Literature Review of Wind Turbines

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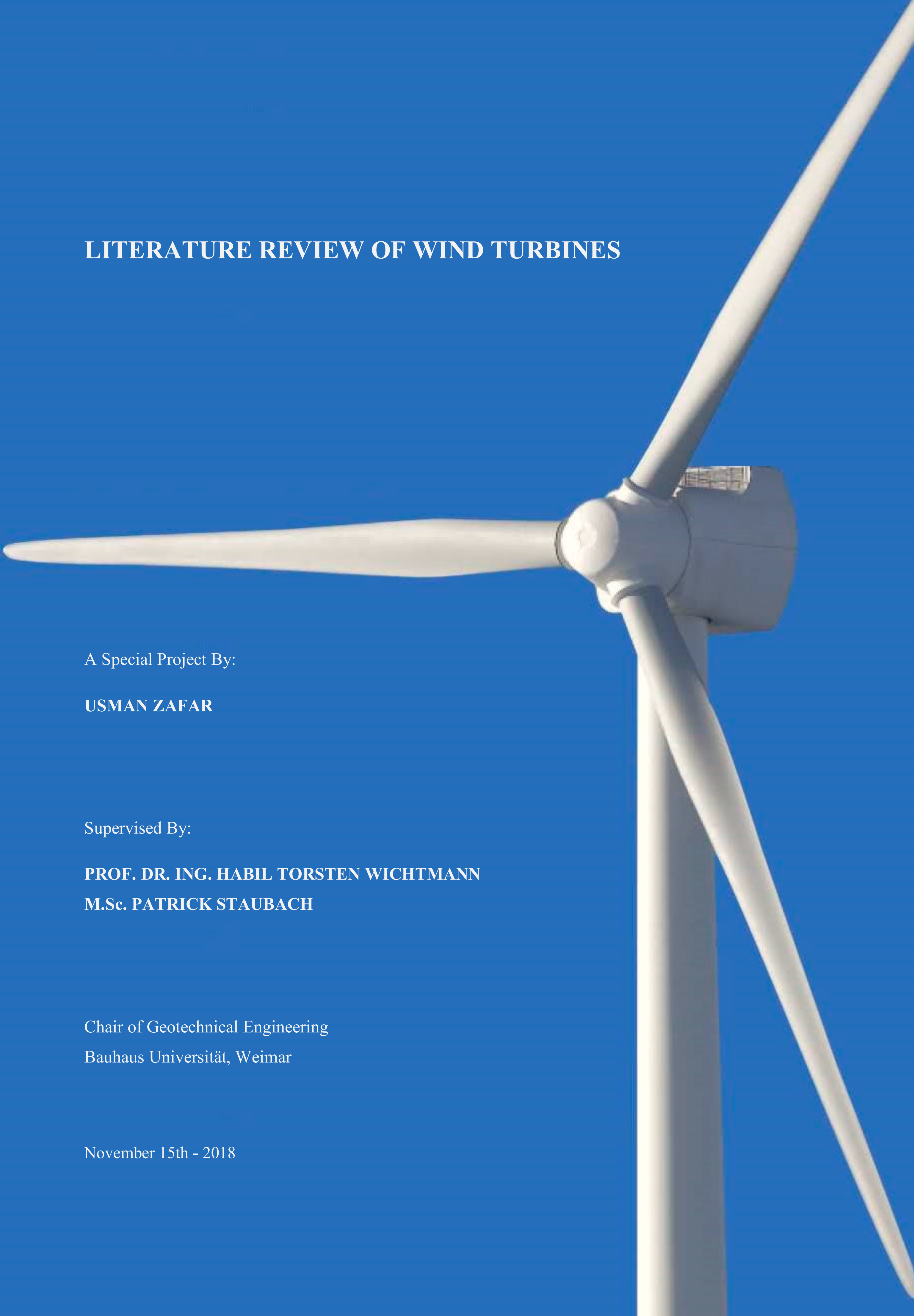

LITERATURE REVIEW OF WIND TURBINES

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ABSTRACT

Wind has been in use by the mankind for thousands of years. Its usage can be traced back from the medieval times. Around 3000 years, wind was mostly used for pumping water and grinding grains. In earlier times, fossil fuels were significant source of producing electricity. Fossil fuels posed serious damaging effects on the environment and people were exploring for alternative resource. Wind energy was cheapest, widely available, renewable and posed minimal damaging effects on the environment. This raised the interest and attention towards wind energy. Government institutions funded the research in wind technology to be adopted as the mainstream source of power production in the world. Scientists and researchers successfully designed several wind turbine prototypes which worked really good with the site conditions. By the late nineteenth century, wind energy was in operation to produce electricity. Later, this technology was enlarged and utilized as onshore wind energy. Latest developments and some risks involved in the onshore wind energy has evolved the offshore wind technology. Offshore wind energy is more sophisticated and capable of producing more power than its predecessor. Now-a-days, wind energy has become more reliable source of power. It is one of the fastest growing sources of electricity which is believed to have the potential to meet the electricity demands around the world.

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NOMENCLATURE

KW	-	Kilowatt
MW	-	Megawatt
GW	-	Gigawatt
kWh	-	Kilo watt hour
GWh	-	Giga watt hour
WPD	-	Wind power density
ρ	-	Air density
EIA	-	United States Energy Information Administration
m/s	-	Meters per second
GWEC	-	Global Wind Energy Council
NREL	-	National Renewable Energy Laboratory

Chapter 1

Introduction and Related Terminologies

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1. Introduction and Related Terminologies

Wind is not a new terminology for humans. Mankind have been using wind that can be traced back to 3000 years. In earlier times, humans were mostly using wind for agricultural, irrigation and navigation purposes however, fossil fuels were the main source of power production. In 19th century, the commercial exploration shifted from coal to petroleum. Coal and natural gas are still considered the most common and cheapest form of power production in the wind. Many scientist and researchers consider wind as a potential resource for meeting future's electricity demands. The damaging effects caused by the burning of fossils fuels started the need for alternative source of power generation. Social and eco-environment consciousness spread around many countries demanding for new reliable and clean source of energy. That was the beginning of research and development in the wind industry which continue to flourish till today. Wind power, is an alternative resource to coal, petroleum and nuclear energy which is more abundant, renewable, widely distributed and has fewer damaging effects on the environment.

Wind is the result of an air pressure gradient. It is generated due to the changes in the temperature of different areas. Land and sea have different composition which give them unique temperature characteristics. Generally, more wind is available on sea as compared to the land. Wind turbine is a machine that utilizes wind power and converts it into electric power. Wind is feed into the mechanically driven shaft that rotates and produces electricity. The output of electricity depends upon the available wind speed. Wind speed varies very significantly in each hour of the day but the average wind speed remains consistent throughout each day. This average wind speed is used for performance and output power calculations. Therefore wind turbines are always used in conjunction with some electric power source to stabilize the output [1].

1.1 Onshore Wind Turbines

Onshore wind turbines are referred to the turbines that are constructed and located on lands. They are cheaper to construct and one of the most affordable renewable source of power generation. They are often criticized for their visual impairment problem. It has the half of the cost of power per kWh than offshore wind energy and a quarter of the cost of solar panels. Onshore wind industry dominates mostly in Europe. China, USA, Germany and India are top contributing countries with a total cumulative capacity of 540 GW in December, 2017. USA and China have put a lot of research and funding in the onshore wind industry. This development and the interest in the onshore wind industry was very encouraging in the previous years which led to the advanced and sophisticated offshore wind industry. As a result of the emergence of offshore wind industry, an overall decline in the addition of onshore wind capacity has been observed to 10% in 2017 [2][3]. The foundation for onshore wind turbines is casted on site, whereas the tower, blades and other machinery are pre-fabricated and transported on site. The transportation of onshore wind turbines is relatively easier than offshore wind turbines however, it involves significant prior planning and discussions with logistics companies and government institutions.

1.2 Offshore Wind Turbines

Offshore wind turbines are referred to the wind turbines that are constructed in sea or oceans. Higher wind speeds are available and hence, offshore wind turbines are capable to produce more power. By the end of 2017, the cumulative capacity for offshore wind energy was 18.8 GW. All the largest offshore wind farms are currently in northern European countries. United Kingdom leads the offshore wind industry while Germany and USA are also big contributors in offshore wind energy. Walney Wind Farm is the largest offshore wind farm constructed in the Irish sea, United Kingdom. It is constructed in 3 phases with 189 turbines capable of producing 659 MW to supply electricity to 600,000 homes in United Kingdom [4]. General Electric has developed 12 MW offshore wind turbine which is the largest offshore wind turbine in the world, which will operational in 2019. The offshore wind turbines are expensive to construct and requires very heavy and dedicated means of transportation. Developments in the recent years in the offshore wind technology have reduced the overall expenditure and offshore wind farms are now a competitive power resource in the Europe [5].

1.3 History of Wind Turbines

For thousands of years, humans have been using wind as a source for irrigation, water pumping and navigation purposes. People used wind energy to propel boats along the river Nile that can be traced back 5000 years BC. By 200 BC, people in Persia and China were using wooden wind powered water mills for pumping water and grain grinding purposes. These wind mills were of small scale and mostly used for remote areas and minor works. When power lines were built to transmit electricity, the trend and usage of small wind mills started to decline and remained confined to the rural regions. New ways to use wind energy as a reliable and commercial source of power started around 1990's. In 1903, the Wright Brothers successfully invented the first airplane. The concept of commercial onshore wind turbines originated from the invention of the airplane. Scientists and researchers were successful in adopting the technology of airplane propeller and wings to the onshore wind energy [6]. The first ever wind turbine was built by the American scientist Charles Bush in 1888. However, the commercial production of wind turbines begun around 1990’s. Initially, due to less development and lack of sophisticated construction technology, production of electricity was only limited to onshore wind turbines. The offshore wind turbines technology evolved from the already developed oil and gas industry. A lot of modern-day offshore wind turbines structures have been taken from the oil and gas industry like jacket, tripile and tripod structures. The first offshore wind farm was built in Denmark in 1991. It was named as Vindeby and operated 1.5 to 3 km off the southern Danish coast. It had 11 wind turbines each of 450 kW capacity capable of producing 4.95 MW. Vindeby generated 243 GWh of power in its 26 years life span. Dong Energy decommissioned them in February 2016 [7].

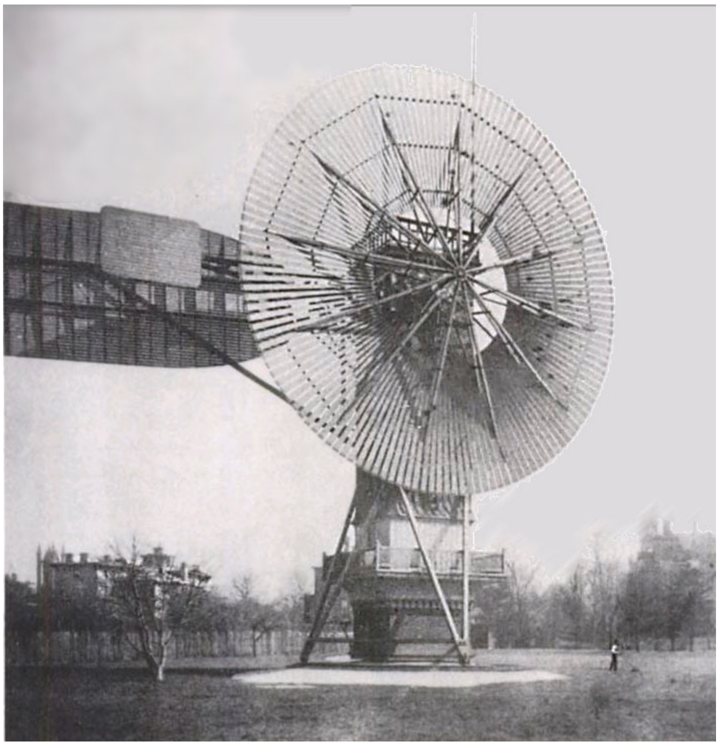

Figure 1.1 - First wind mill built by Charles Brush in 1888 [6]

Figure 1.2 - Vindeby (world's first offshore wind farm) [8]

Figure 1.3 - Water pump wind mill in South Dakota, USA [9]

1.4 Wind Power

A measure of available energy at any location is called the Wind Power. The power contained in a wind is "P" and power that can be extracted from the incoming power of wind "P_a" power can be calculated by the following equations:

$$P = \frac{1}{2}\,\rho\,A\,v^3 \qquad\qquad P_a = \frac{1}{2}\,\rho\,A\,v^3 C_p$$

P	=	Power that is contained in the wind (watts)
ρ	=	Air density – varies by temperature and altitude
A	=	Rotor swept area (m^2)
v	=	Wind speed (m/s)
P_a	=	Power that can be extracted by a wind turbine (watts)
C_p	=	Power Coefficient due to losses

Power Coefficient (C_p) is the measure of the efficiency of a wind turbine. Power coefficient is measured and provided by the turbine manufacturers against various wind speeds. Generally, it contains all the combined losses including mechanical components losses, aerodynamic and electrical losses. The German physicist Albert Betz concluded in 1919 that no wind turbine can convert more than 59.3% of the kinetic energy of the wind which is called the Betz Law. It is also noted that the Betz limit is actually the theoretical maximum value that no practical wind turbine can operate. Practically, this value is around 35% to 40% [10].

Example: How much power can be extracted from a wind turbine with the following parameters.

Blade length	=	52 m		
Wind speed	=	12 m/s		
Air density	=	1.23 kg /m^3		
Power Coefficient	=	0.4		
Swept area of rotor	=	$A = \pi r^2$		
		$A = \pi \times (52)^2$	=	8495 m^2
Power in the wind	=	$P = 0.5 \times 1.23 \times 8495 \times (12)^3$	=	9.02 MW
Power generated	=	$Pa = 0.4 \times 9.02$	=	3.6 MW

3.6 MW rated capacity means that a wind turbine can produce 3.6 MW per hour at the availability of optimum wind speed for 1 hour continuously.

Capacity Factor of a wind farm is the ratio of its actual output over a period of time to its maximum output. It is also called Load Factor in wind energy industry. It describes how much generators are in run. It can be from 0 to 100%. Usually higher capacity factor has bigger outputs but they will be more expensive. For higher capacity factors, the average reduction in the energy generation will be greater and hence its cost to performance ratio will be not be economical. For the entire lifespan performance of a wind turbine, the capacity factor becomes insignificant. According to EIA, the capacity factor of around 40% is considered good and economic in the wind industry [11].

Example: **A wind farm consists of 10 wind turbines each of 2 MW capacity, produces 44,000 MWh of electricity in 1 year. The capacity factor of this wind farm will be.**

$$Capacity\ Factor = \frac{44{,}000\ MWh\ in\ 1\ year}{(365\ days)(24\ hours/day)(2\ x\ 10\ MW)} = 0.25 \sim 25\%$$

Annual power generation of a wind turbine is the amount of electricity it will produce per year regardless of the variations in speed and power. It is measured in kWh and can be estimated as below:

Example: **How much annual power a wind turbine will generate with the rated capacity of 2 KW and a capacity factor of 25%.**

Annual power (kWh)	=	365 (days) x 24 (hr) x 2 (kW) x 0.25
	=	4,380 kWh

1.5 Wind Power Density

Wind power density (WPD) of an area helps in the comparison and selection of best suited sites for the wind turbines. Turbines that are installed at areas having higher WPD usually generate more electrical energy. WPD is defined as:

$$WPD = \frac{1}{2}\,\rho\, v^3$$

WPD	=	Wind power density (watt / sq. area)
ρ	=	Air density
v	=	Wind speed

According to American Wind Energy Association, wind can be classified into categories, which can be used as an indication for a potential site for future wind farms.

Table 1 - Wind power density classification [12]

Wind Power Class	Resource Potential	WPD at 50 m	Wind Speed at 50 m
		W/m^2	m/s
1	Poor	0 - 200	0 - 6
2	Marginal	200 - 300	6 - 6.8
3	Fair	300 - 400	6.8 - 7.5
4	Good	400 - 500	7.5 - 8.1
5	Excellent	500 - 600	8.1 - 8.6
6	Outstanding	600 - 800	8.6 - 9.5
7	Superb	> 800	> 9.5

1.6 Wind Turbine Capacity and Sizes

Wind industry is flourishing day by day and the sizes and capacities of wind turbines are also getting bigger. Increasingly large wind turbines are being designed and developed. The interest and development in the onshore wind turbines have declined in the recent years and the offshore industry has become more technological advanced than the onshore wind industry. The average capacity of currently operational and manufactured offshore wind turbines is around 2.5 MW to 3.5 MW. 8 MW turbines are the largest in operation today. 15 MW turbines are planned, and 20 MW turbines are considered theoretically possible. The overall newly manufactured wind turbines have bigger capacities than ever before [13].

Wind speed is more at higher altitudes and they have a significant effect on the overall output power of the wind turbine. Taller the wind turbine experiences higher wind speeds, which in return can yield more power. The Figure 1.4 shows the development of wind turbine's rotor diameter and hub height over the recent years. The Vestas V126 was the tallest wind turbine that was erected in 2017 with a hub height of 166 m. The maximum overall height of the wind turbines which were installed in 2016 was on a rising trend with measurements up to 230 m [14].

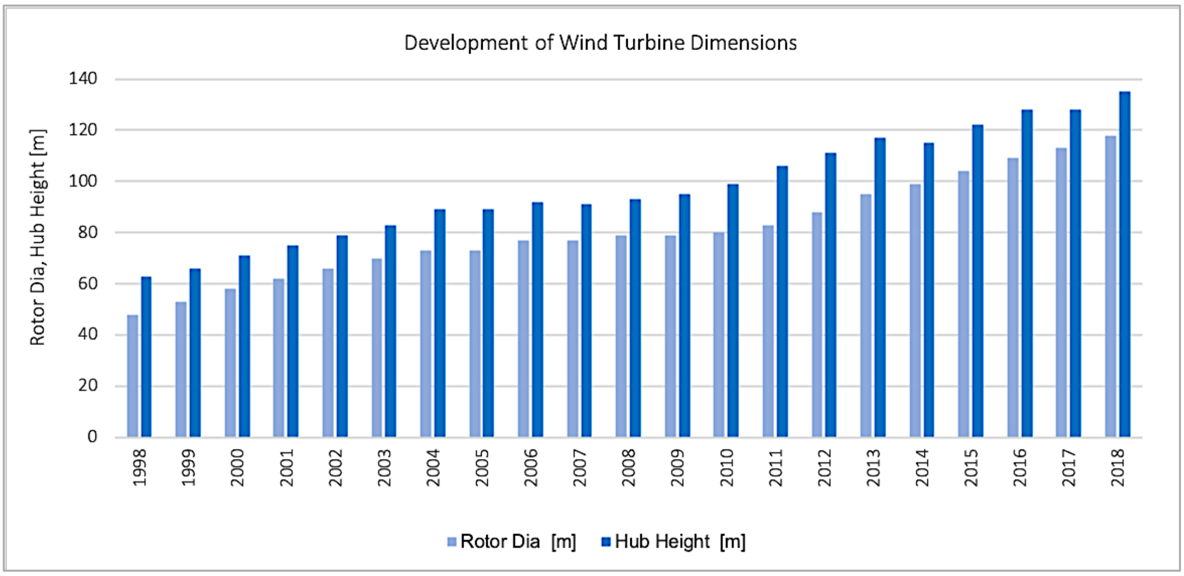

Figure 1.4 - Development of wind turbine dimensions [14]

1.7 Wind Profile

Wind is unpredictable in nature and wind speed has a dependency on time and location. Wind speed varies during the day as well as with the surface roughness of different sites. Wind profile is a key factor in deciding for the capacities of the wind turbines to be installed. The terrains that don't have a lot of hindrances like trees, houses or buildings will have less roughness length and can have higher wind speeds, whereas, urban areas are usually the regions with low wind speeds.

On seas or oceans, much higher wind speeds are faced compared to wind speeds on land. On sunny days, wind speed is more as compared to the overcast or cloudy days. At low altitudes, wind speed variation is more significant on the oceans than on the land. During day time, wind speeds are generally lower than during the nights.

At lower altitudes, wind speeds are higher in day time than in nights and at higher altitudes, wind speeds are higher in nights than in the day time. This different behavior can be counted for the more temperature change near the surface than the higher altitudes where temperature exchange between different air layers is not significant.

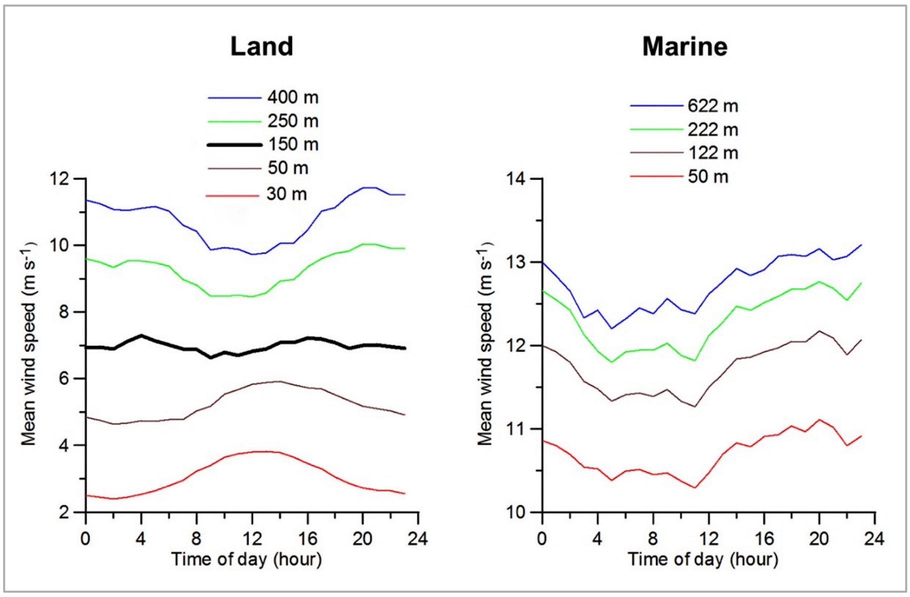

Figure 1.5 - Variations of wind speeds with heights, surfaces & times of a day

1.8 Electricity Requirement of a Household

About 80% of people in the world have access to the electricity. This number has increased in the last decade, mainly due to the increasing urbanization. There are numerous things that drive these differences, including wealth, physical house size, appliance standards, electricity prices and access to cooking, heating and cooling fuels. Canada, United States and Australia are among top consumers of annual electricity. Annual consumption of electricity in a neighborhood is a key factor when deciding the size of any wind farm. It is the actual output power that a wind farm needs to generate to meet the electricity needs of a community or a state.

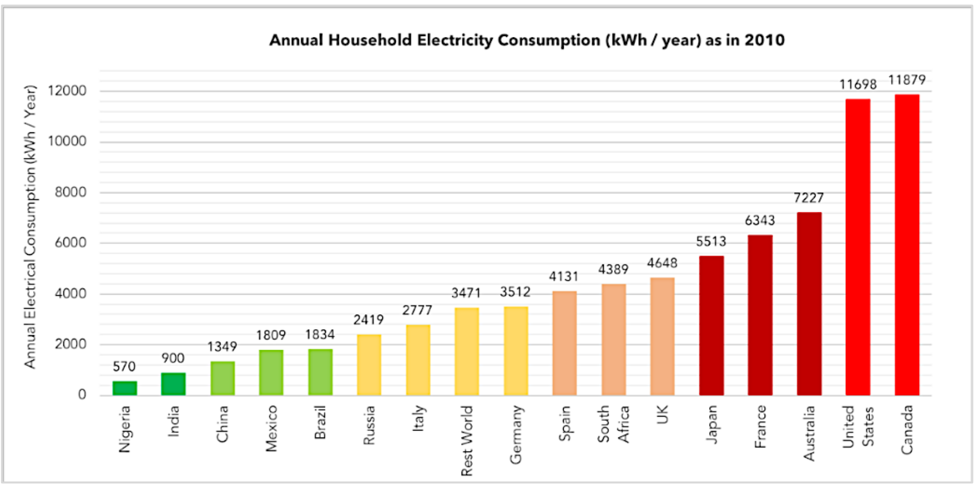

Figure 1.6 - Annual household electrical consumption (Enerdata via World Energy Council) [15]

1.9 Wind Turbine Cost Figures

The cost of a wind turbine varies from each design and specification but the biggest cost is the turbine itself. This is a capital investment that buyers have to pay upfront which is typically around 75% of the total cost of the project. As wind is a free source of powering wind turbines, only operational and maintenance expenditures remain accountable after the wind turbine is set up. These O&M costs are minimal as compared to the overall cost of the project. For the wind turbine, the largest cost components are the rotor blades, the tower and the gearbox which altogether contributes to around 50 to 60% of the cost of a wind turbine. The electrical components like generator, transformer and power converters accounts for about 13% of the turbine costs. The cost of onshore wind turbines is less than the offshore wind turbines. According to International Renewable Energy Agency, the typical installation range of an onshore wind turbine in 2010 was between USD 1800/kW and 2200/kW, while offshore wind turbine stood between 4000/kW and 4500/kW. The prices of wind turbines from 2004 to 2010 continued to rise however, since 2010 a reduction in cost has been observed. The reasons for this reduction is the improved design and overall performance of turbine components and reduction in steel and carbon prices in the global markets [16].

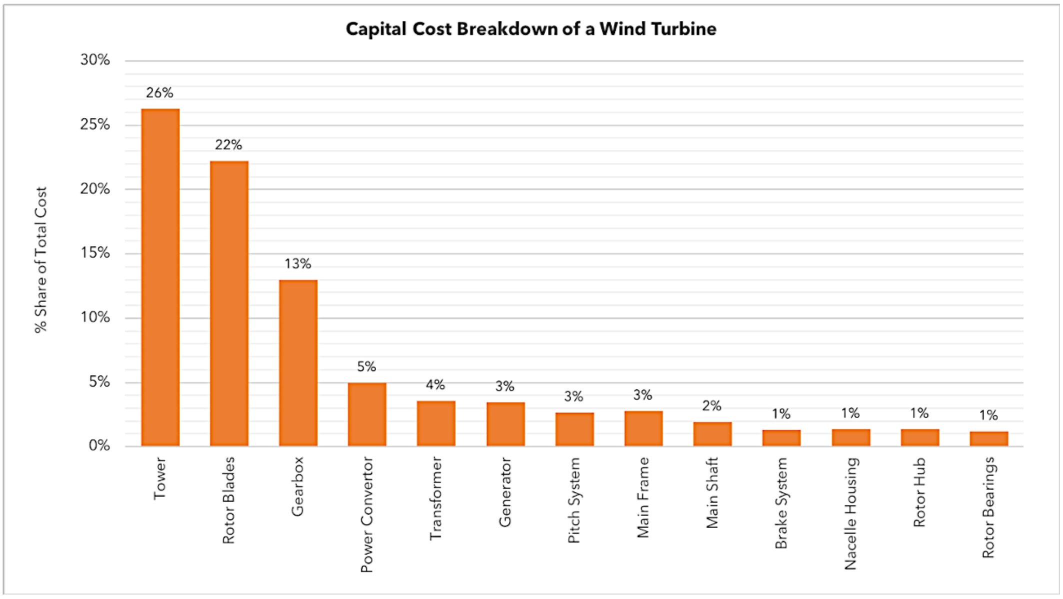

Figure 1.7 - Capital cost breakdown of a wind turbine [16]

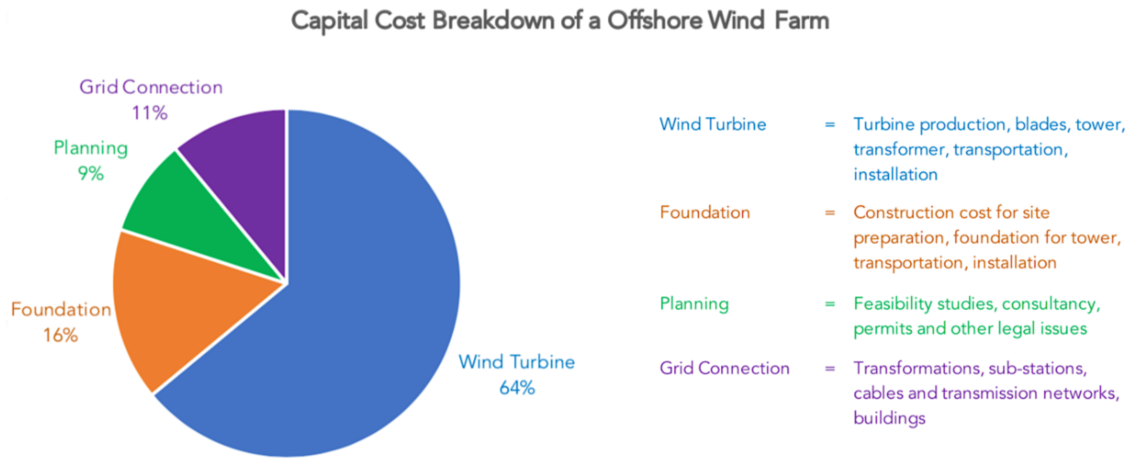

Figure 1.8 - Capital cost breakdown of an offshore wind farm [16]

1.10 Wind Turbine Speed & Performance

The performance and safety of the wind turbine depends upon the wind speed. The wind industry has defined three clear sets of wind speeds for evaluating performance and reliability of a wind turbine. Generally, all the wind turbine manufactures evaluate the performance and design of their wind turbines and provide the cut-in speed, rated output wind speed and cut-out speed.

Cut-in speed. It is the speed at which the wind turbine blades first start to rotate and generate electrical power. At very low wind speeds, due to the weight and insufficient power available, wind turbine blades are unable to rotate. However, as the speed increases, the wind turbine will get sufficient torque to rotate and generate electrical power. The cut-in speed is typically between 3 and 4 m/s [17].

Rated output wind speed. As the wind speed rises above the cut-in speed, the electrical output power also increases rapidly. However, typically between 12 and 17 m/s, the power output reaches the maximum limit that the electrical generator is capable of producing. This limit to the generator output is called the rated power output and the wind speed at which it is reached is called the rated output wind speed [17].

Cut-out speed. This is the maximum operating speed of a wind turbine beyond which a turbine faces very high forces that can risk its stability. Generally, all the turbines are equipped with automatic or manual braking system. At cut-out speed, braking system is applied which brings them to standstill. The cut-out speed and is usually around 25 m/s [17].

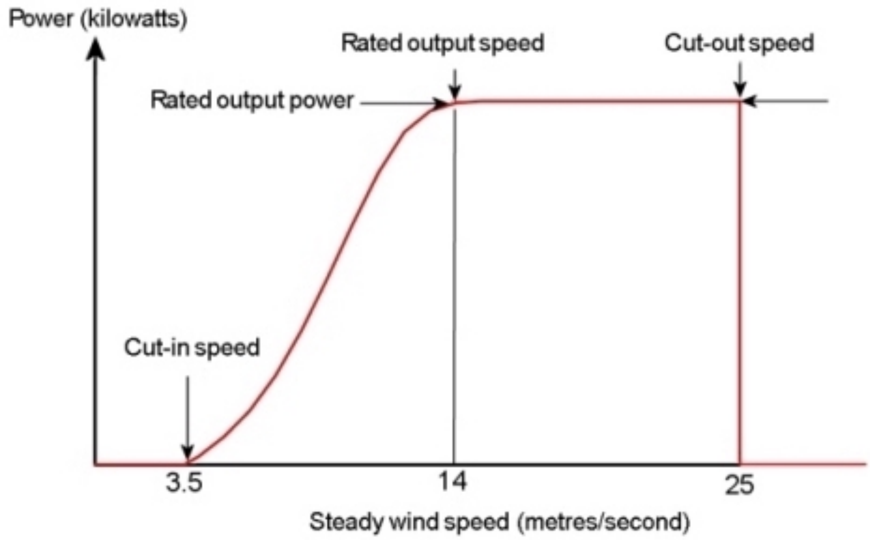

Figure 1.9 - Typical wind turbine power output curve [17]

1.11 Wind Power Statistics

According to GWEC, 2017 was a year of global expansion for wind and solar industry. New markets have emerged across many countries which outlines the development and sustainable future of the renewable energy. Total installations in 2017 were about 52 GW bringing the total of wind energy installations at 539 GW worldwide. China, USA and Germany were top contributing countries in 2017 making them also the top wind power producing countries by the end of 2017. 2017 has seen 16% increase in the world's total capacity of wind power than 2016. The 2015 was a record-breaking year for wind energy with 22% annual market growth resulted in the 60 GW mark being passed alone in 2015 [18].

Table 2 - Top wind energy producing countries in 2017 [18]

Sr. No	Country	Wind Energy Production (MW)	Percentage In Total
1	China	19,660	37%
2	USA	7,017	13%
3	Germany	6,584	12%
4	United Kingdom	4,270	8%
5	India	4,148	8%

6	Brazil	2,022	4%
7	France	1,694	3%
8	Turkey	766	1%
9	South Africa	618	1%
10	Finland	535	1%
11	**Rest of the World**	**5,182**	**10%**
12	**Top 10 Total**	**47,310**	**90%**
13	**World Total**	**52,492**	**100%**

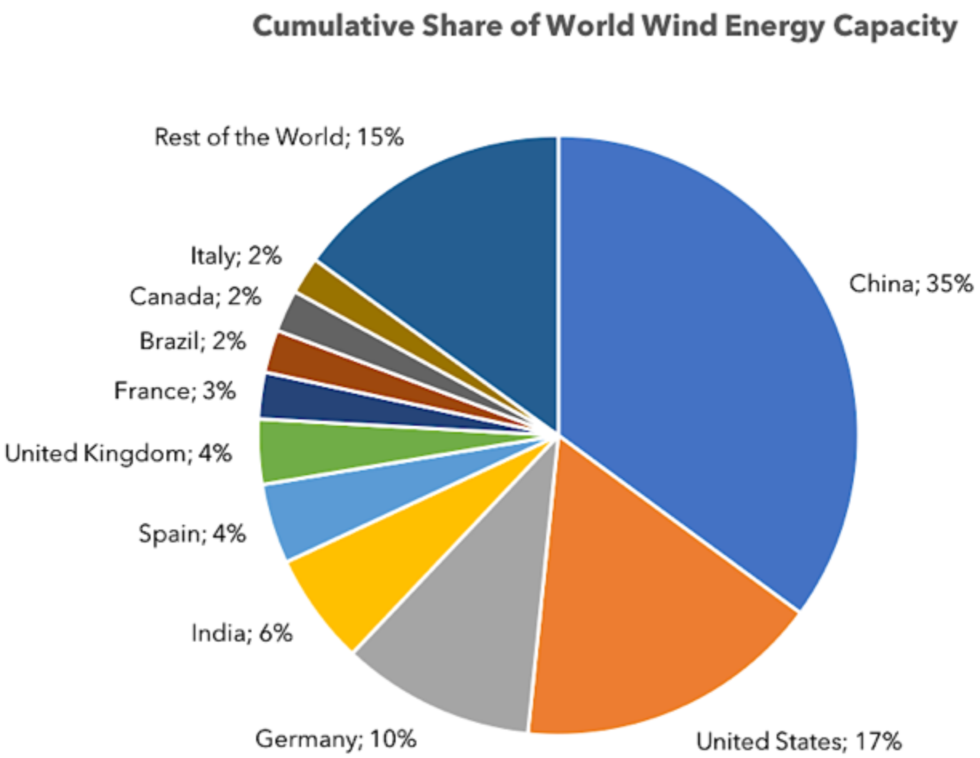

Figure 1.10 - Cumulative of world wind energy capacity share as of 2017 [18]

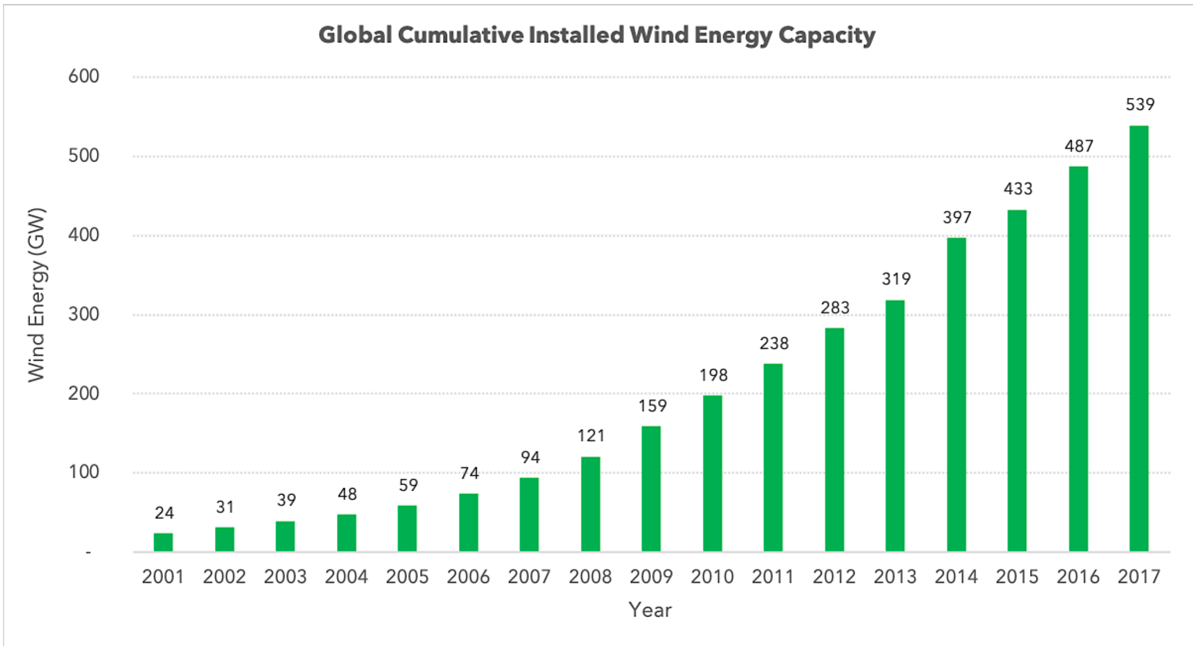

Figure 1.11 - Global cumulative wind energy capacity (2001 to 2017) [18]

1.12 Advantages and Disadvantages of Onshore Wind Turbines

\+ The infrastructure necessary to transmit electricity is less expensive in case of onshore wind turbines.

\+ Onshore turbine production could boost local economies by creating jobs opportunity and potential for future investments in the region.

\+ There would be less emissions from transporting wind structures if they are installed closer to the manufacturing site.

– Onshore wind speeds are more unpredictable than offshore. Wind turbines are designed at a certain optimized speed. Optimum wind speed may not be available to the onshore wind turbines due to variations and unavailability of consistent wind speeds in the vicinity.

– Turbines must be facing the direction of wind to perform efficiently. Onshore wind direction can change more often making performance of onshore wind turbine harder to predict.

– Onshore wind farms have been criticized for their visual impact. They are typically more spread out than other large-scale energy infrastructure projects.

- Turbines can contribute to noise pollution but new regulations have been prepared and adopted so that noise should not significantly impact on nearby residents [19].

1.13 Advantages and Disadvantages of Offshore Wind Turbines

+ Offshore wind turbines are more efficient than onshore turbines. Higher wind speeds are available in the regions of oceans. Higher wind speeds can result in higher output of the wind turbines.
+ They can be built a lot bigger and taller allowing for more energy collection from larger wind turbines. For installation of mega projects, offshore wind farms can utilize vast basins of oceans. Larger area is available to construct and build mega wind farms avoiding the conflict of lands in case of onshore wind farms.
+ Bigger wind turbines are prone to produce more noise. Offshore wind turbines are built few km's away from the land and hence, they do not pose any noise problem in the communities living nearby the oceans.
+ Fatigue effects are much lower in offshore wind turbines. Less turbulence will have more efficiency and greater lifespan of offshore wind turbines.
+ Offshore wind turbines pose no threat to farms or other private land.

- One of the main disadvantages in the installation of offshore wind turbines is the up-front capital cost. They are expensive to construct and require straight ahead a lot of investment at first place.
- The operation and maintenance expenditure of offshore wind turbines is generally higher. Offshore turbines endure more wear and tear from wind and waves than onshore. This brings up the operation and maintenance costs. Offshore wind farms have limited access for operation and maintenance works. Access of technicians and transportation of parts remains dependent on the expensive means of transportation.
- Because offshore turbines are harder to get to, it could take longer to fix problems and restore them to function properly.
- Sea animals are also known to be affected by the offshore wind farms construction however, this impact is not yet significantly studied.
- Due to harsh and unpredictable marine environment, foundation of an offshore wind turbine possesses significant challenges to construct. For accurate dimensioning, a lot of investigation and sophisticated equipment is required [19].

Chapter 2

Wind Turbine Components

- Tower
- Foundation
- Other Components of a Wind Turbine
- Axis of a Wind Turbine

2. Wind Turbine Components

Wind turbine is a machine that utilizes the wind power to generate electricity by converting the kinetic energy of the wind in to the mechanical energy. It is a complex structure which is manufactured with a wide range of components that includes mechanical, electrical and civil construction components. A typical wind energy system includes the rotors, the hub assembly, nacelle, yaw mechanism, generator, transmission system, tower and a foundation system. Figure 2.1 shows the typical wind turbine components.

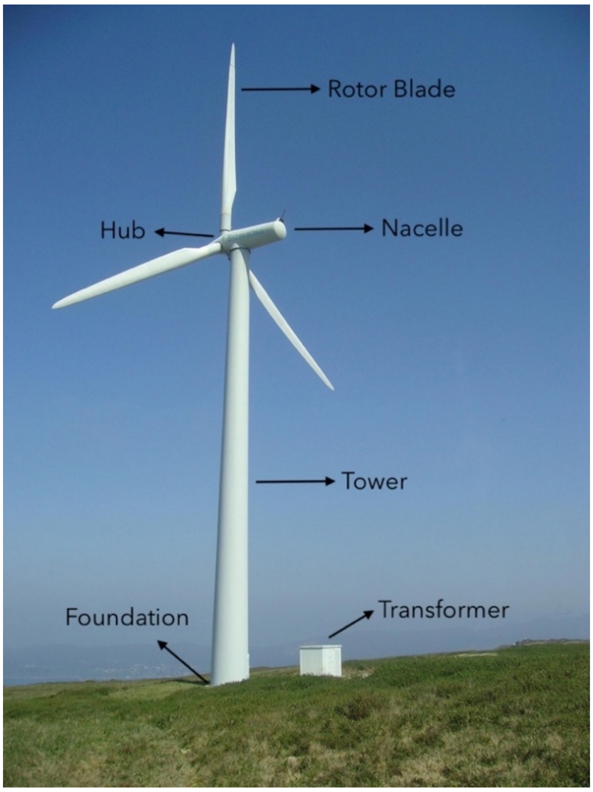

Figure 2.1 - Typical overview of a wind turbine

2.1 Tower

The purpose of the tower is to carry the wind turbine. It carries the weights of the nacelle, the rotor blades, yaw assembly and all the electrical components. It must also absorb the huge wind and vibration loads and safely transfer them to the foundation. Generally, a tubular section of concrete or prefabricated steel is used. Concrete towers are strong but expensive and steel towers are capable of higher turbine construction, so the type and choice of the tower depends upon many factors which vary to location. True vertical alignment is a very core part of construction of a wind turbine and tilting up to only 1 degree is permitted. Figure 2.2 shows the different types of towers that can be used for wind turbines.

Figure 2.2 - Types of wind turbine tower [20][21][22]

- **Steel Towers**

They are made from the prefabricated steel sections and usually consists of two to four segments that are joined together on the site. Mostly large wind turbines are made with tubular steel towers, which are manufactured in the sections of 20 to 30 meters tall with flanges at either end and bolted together on the site. The towers are conical in shape to increase their strength and to save material. The advantage of steel towers against concrete towers is the reusability of steel after the lifespan service of wind turbine. Higher construction of a wind turbine is also possible in steel towers whereas, the tall concrete towers become uneconomical [23].

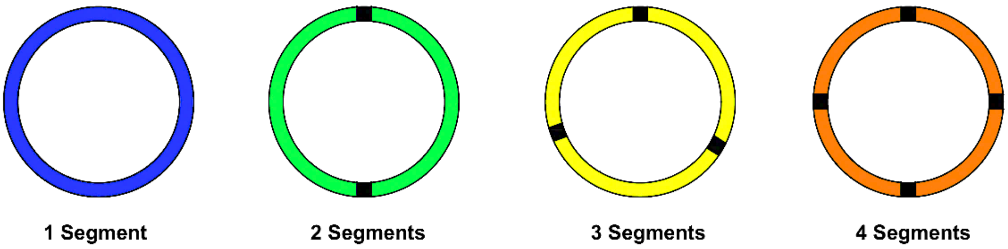

Figure 2.3 - Illustration of segments of steel tower

Figure 2.4 - Concrete foundation with anchoring bolts & flange [24]

Figure 2.5 - Joint between flange, foundation and a tower section of a wind turbine [25][26]

- **Concrete Towers**

Concrete towers are constructed with huge chunks of heavy concrete. They are unpopular and mostly used in the countries where steel prices are very high. Usually, they consist of 3 segments. The base zone is made of thick-walled concrete of 40 to 50 cm in thickness to provide sufficient strength and stiffness to the structure. Middle and upper zones are commonly designed for saving material rather than strength and stiffness. Concrete panels are constructed at loading yard and transported to the site [27].

Figure 2.6 - Typical concrete tower construction [28]

- **Steel Lattice Towers**

Lattice towers are manufactured using welded steel sections. The lattice towers are cheaper to construct, since a lattice tower requires only half as much material as a tubular tower with a similar stiffness. Lattice towers have almost disappeared from the industry due to the aesthetic reasons [23].

- **Hybrid Towers**

The hybrid tower is a combination of different tower materials. It can either be a combination of steel and concrete towers or steel lattice and concrete towers. Generally, it consists of two parts which are different from each other which are connected through an adaptor ring.

Figure 2.7 – Hybrid tower wind turbine [29]

- **Guyed Pole**

Guyed poles were very common in small wind generators. They are lightweight structure which are supported by guy wires. It is suitable especially for home use or small use. The access around guyed pole is difficult which has also further limited the usage.

Figure 2.8- Guyed pole wind turbine [30]

2.2 Foundation

The purpose of the foundation is to safely transfer the loads to the ground and ensure the stability of a wind turbine within permissible deviation and tilting. Foundation bears a lot of different loads including dead loads, wind loads, up thrust, overturning bending moments, vibrations and long-term cyclic wave loadings. Dead load acting on the wind turbine is mainly the self-weight of the structure including tower, rotors, nacelle and electrical components. The additional loadings altogether causes huge bending moments at the foundation [31]. Figure 2.9 shows some of the major and commonly adopted foundations in the wind industry.

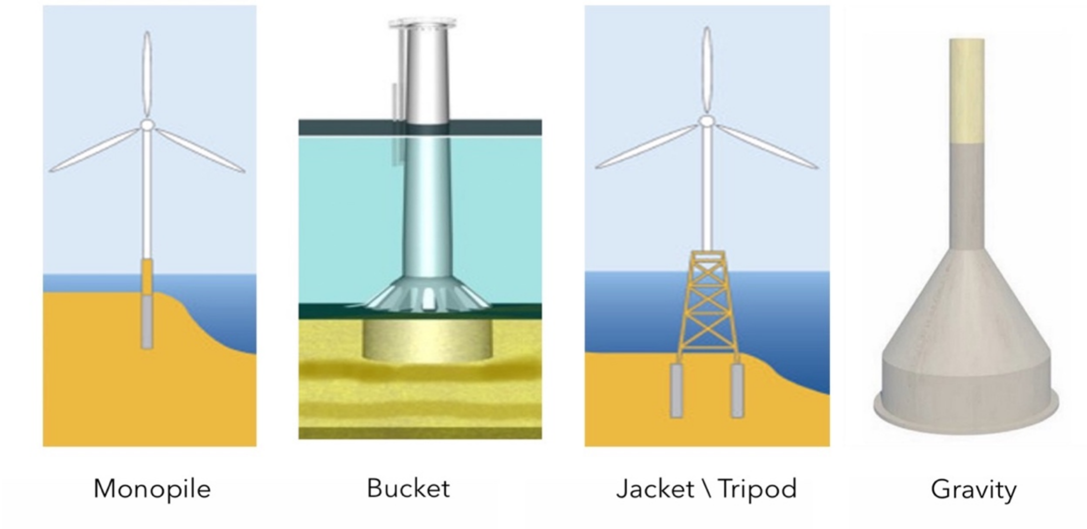

Figure 2.9 - Types of wind turbine foundation [32]

- **Gravity Foundation**

The gravity type support structure is normally a concrete based structure. For onshore wind turbines, gravity foundations are commonly used type of foundations however, they are also been used in offshore wind turbines. They are usually preferred where the ground is so hard for the piles to penetrate. For onshore wind turbines, gravity foundations are at a depth of 2 to 3 meters below the ground surface, and are usually rectangular, circular or octagonal in shape. In general, gravity foundations are designed to utilize the huge self-weight to prevent wind turbine from tipping over. No drilling or hammering in the case of pile foundation is required [33][34].

- **Jacket Foundation**

A jacket structure is a three or four-legged steel structure which are inter connected with welded steel sections. Bracings provide good stiffness to the structure. They are heavy structures and deployed where water depth is around 20 to 50 m. Generally, a hollow steel section is used. There are many variants of jacket foundation. They consist of corner piles interconnected with bracings with a diameter which can be up to 2 m. The piles are driven inside the pile sleeve to the required depth to gain stability for the structure [34].

Figure 2.10 - Jacket type foundation of an offshore wind turbine [35]

- **Suction Bucket Foundation**

Suction bucket foundations are a relatively new development in offshore wind industry. This type of foundation has a reverse bucket made up of steel usually with large diameters up to 10 m. The suction bucket is lowered into the sea and water is pumped out of the bucket to lower the pressure inside the bucket skirt. The resulting negative pressure and weight of foundation causes the foundation to sink in to the sea floor. Suction bucket foundation is suitable for deep waters and large turbines. It can be installed in a wide variety of site conditions including sand, silt, clay and layered strata.

Figure 2.11 - Suction bucket [36]

- **Tripile Foundation**

The tripile foundation is a three-legged jacket structure connected to a monopile in the upper structure. They consist of hollow steel sections and are suitable for depths of 25 to 40 m. The advantage of tripile foundation is the adjustments of the width and pile penetration depth as per site geological condition. First tripile foundation was manufactured by BARD in 2008, each tripile contained 1100 ton of steel [37].

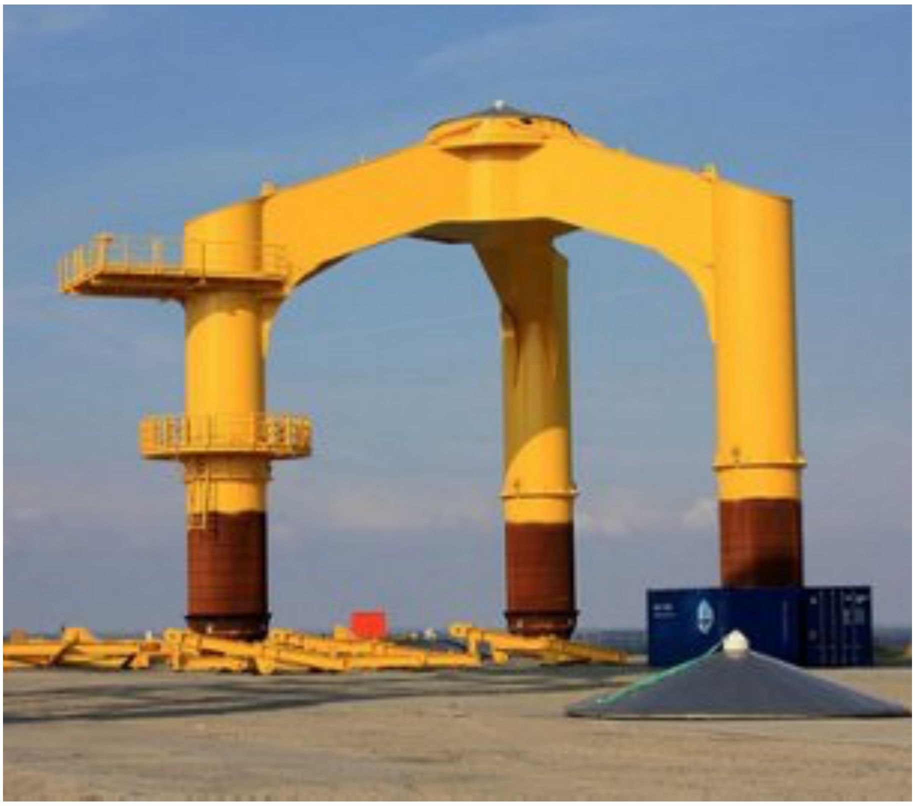

Figure 2.12 - BARD first tripile foundation [37]

- **Monopile Foundation**

The monopile support structure is a very simple design by which the tower is supported by the monopile. The monopile foundation is made of a hollow cylindrical steel tube with diameters up to 12 m and outer thickness of 150 mm. Monopiles are the most commonly used foundation structures in the offshore wind energy. They are suitable for shallow to medium water depths up to 30 m. "*The standard method of installation of piled structures is to lift or float the structure into position and then drive it into the seabed using either steam or hydraulic powered hammers"* [38].

- **Tripod Foundation**

The tripod foundations are one of the heaviest beside of the jacket foundation Three corner piles are installed at each leg position and anchored with the seabed. The anchoring provides a good stability and stiffness against lateral loads. They become uneconomical when used for shallow water depths. The tripod structure is pre-manufactured in a construction yard and transported to the location where it is lowered on to the seabed ensuring the alignment of the turbine [39].

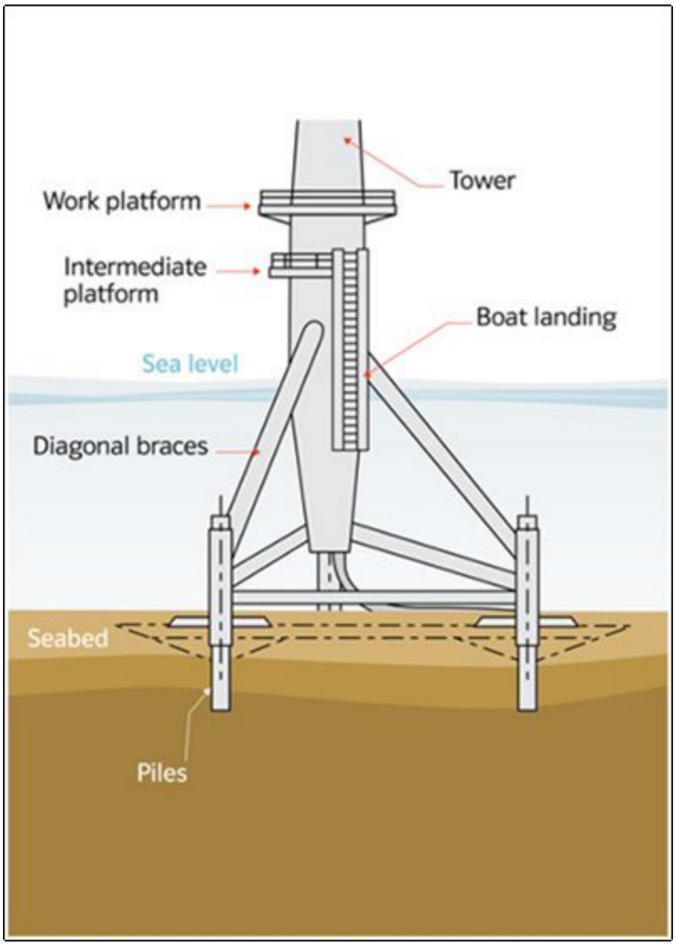

Figure 2.13 - Tripod structure [39]

2.3 Other Components of a Wind Turbine

1. The nacelle provides a housing that contains and protects all the other components of a wind turbines mainly mechanical and electrical components including generator, gearbox, speed shafts, yaw mechanism and the braking system. It sits on the top of a tower. Modern wind turbine nacelles are manufactured with a helicopter landing support for instantaneous maintenance and serviceability.
2. Almost all modern-day wind turbines are equipped with anemometer and wind wanes, which are used to measure the speed and direction of the wind. The wind turbine aligns automatically with the direction of wind using input from anemometer and wind wave.
3. When wind reaches cut-out speed, brakes are applied either mechanically, electrically, or hydraulically to stop the wind turbine. A sophisticated braking system is also incorporated in the wind turbines.

4. Gearbox is a hub that connects the low-speed shaft to the high-speed shaft. This increases the rotational speed to a certain level required by the generator to produce electric power. The gearbox is heavy and most expensive mechanical part of the wind turbine.
5. Generator uses rotational energy coming from the shafts to generate electric power.
6. High-speed shaft drives the generator.
7. Low-speed shaft connects directly the rotor to the gearbox. When rotor blades start to rotate, low-speed shaft rotates first which drives the high-speed shaft to generate electrical power.
8. Yaw mechanism is used to orientate the wind turbine rotors against the wind direction. The orientation of the turbine is controlled by applying the wind direction from the wind wane as directional set point. The yaw mechanism of an upwind turbine is activated by electrical motors.
9. Turns (or pitches) blades out of the wind to control the rotor speed, and to keep the rotor from turning in winds that are too high or too low to produce electricity [40].

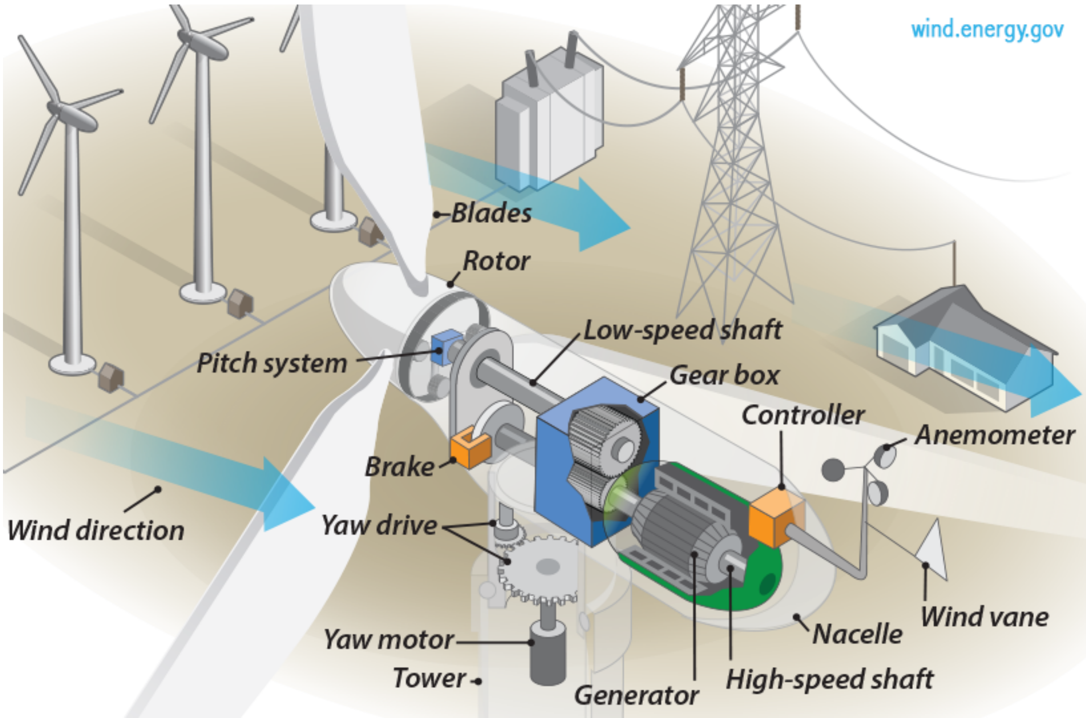

Figure 2.14 - Other components of a wind turbine [40]

SUMMARY

This project intended to insight the literature review of wind turbines. Important terminologies, facts, performance aspects, components and future prospects of wind turbines are also presented in this project. Wind is in long use by humans which continue to grow and flourish the wind industry. In earlier times, wind was used for domestic purposes only however, in modern day, it has become commercial and mainstream source of power production around many developed countries. Most of the wind industry is dominated in Europe. United Kingdom, Germany and USA are the top wind power producing countries in the world however, countries like Taiwan, China and India have shown tremendous interest in adopting to wind industry. The working mechanism of wind turbines is entirely dependent on the wind speed. Higher the wind speed would produce higher yield. Modern wind speeds are equipment with automatic sensor mechanisms which can detect the wind direction and wind speeds. Wind turbines can rotate to align with the wind direction so as to produce electricity throughout their lifespan. They also have the ability to standstill when the risk is involved due to high winds. In 1900's wind turbines were of very small scale with outputs in kW but now a days, even 10 MW and 120 m high wind turbines are in operation. The development, research and funding has successfully implemented several prototypes of turbines resulting in the emergence of onshore and offshore wind industries. Offshore wind turbines have more practical advantages than onshore wind turbines. Offshore wind farms can utilize vast basins of ocean without a visual impairment and can generate more electricity than onshore wind farms. The serviceability of a wind turbine depends on the safely transfer of all loads by the foundation. Monopile are the most common and widely used foundation structure for wind turbines. The reason can be accounted for simplistic structure and economic features. The other structures provide good strength against lateral loads and are usually constructed in the deep waters. With the future dependent source, wind community has developed standard codes and specifications to further enhance and advance the industry. DNV offshore standard, International Electrotechnical Commission (IEC), Germanischer Lloyd, National Renewable Energy Laboratory (NREL), American Petroleum Institute are among widely used codes. Not a doubt, wind industry has a potential of leading the power industry as a reliable source of power production in the future.

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