Proceedings of the Second Australian International Conference on Industrial Engineering and Operations Management, Melbourne, Australia, November 14-16, 2023

Wind Energy in Sustainable Power Generation and Supply

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Abstract

Modern wind turbines capture the kinetic energy of moving air and convert it into shaft power to drive an electrical generator/alternator. The turbine is typically comprised of three basic parts: the rotor, the nacelle, and the tower. The rotor includes the turbine's blades (most often 3 in horizontal wind axis turbines) and the nose cone/hub. The nacelle contains the driveshaft, transmission a, the unit's generator/alternator, the electronic controls to convert the generators or alternator's electrical output to quality suitable for use, and the tail vane or yaw drive that keeps the turbine oriented to the wind, either upwind or downwind depending on the turbine's design. Because wind speed generally increases and turbulence decreases with height, a tower helps the system increase its energy production and reduces turbulence-induced mechanical stresses, thus enhancing its economic benefit. The ability of a turbine to produce energy from the wind fundamentally depends on the wind resource and the swept area of the turbine. Simplifying somewhat, the power output of a turbine is proportional to the cube of the wind velocity and the square of the blade length. A doubling of the wind speed thus yields an eight-fold increase in wind power while a doubling of a turbine's blade length yields a four-fold increase in energy capture (all other things kept constant). Larger turbines with longer blades not only produce more energy for a given wind resource, but they are also more capital cost-effective as well, because of inherent economies of scale as well as inefficiencies in the market for smaller turbines. The installed cost/kW for a small turbine is twice that for a mid-scale turbine and can be several times as expensive as that for a utility-scale turbine. While these factors argue for choosing the windiest sites and installing the largest turbines on the highest towers that are cost-effective for the site – an argument understood by wind farm developers – residential and commercial site hosts cannot follow this logic to its conclusion. It is a rare home or business owner that is going to move their establishment simply to take advantage of a windier site. And several practical constraints prevent home and business owners from using the giant turbines typically found in utility-scale wind farms. Neighbors might object to the presence of a turbine hundreds of feet tall because of safety, noise, and visual concerns. The turbine's capital costs are an additional consideration: even if a site host has the space for a giant turbine, the multi-million-dollar capital cost can be difficult to finance for someone not in the wind industry. As a result of these constraints, most distributed wind turbine installations are sized roughly equivalent to the site host's electrical load and use turbines much smaller than those found in current-day wind farms. This analysis therefore assumes that residential customers will install turbines with nominal capacity ratings of 1-9 kW, while commercial customers will install turbines with nominal capacity ratings of 10-100 kW.

Keywords
Wind power, wind turbines; sustainability of wind energy

1. Introduction
Global warming is a reality today and according to the Intergovernmental Panel on Climate Change (IPCC), human activities have caused an approximate warming of 1.0 °C above pre-industrial levels, and this may reach 1.5 °C between 2030 and 2052(Kabeyi and Oludolapo 2020). The energy sector is the largest contributor to the global greenhouse gas (GHG) emissions. This has led to the development of renewable energy resources with lower carbon footprints. Wind energy, for example, became the second largest power generation source in Europe, just after gas, with an installed capacity of 169 GW in 2017 (Kabeyi and Oludolapo 2022). However, wind energy comes with intermittency and unpredictability, due to variable wind conditions (Kaddoura et al, 22020), requiring substantial support technologies for load balancing. Wind power is also perceived as noisy and visually interfering(Vargas et al,

2019) Tidal streams, on the other hand, are easily predicted (Sawant et al, 2022), since they are generated by the rise and fall of the sea level due to gravitational forces of the moon, sun, and earth. Yet, an important factor limiting the application of tidal streams is their relatively slow speed, and the problem associated with constructing turbines with a sufficiently low cut-in speed for starting electricity generation. The first generation tidal farms require 2.5 m/s of current to start (Heidary et al, 2021) making them economically viable in restricted geographical places [3]Generation from renewable sources is necessary to come with environmental challenges caused by global warming and energy security, and also to foster a healthier environment. The presence of wind energy has increased significantly in electrical power systems globally in recent decades. This absolutely necessary in a world that shares a greater and greater energy demand in a climate crisis due to global warming. Wind energy has been identified as vital parts of modern power systems, but the integration of wind-based generation, increases the level of fault current damage the wind generators, microgrid components, and upstream grids besides increased grid instability due to variability and intermittence.Wind energy has always been developed as one of the vital parts of modern power systems. However, by integration of wind-based generation, the level of fault current is likely to be increased which can damage the wind generators, microgrid components, and upstream grids. Consequently, utilizing viable protecting structures might preserve wind generator structures and other sections of the electric system as well (Kabeyi. and Olanrewaju 2023) Wind generators are becoming more practical among renewable energy sources, due to their r potential application features (Heasami et al, 2023). Incorporating renewable energy resource in particular wind power, in the electricity mix, is a leading strategy to mitigate greenhouse gas emissions. Wind is considered an attractive energy resource because it is renewable, clean, socially justifiable, economically competitive and environmentally friendly (Burton et al., 2011). Therefore, the outlook is for increasing participation on wind power in the future, up to at least 18% of global power by 2050 according to the International Energy Agency (IEA, 2013). The Global Wind Energy Council indicated that in 2017 the cumulative total was 11% greater than the 2016 year-end total of 487 GW, and the global production remained above 50 GW in 2017. Furthermore, according to the Global Wind Energy Council, "Beyond the statistics, wind power is becoming a fully commercialized, unsubsidized technology; successfully competing in the marketplace against heavily subsidized fossil and nuclear incumbents" (GWEC, 2018). Among the countries that are promoting wind as a renewable energy resource are 30 countries with more than 1 GW of installed capacity and nine countries with more than 10 GW, including China, USA, Germany, India, Spain, UK, France, Brazil and Canada (GWEC, 2018).

The fluctuating nature of wind, despite the high penetration of wind energy, poses several challenges when integrating wind power into the electric grid, since high costs can be involved for construction of wind farms as well as prior and ongoing assessment studies. Contrary to conventional energy sources, wind speed varies both spatially and temporally, generating fluctuations in wind energy output (Fernández-González et al., 2018). Weather variables such as wind direction, temperature, pressure, and humidity, among others, influence wind power production. Hence, to integrate wind power into the electric grid requires estimates, at least, of future wind speed values (Ammar et al., 2018). The development of new techniques to improve understanding of these variables, through simulation, forecasting, distribution curve fitting, filtering, and modeling, allows making better decisions about expansion of the wind sector and better management of the electricity system. Additionally, accurate estimation of wind speed can improve the safety, reliability, and profitability of the operation of wind farms. This involves understanding the wind regime of a specific region, to enable more accurate forecasting of future values based on past ones.

The earliest application of wind turbines was to generate electricity on farms in areas without electricity. In the 1880s, Charles F Brush, a pioneer of wind energy, first invented a direct current generator for use in public power grids. Then, the idea of wind turbines for electricity generation began with a Danish wind power program in 1890. By 1918, Denmark had 120 wind turbines with a power of 5-25 kW. Around World War II, due to the high energy demand, several large wind turbines were built in several European countries and the United States. In 1941, two-bladed wind turbine with a wind wheel diameter of 53.3 m was built in the United States, capable of an output power of 1250 kW when the wind speed was 13.4 m/s [38]. By 1951, the DC generators began to be replaced by 35 kW AC asynchronous generators [39]. After the 1973 oil crisis, most countries began to target the manufacture of large wind turbines, with designs and installations of 600-800 kW (Toshiba Energy Systems & Solutions Corporation, 2023). It was only in 1998 that megawatt-class wind turbines started to appear and were applied offshore or in areas with few winds turbine installation site Wind energy is used to generate electricity by converting wind energy into mechanical energy and then into electrical energy by wind turbines. The wind speed at which wind turbines can work normally is 2-22 m/s. Wind farms are usually located in areas with high wind speed, strong wind, and high wind density, and can be installed

on land and sea. Due to technical and cost reasons, the installed capacity of wind power on land is much larger than offshore, but offshore wind power generates.
about 40% more capacity than on land. With the advancement of technology, offshore wind energy also maintains a high growth rate. As of 2020, total cumulative installed wind power capacity in various countries and regions is shown in Figure 1, where Figure 1 shows the installed capacity of onshore wind power.

Wind power generation by region worldwide is shown in Figure 2. At the beginning707.4 GW and the cumulative installed capacity of offshore wind power having a scale of 35.3 GW.

By 2020, total installed capacity of wind power worldwide reaches 743 GW and of the 21st century, cumulative installed capacity of wind power in the world was 16.9 GW, and cumulative installed capacity of wind power in the European region was 12.7 GW, leading the world in terms of technology and industrialization, and the wind power industry was at the starting stage. Starting from 2007, cumulative increase in wind power installations began to increase rapidly, and the amount of new wind power installations exceeded 20 GW for the first time that year, and the wind power industry began to enter an acceleration phase. In the following decade, cumulative installed capacity of wind power generation began to increase rapidly, mainly due to the global emphasis on the development of the renewable energy sector.
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In 2020, the world's newly installed onshore wind power capacity is 86.9 GW, China accounts for 56%, the United States 19%, an overall increase of 59% year-on-year. The significant growth throughout the year was mainly attributable to the explosive growth of the two major global wind power markets mentioned above. According to statistics from the IEA (2023), the cumulative data on installed wind power in China and the United States in the 21st century. The United States not only has the world's leading new energy technology but also has a huge market share. They have set an ambitious strategic goal that wind power will meet 20% of the nation's electricity demand by 2030. China's wind power generation started in 1992 with 0.1 TWh, but since 2005, China's installed wind power capacity has been growing at a very high rate due to government policies to support the wind energy market. In 2011, the installed capacity reached 46.2 GW, surpassing the installed capacity of the United States. In 2020, the installed capacity will reach 282 GW, ranking first in the world.

1.1. Problem Statement

It took more than a decade for the total installed capacity of wind power worldwide to exceed 700 GW, but this is still far from enough to deal with the energy crisis. Countries and regions around the world need green and clean energy to improve their energy mix, so the predictable rate of new wind power installations will continue to be high, and wind power will become a strong growth point for new energy sources, with huge potential for future applications.

2. Global Wind Production

The use of renewable energy resources, especially wind power, is receiving strong attention from gov-ernments and private institutions, since it is considered one of the best and most competitive alternative energy sources in the current energy transition that many countries around the world are adopting. Wind power also plays an important role by reducing greenhouse gas emissions and thus attenuating global warming. Another contribution of wind power generation is that it allows countries to diversify their energy mix, which is especially important in countries where hydropower is a large component. The expansion of wind power generation requires a robust understanding of its variability and thus how to reduce uncertainties associated with wind power output. Technical approaches such as simulation and forecasting provide better information to support the decision-making process. This paper provides an overview of how the analysis of wind speed/energy has evolved over the last 30 years for decision-making processes. For this, we employed an innovative and reproducible literature review approach called Systematic Literature Network Analysis (SLNA). The SLNA was performed considering 145 selected articles from peer-reviewed journals and through them it was possible to identify the most represen-tative approaches and future trends. Through this analysis, we identified that in the past 10 years, studies have focused on the use of Measure-Correlate-Predict (MCP) models, first using linear models and then improving them by applying density or kernel functions, as well as studies with alternative techniques, like neural networks or other hybrid models. An important finding is that most of the methods aim to assess wind power generation potential of target sites, and, in recent years the most used approaches are
MCP and artificial neural network method

Over the recent years, one of the most rapidly expanding RE technologies has been wind power. Global usage is increasing, owing in part to falling costs (Vargas et al., 2019). According to the most recent IRENA data (International Renewable Energy Agency, 2021), the worldwide wind power (offshore and onshore) capacity has significantly expanded in the past two decades, rising from 7.5 GW in 1997 to 733 GW by 2020. Figure 1 depicts the recent trend and popularity growth of wind power over the last ten years, from 2011 to 2020. The strong growth in 2020 was owing to significant growth in China in addition to a jump in the US ahead of policy changes; the rest of the world added about the same amount of (net) additional capacity that it did in 2019. By the end of 2020, more than 100 countries had some level of commercial wind power capacity, and 37 countries-representing every region-had more than 1 GW in operation (Global Status Report, 2021; Ha et al., 2021). Wind power accounts for a significant portion of electricity generation in an increasing number of countries. For instance, in Europe, wind energy produced adequate power in 2020 to supply approximately 15% of the EU-27's energy requirements (Wang et al., 2021). Wind energy met an estimated 48% of Denmark's electricity demand in 2020 and accounted for nearly 58.6% of the country's total generation. Other European countries with wind generation shares of at least 20% for the year included Ireland (38%), the UK (24.2%), Portugal (24%), Germany (23.2%) and Spain (21.9%) (Ortega-Izquierdo and del Río, 2020; Leiren et al., 2020).

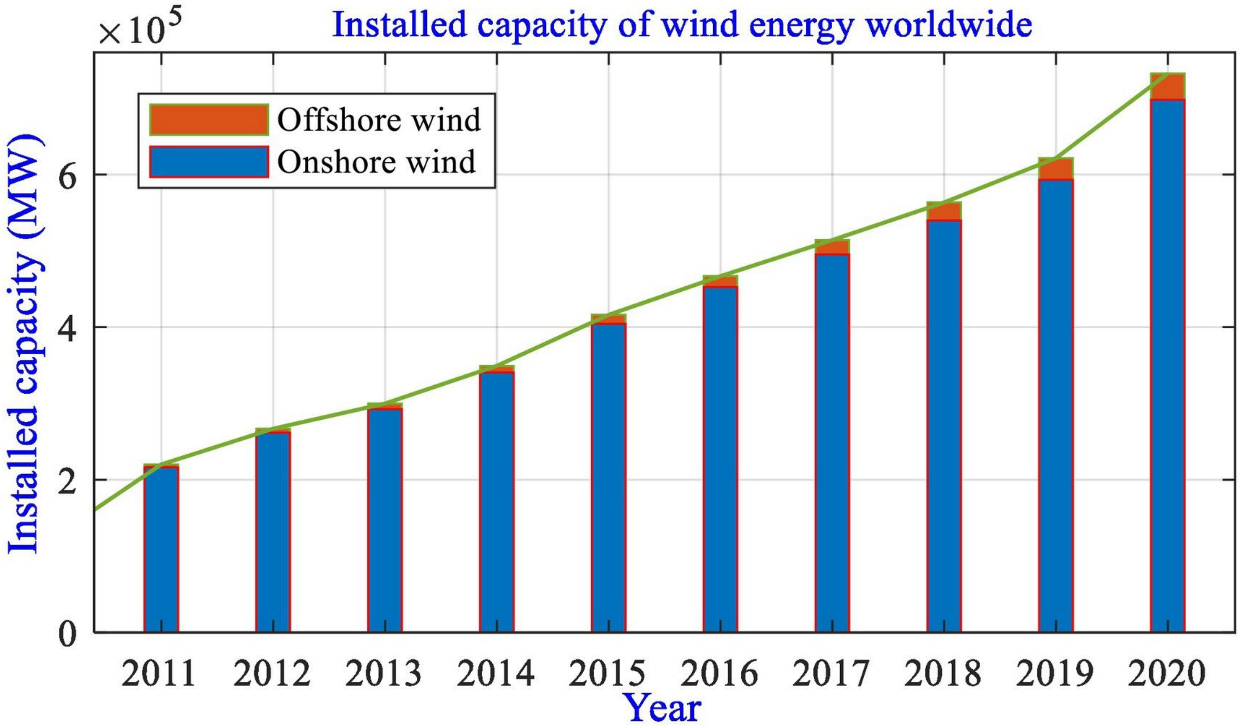

Figure 1. Installed capacity of wind energy worldwide.

From Figure 1, it is noted that onshore wind dominated the global wind power generation followed by minimal contribution from offshore wind power generation.

3. Wind power generation

Wind power generation is the process of converting wind energy to electricity by rotating blades and converting that rotating energy into electrical energy by an electric generator. Energy in wind increases with the cube of the wind speed, and hence the wind turbine generators (WTG) should be installed in areas with high wind speeds (Toshiba Energy Systems & Solutions Corporation 2023).

Wind power technology continues to evolve with development of modern electronic devices including controlling systems and larger capacity and cheaper turbines to offer solutions to meet customer needs in many different situations Figure 2 shows the general configuration of a wind power plant unit exporting power to the grid.

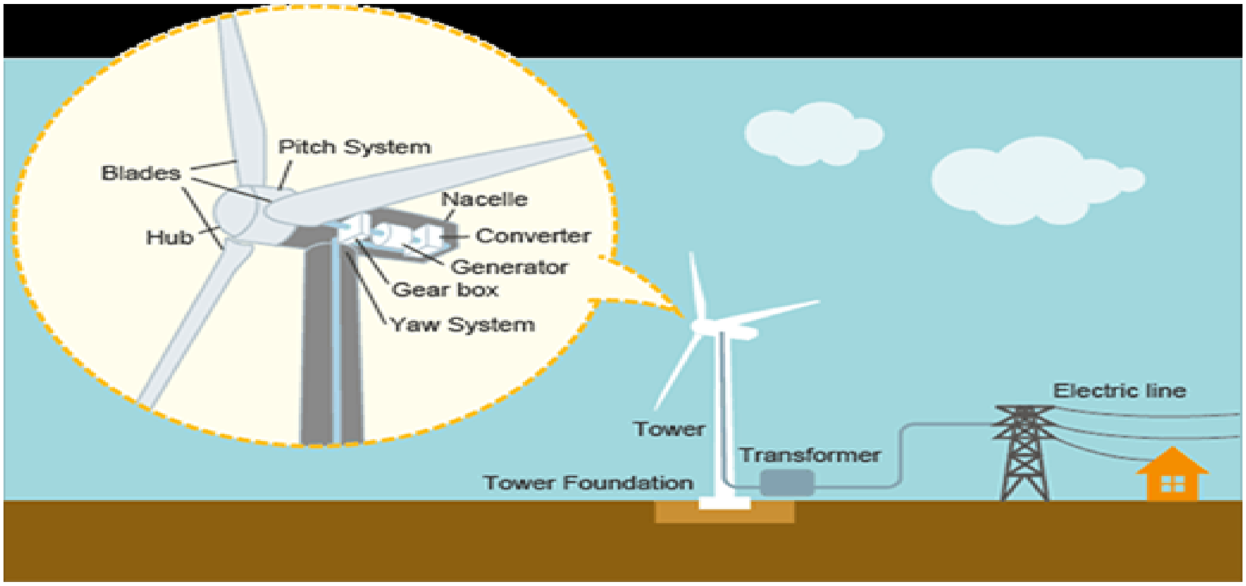

Figure 2. A basic wind power generation system

There has been significant progress in wind power technology leading to the development of large wind turbine generators (WTGs) and bigger wind farms (Toshiba Energy Systems & Solutions Corporation, 2023). The global wind power capacity had been growing motivated by several factors, namely.

i.) Wind is a safe and exists everywhere, hence no concerns over depletion.
ii.) The equipment is simple and easy to operate.
iii.) Less impact to the natural environment

4. Types Of Wind Turbines

Generally, a WGs is constituted of two parts: a power electronic converter and an electromechanical mechanism; both being sensitive and expensive. Hence, WGs require adequate protection against both overvoltage's and overcurrent. There are two basic types of wind turbines, namely the horizontal axis and the vertical axis
Horizontal-axis turbines.

The horizontal axis wind turbines are like propeller airplane engines having blades similar to airplane propellers, and often come in a 3-blade assembly. The largest horizontal-axis turbines cn be as tall as a 20-story building with blades as long as 100 feet. About all of the wind turbines in operation today are the horizontal-axis turbines (IEA, 2023).

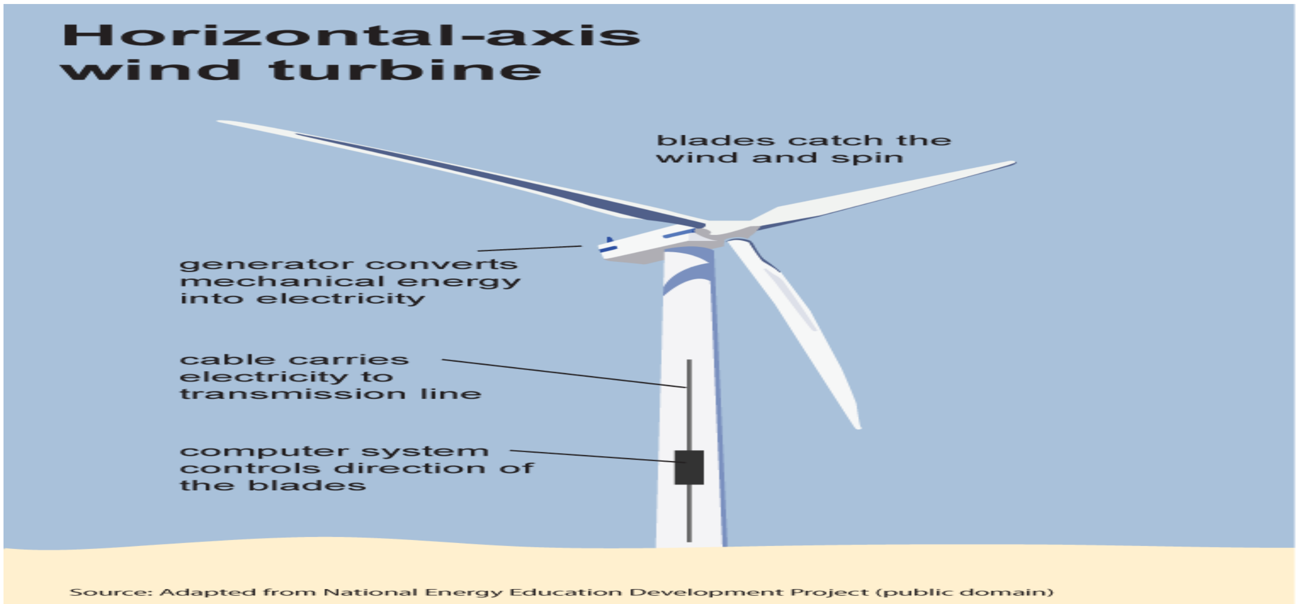

Figure 3. Horizontal -axis turbines

Vertical-axis turbines look like eggbeaters (Figure 3). Vertical-axis turbines have blades attached to the top and the bottom of a vertical rotor. The most common type of vertical-axis turbine—the Darrieus wind turbine, named after the French engineer Georges Darrieus, who patented the design in 1931 is the most common vertical axix turbine. The design looks like a giant, two-bladed eggbeater. The vertical-axis turbine can be as high as 100 feet tall and 50 feet wide. Few vertical vertical-axis wind turbines are in opetaion today because they are inferior to the horizontal-axis turbines in performance (Figure 4).

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Figure 4. Darrieus vertical-axis wind turbine in Martigny, Switzerland

Wind turbines vary in size length with the size of blades being the biggest factor in determining quantity of power a wind turbine can produce. Small wind turbines for homes can have a capacity as low as 10 kilowatts (kW), but the largest. Utility scale wind turbines in operation are about 15,000 kilowatts (15 megawatts), while larger turbines are still under developent. Many turbines are grouped together to create wind power plants, or *wind farms*, for grid power generation(IEA, 2023)

5. Wind farms

Wind farms are clusters of wind turbines that generate large amounts of electric power. A has many turbines scattered over a large area independently producing power. An example is the the Horse Hollow Wind Energy Center in Texas which is one of the the largest wind farm in the US having 422 wind turbines by the end of 2021 spread over about 47,000 acreswith combined electricity generating capacity of about 735 megawatts (or 735,000 kilowatts).

Nacelle layout

PMSG with gear box and full-size converter are used (Figure 5).

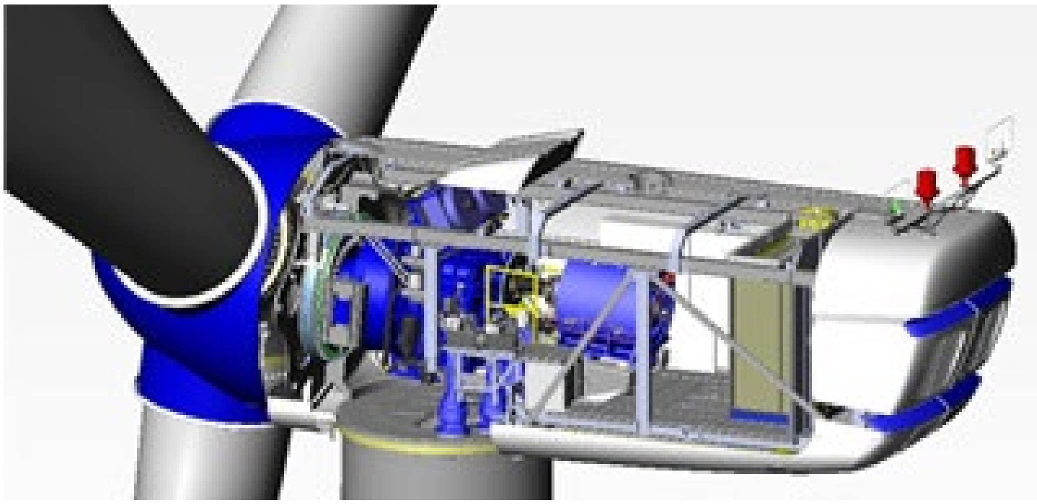

Figure 5. PMSG with gear box and full-size converte

6. Sustainability of wind

Wind energy is considered as the most sustainable form of energy currently available on commercial scale by harnessing the power of moving air to rotate the wind turbines to supply regenerative form of energy with negligible greenhouse gas emissions. A few attributes of wind energy as a sustainable energy resource includer.

i.) No consumption of fuel or combustible energy inputs
ii.) No emission of common dioxide and other greenhouse gas emissions from direct generation related activities
iii.) There is infinite energy from wind, which is powered directly by abundant solar energy.
iv.) Wind energy has got Long-term use potential.
v.) Wind energy resources can be exploited anywhere all over the world.
vi.) Wind energy can be used as a form of carbon offset to lower overall emissions from other energy resources.

6.1. Economics of wind Power Generation

Larger turbines, more efficient manufacturing, and careful siting of wind machines have brought wind power costs down precipitously, from $2600/kW in 1981 to $800/kW in 1998 and still lower today. New wind farms in some areas have now reached economic parity, or have beaten, new coal-based power plants, and as the technology continues to improve, further cost declines are projected, which could make wind power the most economical source of electricity in some countries. Market growth, particularly in Europe, has been stimulated by a combination of favourable governmental policies, lower costs, improved technology, and concern over environmental impacts of energy use. Compared to wind turbines built in 1981, modern turbines generate 56 times the energy at only nine times the cost(Kammen, 2004).

Wind energy is currently one of the most cost-competitive renewable energy technologies. Worldwide, the cost of generating electricity from wind has fallen by more than 80%, from about 38¢/kWh (U.S.) in the early 1980s to a current range of 3–6¢/kWh (U.S.) levelized over a plant's lifetime, and analysts forecast that costs will drop an additional 20–30% in the next 5 years. Consequently, in the not-too-distant future, analysts believe that wind energy costs could fall lower than most conventional fossil fuel generators, reaching a cost of 2.5¢/kWh (U.S.) (Figure 4). Wind technology does not have fuel requirements, as do coal, gas, and petroleum technologies. However, both the equipment costs and the costs of accommodating special characteristics such as intermittence, resource variability, competing demands for land use, and transmission and distribution availability can add substantially to the costs of generating electricity from wind (Kammen, 2004)

6.2. Environmental Impact of Wind

According to our unit-based analysis results, the delivery of 1 kWh of electricity from onshore wind energy conversion causes 16.4 g CO2-eq climate change, 0.016 g N-eq marine eutrophication, 0.075 g NMVOC photochemical oxidant formation, and 0.085 g SO2-eq terrestrial acidification impact potentials. The corresponding values for offshore wind power are 13.7 g CO2-eq, 0.023 g N-eq, 0.095 g NMVOC and 0.084 g SO2-eq. For the onshore case, the wind turbine is the most important single component, contributing 60–69% to total emissions (Figure 1). Of this, the tower holds shares of 35–42%, the nacelle 25–37% and the rotor (including hub) 20–25%. The wind turbine is a much less dominant contributor to the emissions of ocean-based systems (19–35%), for which installation.
and decommissioning become more important (18–52%). The foundation contributes 6–11% (onshore) and 13–25% (offshore). Figure 2 shows the breakdown of the contribution of electricity, materials, and manufacturing processes to the total emissions of components of the wind park. For climate change and terrestrial acidification category indicators, significant portions (20–29%) of total emissions are caused by fossil-fuel burning in the power sector, reflecting the need to use fossil-based electricity of today to develop the renewable energy systems of tomorrow (Arvesen, and Hertwich, 2011). Manufacturing of metals and metal products is responsible for 9–33% of total emissions transportation causes 20% of eutrophication, but only 5% of climate change impact potential. Our scenario analysis yields cumulative greenhouse gas (GHG) emissions due to wind power development of 1.7 Gt and 2.6 Gt CO2-eq, for the BLUE Map and BLUE hi REN scenarios respectively, in the time 2007–50 (Figure 3). Corresponding values for other impact categories are 2.1 (3.2) Mt N-eq, 9.2 (14) Mt NMVOC and 9.5 (15) Mt SO2-eq for the BLUE Map (BLUE hi REN) scenario ooking at GHG emissions, construction of new capacity dominates (64% of cumulative emissions in 2050 in BLUE Map scenario), although repowering becomes increasingly important (38% in 2050). Due to the combined effects of increased load factor, shift from land to ocean sites and cleaner electricity mix in manufacturing, the GHG emission intensity, as calculated with the unit-based analysis with current-year technologies, is reduced to less than 10 g kWh^{-1} in 2050 (Figure 3). Assumed lifetimes and future capacity factors are two important sources of uncertainty and are addressed in the sensitivity analysis.

7. Results and Discussion

Wind energy is widely acknowledged as one of the most sustainable sources of electricity: environmental impacts are relatively low, further reductions in production costs are expected, the distribution of global wind resources is diverse, and the potential for market expansion is large. Life cycle greenhouse gas emissions per unit of wind energy are approximately ninety percent less than emissions from conventional fossil fuel power sources, and bird population impacts and of noise pollution have been reduced significantly in recent years. For these and other reasons, a range of policies have been adopted in various countries to promote wind energy development.

A combination of technological improvements, cost reductions, and economic incentives has made wind energy the fastest growing source of electricity, with installed global capacity doubling approximately every three years over the last decade. The state-of-the-art turbine in 1989 was a 300 kW unit with a rotor diameter of 30 meters. By 1999, 1.5 MW wind turbines with 70 meter rotor diameters were available, and today 4 to 5 MW turbines are under development. Total installed global wind capacity was 4,844 MW by the end of 1995 and had increased over threefold to 17,706 MW by the end of 2000 (Ackerman and Söder 2002). Today's production costs are one-sixth the costs seen in the early 1980's, averaging around $0.04 to $0.06 per kWh, and production costs are projected to drop to $0.027 to $0.045 per kWh by 2030 (this report).

A variety of technological and economic issues underlie these impressive developments in wind energy. Several extensive reviews of wind energy technology have recently been published and cover these developments from various perspectives. Ackerman and Söder (2002) review recent global developments and major wind power characteristics. A recent book by Manwell, McGowan and Rogers (2002) provides detailed information on the theory and analysis of wind turbine design and operation. An updated version of Hau's book on wind technology (2000) provides a detailed account of a range of issues, including turbine design, manufacturing and economics.

This report is intended as a general primer on wind energy technology, with a focus on technological characteristics and how they relate to the economics of wind energy. It draws upon the three major sources mentioned above, as well as a variety of additional sources, to provide a concise survey of four wind energy topics: 1) characteristics and extent of wind resources, 2) fundamentals of wind turbine technology, 3) intermittency of wind energy and the roles of transmission and storage, and 4) the economics of wind energy. Within these topics, there is an emphasis on the theoretical aspects of converting wind energy into electricity, was well as subsequent conversion of electricity into hydrogen.

8. Conclusion

Wind energy is a form of kinetic energy generated by the flow of air caused by temperature differences in various places and hence air pressure leading to air flow. Solar radiation received and the long-wave radiation energy released by different surfaces of the earth are different which is the cause of temperature differences at different paces. Wind energy is inexhaustible energy in the form of air that flows from an area with high air pressure to one with low air pressure. Wind is considered an attractive energy resource because it is renewable, clean, socially justifiable, economically competitive and environmentally friendly (Burton et al., 2011). Therefore, the outlook is for increasing participation on wind power in the future, up to at least 18% of global power by 2050 The fluctuating nature of wind, despite the high penetration of wind energy, poses several challenges when integrating wind power into the electric grid, since high costs can be involved for construction of wind farms as well as prior and ongoing assessment studies. Contrary to conventional energy sources, wind speed varies both spatially and temporally, generating fluctuations in wind energy output. Weather variables such as wind direction, temperature, pressure, and humidity, among others, influence wind power production. Hence, to integrate wind power into the electric grid requires estimates, at least, of future wind speed values.

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