-augmented horizontal axis wind turbines (DAWTs) have been extensively studied, because the diffuser increases the velocity of the turbine rotor, leading to increased power [101].

5 Environmental Impacts of Wind Turbines

Wind turbines have almost no direct emissions during operation. However, there are positive and negative impacts on the environment, discussed below.

5.1 Positive Impacts on the Environment

Wind power requires no fuel and hence it does not contribute to air, water, or soil contamination. However, carbon dioxide (CO_2) emissions generated from wind power are approximately 10 g/kWh, emitted principally during construction, assembly, transportation, and maintenance [51]. Moreover, this value can be reduced to 4.65 g/kWh in the case of recycling the wind turbines [51]. Wind power generation plays a vital role in mitigating climate change by reducing CO_2 emissions in the atmosphere. The main positive environmental impact of wind energy is the reduction in overall energy system carbon and particle emissions. In Denmark, the reduction in carbon emissions is of the order of 800–900 gCO_2/kWh. In Finland, which consumes 10% of electricity from wind power, 600 gCO_2/kWh of emissions are reduced [74]. Wind-based electrical power generation has the lowest emissions of CO_2 per kilowatt compared to other renewable and non-renewable sources of energy generation. In those countries which have large wind sources and territories, a large portion of CO_2 emissions due to wind energy generation can be saved by sustainable transportation of wind turbines during the transport phase. For example, in China, CO_2 emissions can be reduced by as much as 33% by choosing shorter routes [102]. However, in the case of onshore wind power plants, CO_2 emissions per kilowatt of electricity generation are lower compared to offshore power plants.

5.2 Negative Impacts on the Environment

The negative environmental impacts are caused during construction, manufacturing, transportation, operation, and decommissioning. Local communities have reported several negative environmental impacts like noise, structural vibra-

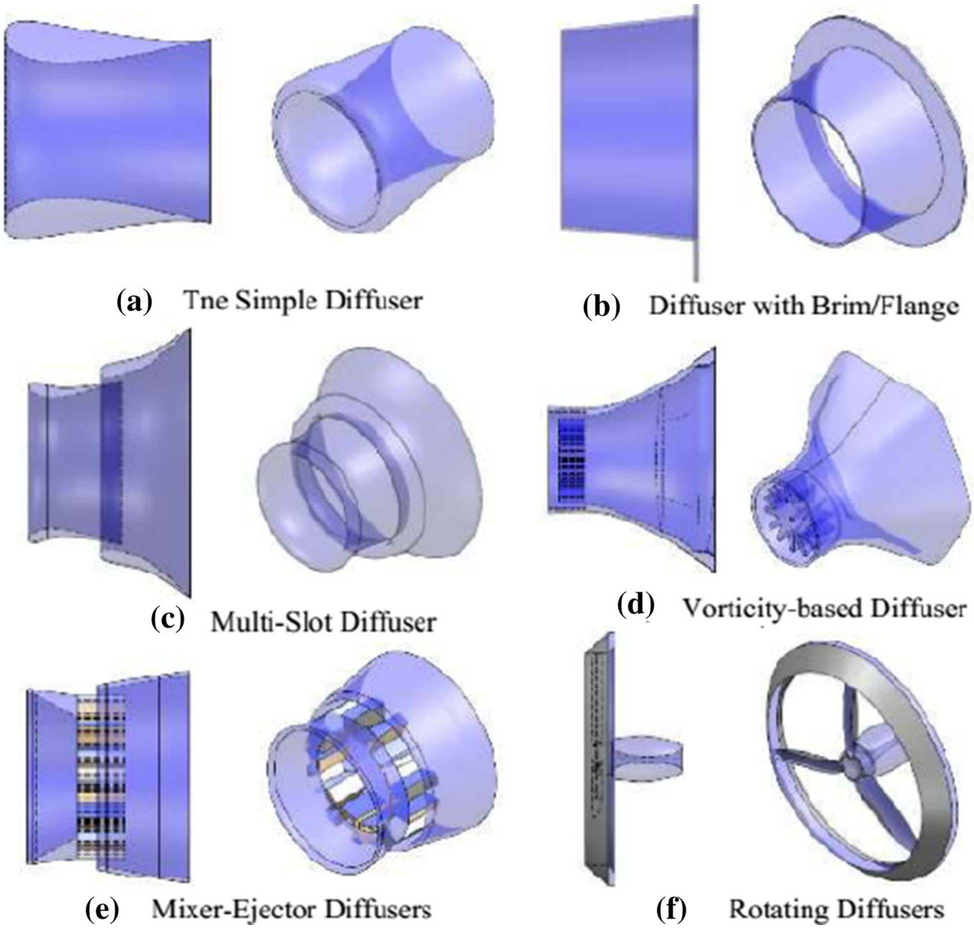


Fig. 12 The main types of diffusers [48]

tion, and visual impact [103–105]. Another major impact that has drawn attention is harmful to birds and bats, which get maimed or killed due to inappropriate location [63]. An appropriate location should be taken in planning and design to minimize impacts and to avoid danger to bats, and similarly to bird populations. Moreover, the components of a wind turbine such as the gearbox and blade affect the environment during maintenance. The reliability of the gearbox and the number of components that can be reused can play an important role in generating clean electricity and reducing greenhouse gas emissions [106, 107].

Several studies have illustrated the environmental impact of maintenance of multi-megawatt wind turbines blades and gearbox may increase by 29.1% without reusing any of their parts [107], whereas while reusing 50% of parts could reduce the negative environmental impacts by 14.6%. A study by Uddin and Kumar [108] found that the reuse of materials can reduce the embodied energy and environmental impact of a 500 W wind turbine by 60% and 50%, respectively, and the reuse of the turbine head, tail, and magnet can reduce the global warming impact by 63%. Furthermore, a study by Jiang et al. [107] concludes that the reuse of components of a 2 MW LCA model wind turbine could reduce the impact by around 10%. The reliability and sensitivity analysis indicates that the environmental impacts increase to 25.25% as the reliability of the gearbox is reduced from 78.25 to 40.03%.

Offshore wind energy is the major component; the global wind energy and the majority of environmental hazards are also related to it. One of these hazards incorporates during the initial stage when the turbine and its accessories are being transported. The transportation of turbines and apparatus to the sea site creates an increase in sea vessel traffic, which also creates noise pollution. This has a major impact on other business activities, such as fishing, sea transportation of goods, and biodiversity [109]. After transportation, the other environmental hazards are related to the foundation stage, which mainly affects the morphology of the seafloor, aquatic plants and animals, marine life, and the fishing economy [110]. Installation of turbine foundation in the sea alters the seabed topology, release of particles, and sedimentation. Furthermore, three methods are commonly employed for energy transmission in the sea, *i.e.,* trenching, burial, and rock dumping. These methods also increase the level of turbidity in seawater, modifying the seabed topology, and sedimentation

[110]. However, the environmental hazards of offshore wind energy are less during operation compared to the installation stage, but these hazards last for 10 to 20 years. One of the main hazards during the operation of both onshore and offshore wind turbines is related to the migration of the birds. Most of the turbines are installed in the migratory routes of the birds, demanding extra energy for birds during migration and hence the loss of habitat. However, the magnitude of this hazard is generally low, and it also depends on the type of species [111].

The mitigation approaches do not eliminate the hazards, but the magnitude can be lowered to a certain level so that the natural environment is sustained during power generation. The environmental hazard likelihood can be mitigated by performing the proper environmental impact assessment for the wind power site. The requirements of the rising hazards need to be addressed properly and the areas of higher objections need to be highlighted before finalizing the wind power site. In some cases, birds and mammals prevent their nesting sites due to the installation of wind farms; this issue needs to be considered in the initial stage. The development in wind power technology is also an important aspect; for example, during the last few decades, the majority of offshore wind turbines are installed in shallow water environments. With the increasing development in offshore wind turbines, future technology can be installed in the deep-sea environment and marine hazardous emissions will be significantly reduced [112].

Therefore, from the above investigation, it can be concluded that lifetime and component reuse have a big influence on the environmental impacts of wind turbines and greenhouse CO_2 emissions. Moreover, the location of turbines should be avoided from being close to major migration pathways and important habitats to minimize any environmental problems.

6 Conclusion

This paper presents a comprehensive review on the current global primary energy consumption, wind energy generation, wind turbine, and manufacturers. The aim of the paper is to identify the parameters that affect the performance of wind turbines. In particular, the following conclusions are drawn:

- Fossil fuels still the major energy consumption. The sustainable development scenarios are mainly focused to reduce fossil fuel dependency in global energy generation.
- Industrialization and urbanization have increased rapidly in China, consequently, the energy consumption of China is highest compared to other countries.
- Wind energy installation capacity has increased rapidly during recent years to reduce the dependency on fossil fuels. It is estimated that the installation would be increased to 965 TWh in Europe by the year 2030. However, technological improvement and reduction of the installation cost are still a challenge to increase the wind power generation globally.
- The wind turbines are manufactured from glass fibers, carbon fibers, and thermoplastic components. These materials are only able to provide semi-support against the physical loads. However, there is still a challenge to researchers to find alternative composites which will be environmentally friendly and having a higher damage resistance ability.
- In order to increase wind power generation; the turbines performance needs to be improved thoroughly. The main parameters to be considered while installing a turbine include rated speed, the efficiency of the turbine, power production, and reliability.
- Numerous factors are considered to improve wind turbine performance such as; turbine swept area, air density, wind speed, and power coefficient. On the other hand, very high humidity combined with foggy, rainy weather, and icing are caused to reduce power generation of wind turbine.
- Serious environmental impacts of wind turbines are caused during construction, manufacturing, transportation, operation, and decommissioning.

In addition, wind turbine is promising technology due to abundant energy potential, environmentally friendly, and low maintenance operation compared to conventional energy generations. Future research on wind turbines is suggested to focus on the recycling ability of the wind turbines. Performing the investigation of fiber recovered from wind turbine material, its mechanical properties, and its feasibility for reuse. Furthermore, much research needs to be conducted on finalizing the lifecycle loop of fibers and polymers used in the manufacturing of wind turbines.

Acknowledgements The authors would like to appreciate the Deputyship for Research and Innovation, Ministry of Education in Saudi Arabia, for funding this work through the Grant Number “375213500.” The authors also extend their sincere appreciation to the central laboratory at Jouf University for the support of this study

References

1. Duc, L.N.: A critical review on potential and current status of wind energy in Vietnam. Renew. Sustain Energy Rev. **43**, 440–448 (2015). https://doi.org/10.1016/j.rser.2014.11.060
2. Lombardi, L., Mendecka, B., Carnevale, E., Stanek, W., Mendecka, B., Santoni, G., et al.: Environmental impacts of electricity production of micro wind turbines with vertical axis. In: ECOS 2016 Proceedings of the 29th International Conference on Efficient Cost, Optimisation, Simulation in Environment Impact Energy System 128:553–64 (2018)
3. Ahmad, T.; Zhang, D.: A critical review of comparative global historical energy consumption and future demand: the story told

so far. Energy Rep. **6**, 1973–1991 (2020). https://doi.org/10.1016/j.egyr.2020.07.020
4. Chong, W.T.; Poh, S.C.; Fazlizan, A.; Yip, S.Y.; Chang, C.K.; Hew, W.P.: Early development of an energy recovery wind turbine generator for exhaust air system. Appl. Energy **112**, 568–575 (2013). https://doi.org/10.1016/j.apenergy.2013.01.042
5. Yaniktepe, B.; Savrun, M.M.; Koroglu, T.: Current status of wind energy and wind energy policy in Turkey. Energy Conv. Manag. **72**, 103–110 (2013). https://doi.org/10.1016/j.enconman.2012.08.028
6. Al, B.C.; Klumpner, C.; Hann, D.B.: Effect of rain on vertical axis wind turbines. Renew. Energy Power Qual. J. **1**, 1263–1268 (2011). https://doi.org/10.24084/repqj09.618
7. Hernández-Escobedo, Q.; Saldaña-Flores, R.; Rodríguez-García, E.R.; Manzano-Agugliaro, F.: Wind energy resource in Northern Mexico. Renew. Sustain Energy Rev. **32**, 890–914 (2014)
8. Tavner, P.; Edwards, C.; Brinkman, A.; Spinato, F.: Influence of wind speed on wind turbine reliability. Wind Eng. **30**, 55–72 (2006). https://doi.org/10.1260/030952406777641441
9. Amirzadeh, B.; Louhghalam, A.; Raessi, M.; Tootkaboni, M.: A computational framework for the analysis of rain-induced erosion in wind turbine blades, part I: stochastic rain texture model and drop impact simulations. J. Wind Eng. Ind. Aerodyn. **163**, 33–43 (2017). https://doi.org/10.1016/j.jweia.2016.12.006
10. Cao, Y.; Wu, Z.; Xu, Z.: Effects of rainfall on aircraft aerodynamics. Prog. Aerosp. Sci. **71**, 85–127 (2014). https://doi.org/10.1016/j.paerosci.2014.07.003
11. Moné, C., Smith, A., Maples, B., Hand, M.: 2013 cost of wind energy review. Natl. Renew. Energy Lab. (NREL) (2015)
12. Anshelm, J.; Simon, H.: Power production and environmental opinions: environmentally motivated resistance to wind power in Sweden. Renew. Sustain. Energy Rev. **57**, 1545–1555 (2016). https://doi.org/10.1016/j.rser.2015.12.211
13. Gupta, N.: A review on the inclusion of wind generation in power system studies. Renew. Sustain Energy Rev. **59**, 530–543 (2016). https://doi.org/10.1016/j.rser.2016.01.009
14. Chong, C.H.; Rigit, A.R.H.; Ali, I.: Wind turbine modelling and simulation using Matlab/SIMULINK. IOP Conf. Ser. Mater. Sci. Eng. **1101**, 012034 (2021). https://doi.org/10.1088/1757-899x/1101/1/012034
15. Siddique, S.; Wazir, R.; Siddique, S.: A review of the wind power developments in Pakistan. Renew. Sustain. Energy Rev. **57**, 351–361 (2016). https://doi.org/10.1016/j.rser.2015.12.050
16. Papież, M.; Śmiech, S.; Frodyma, K.: Factors affecting the efficiency of wind power in the European Union countries. Energy Policy **132**, 965–977 (2019)
17. Dalili, N.; Edrisy, A.; Carriveau, R.: A review of surface engineering issues critical to wind turbine performance. Renew. Sustain. Energy Rev. **13**, 428–438 (2009)
18. Ribrant, J., Bertling, L.: Survey of failures in wind power systems with focus on Swedish wind power plants during 1997–2005. In: Proceedings of the 2007 IEEE power Engineering Society of General Meeting, p. 1–8 (2007)
19. Tjiu, W.; Marnoto, T.; Mat, S.; Ruslan, M.H.; Sopian, K.: Darrieus vertical axis wind turbine for power generation I: assessment of Darrieus VAWT configurations. Renew. Energy **75**, 50–67 (2015)
20. Li, H.; Chen, Z.: Overview of different wind generator systems and their comparisons. IET Renew. Power Gener. **2**, 123–138 (2008)
21. Hand, B.; Kelly, G.; Cashman, A.: Aerodynamic design and performance parameters of a lift-type vertical axis wind turbine: a comprehensive review. Renew. Sustain. Energy Rev. **139**, 110699 (2021)
22. Sutherland, H.J.; Berg, D.E.; Ashwill, T.D.: A retrospective of VAWT technology. Sandia Natl. Lab. **2012**, 1–64 (2012)
23. Paquette, J.A., Barone, M.F.: Innovative offshore vertical-axis wind turbine rotor project (2012)
24. Razykov, T.M.; Ferekides, C.S.; Morel, D.; Stefanakos, E.; Ullal, H.S.; Upadhyaya, H.M.: Solar photovoltaic electricity: current status and future prospects. Sol. Energy **85**, 1580–1608 (2011). https://doi.org/10.1016/j.solener.2010.12.002
25. Sahaym, U.; Norton, M.G.: Advances in the application of nanotechnology in enabling a "hydrogen economy." J. Mater. Sci. **43**, 5395–5429 (2008). https://doi.org/10.1007/s10853-008-2749-0
26. Li, Y.; Tagawa, K.; Feng, F.; Li, Q.; He, Q.: A wind tunnel experimental study of icing on wind turbine blade airfoil. Energy Convers. Manag. **85**, 591–595 (2014). https://doi.org/10.1016/j.enconman.2014.05.026
27. Liu, J.; Lin, H.; Zhang, J.: Review on the technical perspectives and commercial viability of vertical axis wind turbines. Ocean Eng. **182**, 608–626 (2019). https://doi.org/10.1016/j.oceaneng.2019.04.086
28. Jolin, N.; Bolduc, D.; Swytink-Binnema, N.; Rosso, G.; Godreau, C.: Wind turbine blade ice accretion: A correlation with nacelle ice accretion. Cold Reg. Sci. Technol. **157**, 235–241 (2019). https://doi.org/10.1016/j.coldregions.2018.10.009
29. Roser, M.: Energy n.d. (2021). https://ourworldindata.org/energy.
30. Kumar, K.V.; Safiulla, M.; Ahmed, A.N.K.: An experimental evaluation of fiber reinforced polypropylene thermoplastics for aerospace applications. J. Mech. Eng. **43**, 92–97 (2014). https://doi.org/10.3329/jme.v43i2.17832
31. Akwa, J.V., Alves Da Silva Júnior, G., Petry, A.P.: Discussion on the verification of the overlap ratio influence on performance coefficients of a Savonius wind rotor using computational fluid dynamics. Renew. Energy 38:141–149 (2012). doi:https://doi.org/10.1016/j.renene.2011.07.013.
32. Gielen, D.; Boshell, F.; Saygin, D.; Bazilian, M.D.; Wagner, N.; Gorini, R.: The role of renewable energy in the global energy transformation. Energy Strateg. Rev. **24**, 38–50 (2019)
33. Chen, J.; Wang, F.; Stelson, K.A.: A mathematical approach to minimizing the cost of energy for large utility wind turbines. Appl. Energy **228**, 1413–1422 (2018). https://doi.org/10.1016/j.apenergy.2018.06.150
34. IRENA I.: Future of wind: deployment, investment, technology, grid integration and socio-economic aspects (2019)
35. Wu, Z.; Cao, Y.; Nie, S.; Yang, Y.: Effects of rain on vertical axis wind turbine performance. J. Wind Eng. Ind. Aerodyn. **170**, 128–140 (2017). https://doi.org/10.1016/j.jweia.2017.08.010
36. Menet, J.-L., Bourabaa, N.: Increase the savonius rotor efficiency via a parametric investigation. In: National Scheme of Engineering EComputer AutoAUTO Mechnical and Electronics Energy Valuation, London, UK, p. 11 (2003)
37. Ong, C., Tsai, S.W.: The use of carbon fibers in wind turbine blade design: the use of carbon fibers in wind turbine blade design: a. Sandia National Labs., Albuquerque, NM (US); Sandia National Labs (2000)
38. Modi, V.J.; Roth, N.J.; Fernando, M.S.U.K.: Optimum-configuration studies and prototype design of a wind-energy-operated irrigation system. J. Wind Eng. Ind. Aerodyn. **16**, 85–96 (1984). https://doi.org/10.1016/0167-6105(84)90050-3
39. Cooperman, A.; Eberle, A.; Lantz, E.: Wind turbine blade material in the United States: quantities, costs, and end-of-life options. Resour. Conserv. Recycl. **168**, 105439 (2021). https://doi.org/10.1016/j.resconrec.2021.105439
40. GWEC: Global Wind Report (2014)
41. Gielen, D., Gorini, R., Wagner, N., Leme, R., Gutierrez, L., Prakash, G., et al.: Global energy transformation: a roadmap to 2050 (2019)
42. Kamoji, M.; Kedare, S.; Prabhu, S.V.: Experimental investigations on two and three stage modified savonius rotor. Wind Eng. **35**, 483–510 (2011). https://doi.org/10.1260/0309-524X.35.4.483

43. Bel Mabrouk, I.; El Hami, A.: Effect of number of blades on the dynamic behavior of a Darrieus turbine geared transmission system. Mech. Syst. Signal Process. **121**, 562–578 (2019). https://doi.org/10.1016/j.ymssp.2018.11.048
44. Sheldahl, R.E.; Blackwell, B.F.; Feltz, L.V.: Wind tunnel performance data for two- and three-bucket savonius rotors. J. Energy **2**, 160–164 (1978). https://doi.org/10.2514/3.47966
45. Yirtici, O.; Tuncer, I.H.; Ozgen, S.: Ice accretion prediction on wind turbines and consequent power losses. J. Phys. Conf. Ser. **753**, 22022 (2016). https://doi.org/10.1088/1742-6596/753/2/022022
46. Xiaoni, W.; Yu, H.; Li, Y.; Wu, X.; Hu, Y.; Li, Y., et al.: Foundations of offshore wind turbines: a review. Renew. Sustain Energy Rev. **104**, 379–393 (2019). https://doi.org/10.1016/j.rser.2019.01.012
47. Salih, S.M.; Taha, M.Q.; Alawsaj, M.K.: Performance analysis of wind turbine systems under different parameters effect performance analysis of wind turbine systems under different parameters effect view project international journal of energy and environment performance analysis of wind turbine. Int. J. Energy Environ. **2012**, 2076–2909 (2012)
48. Agha, A.; Chaudhry, H.N.; Wang, F.: Diffuser Augmented Wind Turbine (DAWT) technologies: a review. Int. J. Renew. Energy Res. **8**, 1369–1385 (2018)
49. Mishnaevsky, L.; Branner, K.; Petersen, H.N.; Beauson, J.; McGugan, M.; Sørensen, B.F.: Materials for wind turbine blades: an overview. Materials (Basel) (2017). https://doi.org/10.3390/ma10111285
50. Zemamou, M.; Aggour, M.; Toumi, A.: Review of savonius wind turbine design and performance. Energy Proc. **141**, 383–388 (2017). https://doi.org/10.1016/j.egypro.2017.11.047
51. Al-Behadili, S.H.; El-Osta, W.B.: Life cycle assessment of Dernah (Libya) wind farm. Renew. Energy **83**, 1227–1233 (2015). https://doi.org/10.1016/j.renene.2015.05.041
52. Li, G.; Zhi, J.: Analysis of wind power characteristics Large-scale wind power grid integration, p. 19–51. Elsevier, Amsterdam (2016)
53. Timilsina, G.R.; Cornelis van Kooten, G.; Narbel, P.A.: Global wind power development: economics and policies. Energy Policy **61**, 642–652 (2013). https://doi.org/10.1016/j.enpol.2013.06.062
54. Shawon, M.J.; El Chaar, L.; Lamont, L.A.: Overview of wind energy and its cost in the Middle East. Sustain. Energy Technol. Assessm. (2013). https://doi.org/10.1016/j.seta.2013.01.002
55. Qasemi, K.; Azadani, L.N.: Optimization of the power output of a vertical axis wind turbine augmented with a flat plate deflector. Energy **202**, 117745 (2020). https://doi.org/10.1016/j.energy.2020.117745
56. Zahedi, A.: Developing a linear model for estimating the capacity factor of wind turbines. AUPEC **2011**, 1–5 (2011)
57. Sedaghat, A.; Alkhatib, F.; Eilaghi, A.; Sabati, M.; Borvayeh, L.; Mostafaeipour, A.: A new strategy for wind turbine selection using optimization based on rated wind speed. Energy Proced. **160**, 582–589 (2019). https://doi.org/10.1016/j.egypro.2019.02.209
58. Sedaghat, A.; Hassanzadeh, A.; Jamali, J.; Mostafaeipour, A.; Chen, W.-H.: Determination of rated wind speed for maximum annual energy production of variable speed wind turbines. Appl. Energy **205**, 781–789 (2017)
59. Chehouri, A.; Younes, R.; Ilinca, A.; Perron, J.: Review of performance optimization techniques applied to wind turbines. Appl. Energy **142**, 361–388 (2015)
60. Fingersh, L., Hand, M., Laxson, A.: Wind turbine design cost and scaling model. 29 (2006)
61. Dupré, A.; Drobinski, P.; Badosa, J.; Briard, C.; Plougonven, R.: Air density induced error on wind energy estimation.(2019). https://doi.org/10.5194/angeo-2019-88
62. Wagner, R.; Antoniou, I.; Pedersen, S.M.; Courtney, M.S.; Jørgensen, H.E.: The influence of the wind speed profile on wind turbine performance measurements. Wind Energy **12**, 348–362 (2009). https://doi.org/10.1002/we.297
63. Tabassum, A.; Premalatha, M.; Abbasi, T.; Abbasi, S.A.: Wind energy: increasing deployment, rising environmental concerns. Renew. Sustain. Energy Rev. **31**, 270–288 (2014). https://doi.org/10.1016/j.rser.2013.11.019
64. Wang, Y.; Tong, H.; Sima, H.; Wang, J.; Sun, J.; Huang, D.: Experimental study on aerodynamic performance of deformable blade for vertical axis wind turbine. Energy **181**, 187–201 (2019). https://doi.org/10.1016/j.energy.2019.03.181
65. Rezaeiha, A.; Montazeri, H.; Blocken, B.: Characterization of aerodynamic performance of vertical axis wind turbines: impact of operational parameters. Energy Convers. Manag. **169**, 45–77 (2018). https://doi.org/10.1016/j.enconman.2018.05.042
66. Abkar, M.; Dabiri, J.O.: Self-similarity and flow characteristics of vertical-axis wind turbine wakes: an LES study. J. Turbul. **18**, 373–389 (2017). https://doi.org/10.1080/14685248.2017.1284327
67. Araya, D.B.; Dabiri, J.O.: Vertical axis wind turbine in a falling soap film. Phys. Fluids **27**, 91108 (2015). https://doi.org/10.1063/1.4930912
68. Brownstein, I.D.; Kinzel, M.; Dabiri, J.O.: Performance enhancement of downstream vertical-axis wind turbines. J. Renew. Sustain Energy **8**, 53306 (2016). https://doi.org/10.1063/1.4964311
69. Rezaeiha, A.; Kalkman, I.; Blocken, B.; Rezaeiha, A.; Kalkman, I.: Effect of pitch angle on power performance and aerodynamics of a vertical axis wind turbine. Appl. Energy **197**, 132–150 (2017). https://doi.org/10.1016/j.apenergy.2017.03.128
70. Rezaeian, M.; Montazeri, H.; Loonen, R.C.G.M.: Science foresight using life-cycle analysis, text mining and clustering: a case study on natural ventilation. Technol. Forecast Soc. Change **118**, 270–280 (2017). https://doi.org/10.1016/j.techfore.2017.02.027
71. Chen, W.H.; Chen, C.Y.; Huang, C.Y.; Hwang, C.J.: Power output analysis and optimization of two straight-bladed vertical-axis wind turbines. Appl. Energy **185**, 223–232 (2017). https://doi.org/10.1016/j.apenergy.2016.10.076
72. Molina, A.C.; Bartoli, G.; De Troyer, T.: Wind tunnel testing of small vertical-axis wind turbines in turbulent flows. Proc. Eng. **199**, 3176–3181 (2017). https://doi.org/10.1016/j.proeng.2017.09.518
73. Carbó Molina, A.; Bartoli, G.; De Troyer, T.: Generation of uniform turbulence profiles in the wind tunnel for urban VAWT testing. Green Energy Technol. **10**, 27–43 (2018). https://doi.org/10.1007/978-3-319-74944-0_3
74. Holttinen, H.; Tuhkanen, S.: The effect of wind power on CO_2 abatement in the Nordic Countries. Energy Policy **32**, 1639–1652 (2004). https://doi.org/10.1016/S0301-4215(03)00158-7
75. Ashwindran, S.N.; Azizuddin, A.A.; Oumer, A.N.; Sulaiman, M.Z.: A review on the prospect of wind power as an alternative source of energy in Malaysia. IOP Conf. Ser. Mater. Sci. Eng. **1078**, 12017 (2021)
76. Azorin-Molina, C.; Asin, J.; McVicar, T.R.; Minola, L.; Lopez-Moreno, J.I.; Vicente-Serrano, S.M., et al.: Evaluating anemometer drift: a statistical approach to correct biases in wind speed measurement. Atmos. Res. **203**, 175–188 (2018)
77. Cindric, L.: Autonomus hybrid system for household energy supply on island of Rab, Croatia. Universitat Politècnica de Catalunya (2017)
78. Rashad, A.; Kamel, S.; Jurado, F.: The basic principles of wind farms. Distrib. Gener. Syst. **2017**, 21–67 (2017)
79. Schubel, P.J.; Crossley, R.J.: Wind turbine blade design. Energies **5**, 3425–3449 (2012)

80. Islam, S.M., Nayar, C.V., Abu-Siada, A., Hasan, M.M.: Power electronics for renewable energy sources. In: Power Electronics Handbook. Elsevier, Amsterdam, p. 783–827 (2018)
81. Yue, W.; Xue, Y.; Liu, Y.: High humidity aerodynamic effects study on offshore wind turbine airfoil/blade performance through CFD analysis. Int. J. Rotat. Mach. (2017). https://doi.org/10.1155/2017/7570519
82. Oukassou, K.; El Mouhsine, S.; El Hajjaji, A.; Kharbouch, B.: Comparison of the power, lift and drag coefficients of wind turbine blade from aerodynamics characteristics of Naca0012 and Naca2412. Proc. Manuf. **32**, 983–990 (2019). https://doi.org/10.1016/j.promfg.2019.02.312
83. Thomas, L.; Ramachandra, M.: Advanced materials for wind turbine blade: a review. Mater. Today Proc. **5**, 2635–2640 (2018). https://doi.org/10.1016/j.matpr.2018.01.043
84. Harper, N.: Detecting ice on wind turbine blades. Wind Power Eng. Dev. **2011**, 1–2 (2011)
85. Beckman, I.P.; Lozano, C.; Freeman, E.; Riveros, G.: Fiber selection for reinforced additive manufacturing. Polym. (Basel) **13**, 2231 (2021)
86. Chingulpitak, S.; Wongwises, S.: Critical review of the current status of wind energy in Thailand. Renew. Sustain. Energy Rev. **31**, 312–318 (2014). https://doi.org/10.1016/j.rser.2013.11.038
87. Westphal, T., Bortolotti, P., Nijssen, R.P.L.: Carbon glass hybrid materials for wind turbine rotor blades. TU Delft (2013)
88. Gopalraj, S.K.; Kärki, T.: A review on the recycling of waste carbon fibre/glass fibre-reinforced composites: fibre recovery, properties and life-cycle analysis. SN Appl. Sci. **2**, 1–21 (2020)
89. Mishnaevsky, L.; Branner, K.; Petersen, H.N.; Beauson, J.; McGugan, M.; Sørensen, B.F., et al.: Materials for wind turbine blades: an overview. Mater. (Basel) (2017). https://doi.org/10.3390/ma10111285
90. Wiser, R.H., Bolinger, M., Hoen, B., Millstein, D., Rand, J., Barbose, G.L., et al.: Land-based wind market report: 2021 Edition (2021)
91. BizVibe: Global wind turbine industry factsheet 2020: top 10 largest wind turbine manufacturers (2020). https://blog.bizvibe.com/blog/energy-and-fuels/top-10-wind-turbine-manufacturers-world.
92. Ingram, E.: Vestas tops BloombergNEF's list of top wind turbine manufacturers by installations. Renew Energy World (2020). https://www.renewableenergyworld.com/wind-power/vestas-tops-bloombergnefs-list-of-top-wind-turbine-manufacturers-by-installations/. Accessed on 10 Oct 2021
93. Honrubia, A., Vigueras-Rodríguez, A., Ǵomez Ĺazaro, E., Rodŕiguez-Śanchez, D.: The influence of wind shear in wind turbine power estimation. Eur. Wind Energy Conf. Exhib. 2010, EWEC 2010 6:4130–4139 (2010)
94. Pourrajabian, A.; Mirzaei, M.; Ebrahimi, R.; Wood, D.: Effect of air density on the performance of a small wind turbine blade: a case study in Iran. J. Wind Eng. Ind. Aerodyn. **126**, 1–10 (2014)
95. Brusca, S.; Lanzafame, R.; Messina, M.: Design of a vertical-axis wind turbine: how the aspect ratio affects the turbine's performance. Int. J. Energy Environ. Eng. **5**, 333–340 (2014)
96. Lilley GM, Rainbird WJ. A preliminary report on the design and performance of a ducted windmill. Rep No 102:73 (1956)
97. Sareen, A.; Sapre, C.A.; Selig, M.S.: Effects of leading edge erosion on wind turbine blade performance. Wind Energy **17**, 1531–1542 (2014). https://doi.org/10.1002/we.1649
98. Roy, S.; Saha, U.K.: Computational study to assess the influence of overlap ratio on static torque characteristics of a vertical axis wind turbine. Proced. Eng. **51**, 694–702 (2013)
99. Madi, E.; Pope, K.; Huang, W.; Iqbal, T.: A review of integrating ice detection and mitigation for wind turbine blades. Renew. Sustain. Energy Rev. **103**, 269–281 (2019). https://doi.org/10.1016/j.rser.2018.12.019
100. Pinar Pérez, J.M.; García Márquez, F.P.; Ruiz, H.D.: Economic viability analysis for icing blades detection in wind turbines. J. Clean. Prod. **135**, 1150–1160 (2016). https://doi.org/10.1016/j.jclepro.2016.07.026
101. Rajpar, A.H., Ali, I., Eladwi, A.E.: Recent development in the design of wind deflectors for vertical axis wind turbine : a review (2021)
102. Wang, Y.; Sun, T.: Life cycle assessment of CO_2 emissions from wind power plants: Methodology and case studies. Renew. Energy **43**, 30–36 (2012)
103. Abbasi, S.A.; Abbasi, N.: The likely adverse environmental impacts of renewable energy sources. Appl. Energy **65**, 121–144 (2000). https://doi.org/10.1016/S0306-2619(99)00077-X
104. Harte, J.; Jassby, A.: Energy technologies and natural environments: the search for compatibility. Ann. Rev. Energy **3**, 101–146 (1978). https://doi.org/10.1146/annurev.eg.03.110178.000533
105. Abbasi, S.A.; Tabassum-Abbasi, A.T.: Impact of wind-energy generation on climate: a rising spectre. Renew. Sustain. Energy Rev. **59**, 1591–1598 (2016). https://doi.org/10.1016/j.rser.2015.12.262
106. Ochieng, E.G.; Melaine, Y.; Potts, S.J.; Zuofa, T.; Egbu, C.O.; Price, A.D.F., et al.: Future for offshore wind energy in the United Kingdom: the way forward. Renew. Sustain. Energy Rev. **39**, 655–666 (2014). https://doi.org/10.1016/j.rser.2014.07.105
107. Jiang, L.; Xiang, D.; Tan, Y.F.; Nie, Y.H.; Cao, H.J.; Wei, Y.Z., et al.: Analysis of wind turbine Gearbox's environmental impact considering its reliability. J. Clean. Prod. **180**, 846–857 (2018). https://doi.org/10.1016/j.jclepro.2018.01.078
108. Uddin, M.S.; Kumar, S.: Energy, emissions and environmental impact analysis of wind turbine using life cycle assessment technique. J. Clean. Prod. **69**, 153–164 (2014). https://doi.org/10.1016/j.jclepro.2014.01.073
109. Besnard, F., Patrikssont, M., Strombergt, A.-B., Wojciechowskit, A., Bertling, L.: An optimization framework for opportunistic maintenance of offshore wind power system. In: Proceedings of the 2009 IEEE Bucharest PowerTechnology, p. 1–7 (2009)
110. Wilson, J.C.; Elliott, M.; Cutts, N.D.; Mander, L.; Mendão, V.; Perez-Dominguez, R., et al.: Coastal and offshore wind energy generation: is it environmentally benign? Energies **3**, 1383–1422 (2010)
111. Kaldellis, J.K.; Apostolou, D.; Kapsali, M.; Kondili, E.: Environmental and social footprint of offshore wind energy. Comparison with onshore counterpart. Renew. Energy **92**, 543–556 (2016)
112. Snyder, B.; Kaiser, M.J.: Ecological and economic cost-benefit analysis of offshore wind energy. Renew. Energy **34**, 1567–1578 (2009)