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Høgskulen
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MASTER'S THESIS

Analysis and assessment of damages to wind turbines, onshore and offshore with the objective to reduce the risk of wind turbine failures and collapse.

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03.06.2022

Abstract

Energy shapes our lives and the Earth. Energy, which was used by people in the beginning only for vital and basic needs, is the cornerstone of civilization, with an increasing need in today's modern world. The rapidly increasing energy demand and the inevitable negative effects on the environment caused by energy production, have made renewable energy technologies increasingly important and preferred among the widely used energy sources in the last decades. Wind energy is one of the leading renewable energy technologies. Wind energy comes to mind when it comes to renewable energy, as it is a carbon free, environmentally friendly, competitive technology. A step forward in production of wind energy is offshore and onshore wind turbines, with their numerous advantages.

Today, the increasing energy needs in the world and new searches related to this make onshore and offshore wind turbine applications an increasingly widespread renewable energy source. However, with this spread, challenges arise during the operation phases or being associated with the strength of the wind turbines. Potential failures must be known in advance so that they can be dealt with strongly and effectively. Damages and failures have a negative effect on the continuation of the operation and cause material and moral impacts. The aim of this study is to assess and analyze the damages to wind turbines onshore and offshore in order to reduce the risk of potential failures, damages and collapse of wind turbines. Thus, damages and failures that may occur in wind turbines will be determined, and the importance of strengthening wind turbines and certain maintenance requirements will be discussed. It will be attempted to be aware of the potential challenges that these systems may face and to contribute to their long-term viability.

While obtaining the data, many cases were evaluated, and the appropriate ones were included in this study. The study period is limited, every case does not overlap with the study, the background reasons for the failures are not specified, the transportation and construction phases (other than the operation) are not included because failures at these stages are not related to the operation of the wind turbines or the subject of this study. In addition, data processing is difficult and time consuming, and results such as downtime, cost, total operating hours or age of defective wind turbines were not evaluated while analyzing this data. There are such limitations when collecting data, but the database includes many failures, and all cases have been obtained as a result of serious investigation. According to the results of all these studies and analyzes, the database should represent the general failure rate in the industry. All data are presented in Appendix-A. Paper to be submitted to "Wind Energy", a journal issued by Wiley Publishing Company is in Appendix-B.

Preface

First of all, I would like to thank Professor Ove Tobias Gudmestad, who was my supervisor and from whom I learned a lot during my master education. Apart from his great interest and dedication to science, I am grateful for showing me how to great educator should be, and I will never forget him for the rest of my life.

I would like to thank my grandfather Ismail Yildiz, who contributed to helped me gain this wonderful experience, rest in peace.

I would like to express my gratitude to my family, Hakan, Canan and Deniz Gokce Kavakli, who have always supported me throughout my life. My academic career would not have been possible without your help.

And finally, I would like to express my gratitude to my ancestor Mustafa Kemal Ataturk, who instilled this vision to me and thanks to him I came here, in my opinion who will always hold this torch that belongs to science, civilization, and humanity. Thank you very much to you.

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Chapter 1

1 Introduction

This master thesis is the result of the Maritime Operations master program at the Western Norway University of Applied Sciences, Haugesund Campus.

The research question investigated in this report and thesis organization are mentioned in following sections.

1.1 Overview

Energy shapes our lives and the Earth. Energy, which was used by people in the beginning only for vital and basic needs, is the cornerstone of civilization, with an increasing need in today's modern world. The rapidly increasing energy demand and the inevitable negative effects on the environment caused by energy production, have made renewable energy technologies increasingly important and preferred among the widely used energy sources in the last decades. Wind energy is one of the leading renewable energy technologies. Wind energy comes to mind when it comes to renewable energy, as it is a carbon free, environmentally friendly, competitive technology. A step forward in production of wind energy is offshore and onshore wind turbines, with their numerous advantages.

Today, the increasing energy needs in the world and new searches related to this make onshore and offshore wind turbine applications an increasingly widespread renewable energy source. However, with this spread, challenges arise during the construction, maintenance and, operation phases, often being associated with the strength of the wind turbines. Potential failures must be known in advance so that they can be dealt with strongly and effectively. Damages and failures have a negative effect on the continuation of the operation and cause material and moral impacts.

1.2 Objective

The working title of this master thesis is analysis and assessment of damages to wind turbines, onshore and offshore with the objective to reduce the risk of wind turbine failures and collapse by learning from these failures.

The aim of this study is to assess and analyze the damages to wind turbines onshore and offshore in order to reduce the risk of potential failures, damages and collapse of wind turbines. Thus, damages and failures that may occur in wind turbines will be identified, and the importance of strengthening wind turbines and certain maintenance requirements will be discussed. It will be attempted to be aware of the potential challenges that these systems may face and to contribute to their long-term viability.

1.3 Research Approach

For this research, it is aimed to analyze specific faults by evaluating the data available from the internet, scientific literature, or various sources, and to reach as a result, a categorizing of the faults and damages of wind turbines in the light of the data obtained. It is desired to list, explain and assess the data identified. Thus, it is desired to achieve the best results within the available time.

In addition to the strict follow-up process related to the study, weekly meetings have been held by the supervisor Professor Ove Tobias Gudmestad where the studies on the research question were explained and discussed.

1.4 Structure of thesis

Chapter 1: The first chapter of this report presents an overview of the offshore and onshore wind energy topic and the research question to be answered in the thesis.

Chapter 2: It consists of a broad and comprehensive theoretical background on offshore and onshore wind turbines, and investigation of risk situations and damage failures.

Chapter 3: It consists of wind turbine design aspects and design standards.

Chapter 4: This is the data and method chapter where the failures, examples and experienced failure data are collected.

Chapter 5: In this chapter statistical information about risks and failures are included.

Chapter 6: In this chapter conclusions and recommendations related to damage investigations, and suggested measures to reduce the damages in the future, are presented.

Chapter 2

2 Background

2.1 Historical development of wind energy

The meaning of the wind in meteorology is simply moving air. Although the first people did not know where the source of the wind came from, they used it in their daily lives. The first applications in this field started with the grinding of grain and the flotation of sailing ships. Although the ancient Greeks and later the Romans used the power of the wind to float their sailing ships, they did not make use of this power in different areas. The use of circular motion windmills has been seen in Central and East Asian societies such as Iran, Pakistan, Afghanistan, East Asia, and China. [Durak and Ozer, 2007]

Even in the years before Christ, people used wind energy to raise low levels of water and to grind wheat. Although the use of wind energy by the society is thought to have started in western civilizations, it is known that it was first used in eastern civilizations such as China, Tibet, India and Iran. For example, windmills in Iran moved to the West after the Crusades. Written information has been found about the use of horizontal axis windmills in the 200s BC. In addition, it is known with concrete evidence that the Iranians used vertical axis windmills in 700 BC. Historians also state that in the 1700s BC, Babylonians used windmills for irrigation around Mesopotamia. The use of wind power passed from Asia to Europe around the 10th century, and windmills in England can be shown as the first signs of this transition. In the 1190s, the German Crusaders took the windmills from Syria to their country. [Durak and Ozer, 2007]

After the industrial revolution, with the emergence of steam engines in the 18th century, energy has been started to be supplied worldwide by making use of machines with thermodynamic characteristics. Especially the use of fossil fuels such as oil, gas, coal, these machines have become very advantageous as they can be used as an energy source whenever desired. [Durak and Ozer, 2007]

Today, the use of wind energy is increasing day by day. The main reasons for this are that it does not require raw materials and its operating costs are at very low levels. Electricity generation from wind energy first started in Denmark. In 1897, Danish meteorologist Paul La Cour built the 89-Watt wind power plant for electricity generation for the first time. During the 1940s-1950s in Denmark, the engineering firm F. L. Smidth built 2 and 3 bladed wind power plants. However, these power plants are wind power plants working with direct current (DC). The first alternating current (AC) wind power plant was developed by Johannes Juul who is a student of Paul La Cour. Gedser wind power plant, which is the pioneer of modern wind power plants with an installed power of 200 kW, started to operate in the south of Denmark in 1956 and has been operating for 11 years without any maintenance. Until the 1970s, there was no significant development in wind energy technology. The oil crisis in the 1970s and the increasing environmental awareness since the 1980s led to the search for new energy sources.

Since these years, importance has been given to the development of wind power plant installed power and propeller diameter. Especially the development after 1995 draws great attention. In these years, the wind power plant, which was at the KW level, transferred its place to the wind power plants at the MW level. Today, there are wind power plants with a power of 6 MW. Along with the installed power, the propeller diameters of wind power plants also increase remarkably. As seen in Figure 2-1., while the diameter of the propellers was around 20 m in the 1980s, it reached 100 m in the 2000s. Today, there are wind power plants with a propeller of 150 m in diameter. [Durak and Ozer, 2007]. At the same time, it is possible that we will see much larger structures in the coming years.

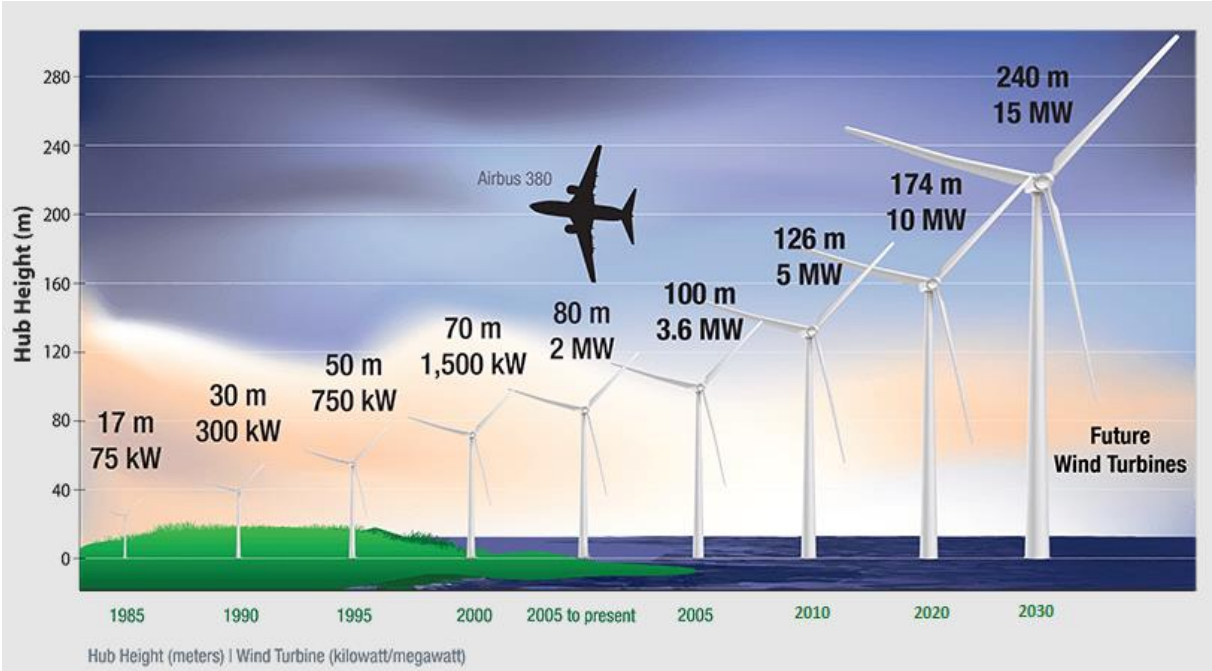


Figure 2-1. Rotor diameters of wind turbines and distribution of power by years, source [Josh Bauer, NREL, 2020]

In the 1990s, studies and investments began on offshore wind turbines. It was established in Negersund, Norway for testing purposes for the first time in 1990, as it is known that higher rates of wind are utilized on the sea. Then in 1991 the first commercial offshore wind farms were established. 11 units have been installed in the Vindeby region of Denmark, each generating 450 kW of power. In the 2000s, with the increase in wind energy orientation, the decrease in productive places for wind energy production on land, and the increase in maintenance and repair costs due to transportation difficulties in places with high wind speed, accelerated the orientation to those offshore wind turbines in these years. The installation of offshore wind turbines has begun in Norway, Denmark, Germany, the Netherlands and England, especially in the countries around the North Sea. [Durak and Ozer, 2007]

In 2009, the first prototype known as 'floating wind turbines' was installed in Hywind, Norway. This floating wind turbine, located 10 km from land and 200 meters deep, produces 2.3 MW of power. This development also allows the establishment of wind farms in deeper waters. [AWS Truewind, September 17, 2009, Offshore Wind Technology Overview]

Interest in offshore wind farms, which started to be installed in Europe, is increasing day by day and it is possible to come across these projects in many different regions of the world. In recent years, even the world's leading wind power plant manufacturers have aimed to create more farms in their new designs. [AWS Truewind, September 17, 2009, Offshore Wind Technology Overview]

2.2 Wind energy in the world

As a result of the gradual depletion of fossil and nuclear resources, the increase in oil prices, global warming and climate change, the need for alternative and clean energy sources has increased rapidly, especially in the last 40 years. The fact that wind energy is an economically, socially and ecologically sustainable energy source proves that it is the ideal solution for this need, with its rapidly increasing installed capacity for the last 20 years.

Year of 2020 for the global wind industry was the best year in history with 53% annual growth. More than 93 GW of wind installations have proven the wind industry's incredible resilience in a challenging year that disrupted both the global supply chain and project processes. The 93 GW new installation increased the global cumulative wind power capacity to 743 GW. This means 1.1 billion tons of CO₂ reduction per year. New capacity installed in onshore wind increased by 59% (86.9 GW) compared to 2019. China and the United States remained the world's largest markets for new onshore wind farm capacity expansion, with the world's two largest economies together increasing their market share by 15% to 76%. Global wind power has roughly quadrupled over the past 10 years, making it one of the most cost competitive and durable energy sources worldwide. [Global Wind Report, 2021]

Thanks to technology innovations and economies of scale, wind power continued to establish its competitive advantage across the globe in the 2020 year. Investment in offshore wind exceeded 2019 levels, reaching US \$330 billion in 2020, partly due to the industry's longer project development timelines that are more resilient to pandemic impacts. [Global Wind Report, 2021]

As can be seen in Figure 2-2 and Table 2-1 below, the distribution of the total energy obtained from wind turbines in the world by years, the distribution of land and offshore and country rankings are given.

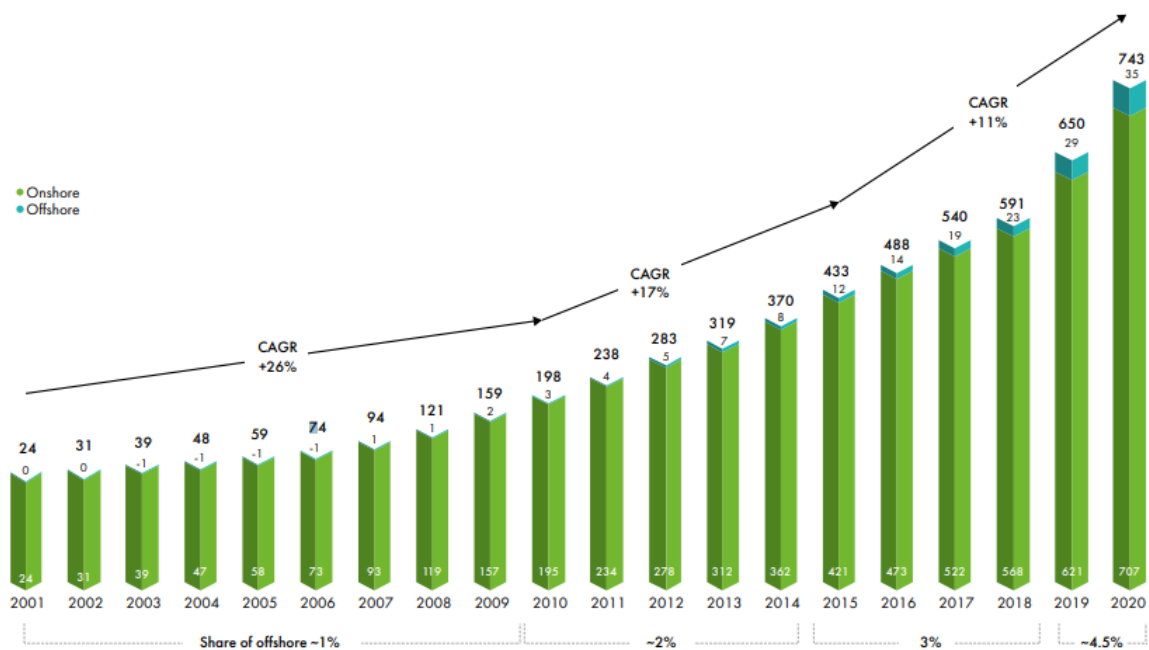


Figure 2-2. Historic development of total installations, source [GW, 2021]

Country/Region	2020	New Capacity 2020	2019	2018
China*	290'000	52'000	237'029	209'529
United States	122'328	16'895	105'433	96'363
Germany	62'784	1'427	61'357	59'313
India	38'625	1'096	37'529	35'129
Spain	27'446	1'638	25'808	23'494
United Kingdom	24'167	652	23'515	20'743
France*	17'949	1303	16'646	15'313
Brazil	18'010	2'558	15'452	14'707
Canada	13'588	175	13'413	12'816
Italy*	10'850	280	10'512	9'958
Turkey	9'305	1'249	8'056	7'369
Rest of the World*	110'000	14'000	96'035	84'814
Total*	744'000	93'000	650'785	589'547

Table 2-1. Leading countries and new capacity changes for 2020, source [WWEA, 2021]

2.3 Wind turbine and components

2.3.1 Overview of wind turbines

A wind turbine is a machine that converts the power in the wind into electricity. It can also be called a modified version of windmills that transform the power of the wind into mechanical power. As electricity generators, wind turbines are connected to the electricity grid. These networks can be a battery-charging circuit, a residential scale power system, an isolated grid, or a public utility grid. Energy conversion in wind turbines takes place in the form of converting the basic aerodynamic force to mechanical energy, and then to electricity by means of a generator, by applying torque to a rotating shaft through the blades.

It has become possible to generate electricity from wind turbines from kW to MW. Generally, wind turbines capture between 20% and 40% of the energy in the wind. The better the blade efficiency, the higher the power to be obtained. Wind turbines have developed very rapidly in terms of size and power generation, and these developments continue. [Union of Concerned Scientists (UCSUSA), October 21, 2013, How wind energy works]. Wind turbines: The amount of energy produced varies depending on the rotor radius.

2.3.2 Classification of wind turbines

The most common wind turbine design today is the horizontal axis wind turbine; This means that the axis of rotation is parallel to the ground. Horizontal axis turbines are classified according to rotor direction (downwind and upwind), rotor control (pitch and stall control), number of blades (usually three or two), and how they change direction with the wind (free yaw or active yaw). [Bianchi, 2007; Hau, 2006]

Wind turbines are classified according to their axes of rotation, revolutions, power, number of blades, wind effect, gear characteristics and installation locations. [Elibuyuk and Ucgul, 2014]

A detailed diagram of wind turbine classification is shown in Figure 2-3. In general, wind turbines are classified according to their axes of rotation, but also in terms of revolution, power, number of blades, etc. classifications are available.

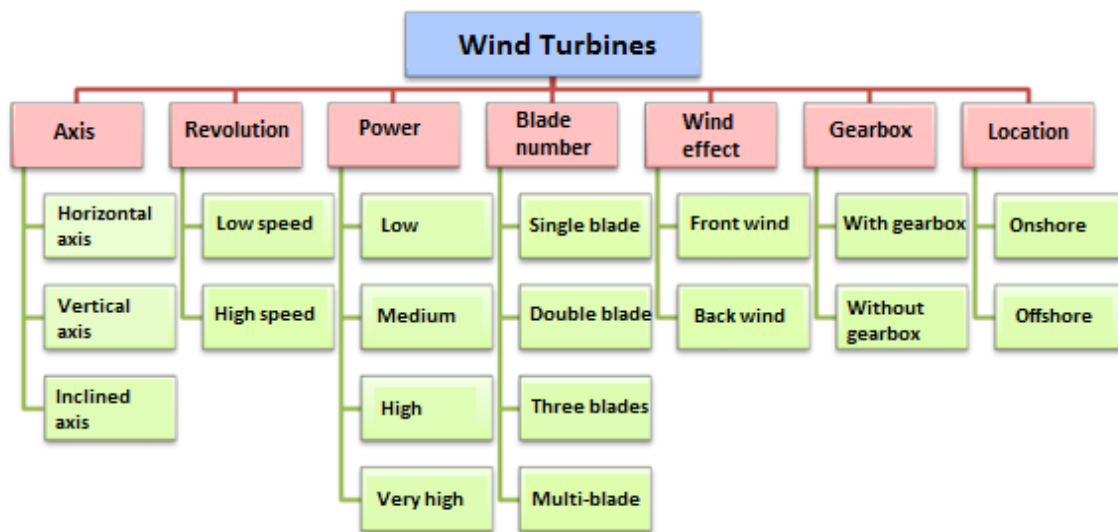


Figure 2-3. Wind turbine classification, source [Elibuyuk and Ucgul, 2014]

2.3.3 Components of wind turbine

Large wind turbines, most often used by utilities to provide power to a grid, range from 250 kilowatts up to the enormous 3.5 to 5 MW machines that are being used offshore. Utility-scale turbines are usually placed in groups or rows to take advantage of prime windy spots. Wind "farms" like these can consist of a few or hundreds of turbines, providing enough power for tens of thousands of homes.

From the outside, horizontal axis wind turbines consist of three big parts: the tower, the blades, and a box behind the blades, called the nacelle. Inside the nacelle is where most of the action takes place, where motion is turned into electricity. Large turbines don't have tail fans; instead, they have hydraulic controls that orient the blades into the wind.

In the most typical design, the blades are attached to an axle that runs into a gearbox. The gearbox, or transmission, steps up the speed of the rotation, from about 50 rpm up to 1,800 rpm. The faster spinning shaft spins inside the generator, producing AC electricity. Electricity must be produced at just the right frequency and voltage to be compatible with a utility grid. Since the wind speed varies, the speed of the generator could vary, producing fluctuations in the electricity. One solution to this problem is to have constant speed turbines, where the blades adjust, by turning slightly to the side, to slow down when wind speeds gust. Another solution is to use variable-speed turbines, where the blades and generator change speeds with the wind, and sophisticated power controls fix the fluctuations of the electrical output. A third approach is to use low-speed generators. [Union of Concerned Scientists (UCSUSA), October 21, 2013, How wind energy works]

A wind turbine consists of five major and many auxiliary parts. The major parts are the tower, rotor, nacelle, generator, and foundation or base. Without all of these, a wind turbine cannot function.

2.3.3.1 Foundation

The foundation is under the ground for the onshore turbines; it cannot be seen because it is covered by soil. It is a large and heavy structured block of concrete that must hold the whole turbine and the forces that affect it. For offshore turbines, the base is under the water and cannot be seen. In offshore turbines that are well into the sea the base is floating, but it is of sufficient mass to support the turbine weight and all the forces exerted on it and to hold it upright.

2.3.3.2 Tower

The tower in most modern turbines is round tubular steel of a diameter of 3–4 m (10–13 ft), with a height of 75–110 m (250–370 ft), depending on the size of the turbine and its location. The rule of thumb for a turbine tower is that it has the same height as the diameter of the circle its blades make when rotating. Normally, the taller a turbine is, it is subject to more of the wind with higher speed. This is because the farther we are from the ground, the faster the wind (wind does not have the same speed at various distances from the ground).

2.3.3.3 Rotor

The rotor is the rotating part of a turbine; it consists of (mostly) three blades and the central part that the blades are attached to, the hub. A turbine does not necessarily have to have three blades; it can have two, four, or another number of blades. But the three-blade rotor has the best efficiency and other advantages. Blades are not solid; they are hollow and are made of composite material to be light and strong. The trend is to make them larger (for more power), lighter, and stronger. The blades have the form of an airfoil (same as the wings of an airplane) to be aerodynamic. As well, they are not flat and have a twist between their root and their tip. The blades can rotate up to 90° about their axes. This motion is called blade pitch.

2.3.3.4 Hub

The function of the hub is to hold the blades and make it possible for them to rotate with respect to the rest of the turbine body.

2.3.3.5 Nacelle

The nacelle is housing on top of the tower that accommodates all the components that need to be on a turbine top. There are quite a number of components for the proper and healthy operation of a complicated electromechanical system that a turbine is. A major turbine part among these components is the generator and the turbine shaft that transfers the harvested power from wind to the generator through a gearbox. The gearbox is a vital component of wind turbines; it resides in the nacelle. A gearbox increases the main shaft speed from around 12–25 rpm (for most of today's turbines) to a speed suitable for its generator. For this reason, the shaft on the generator side is called "high-speed shaft." Because a turbine must follow the wind and adjust its orientation to the wind direction, its rotor needs to rotate with respect to the tower. This rotation is called yaw motion in which the nacelle and the rotor revolve about the tower axis.

2.3.3.6 Generator

The generator is the component that converts the mechanical energy of the rotor, harnessed from wind to electrical energy. A generator has the same structure as an electric motor. At the commercial production level, all electricity generation is in the three-phase alternative current. In general, the choice of generator, therefore, is synchronous or asynchronous (induction) generator. Nevertheless, the generator associated with wind turbines, thus far, is the induction generator because a synchronous generator must turn at a tightly controlled constant speed (to maintain a constant frequency). Some of a wind turbine's principal components are depicted in Figure 2-4. Because a generator must be rotated at a speed corresponding to the frequency of the electric network (50 or 60 Hz in most countries), it must be rotated faster than the turbine rotor. Most generators need to be turned at 1500 rpm (for 50 Hz) and 1800 rpm (for 60 Hz). In no way, it is feasible for a turbine rotor to move that fast. A gearbox, therefore, must increase the turbine rotor (main shaft) rotational speed to a speed that can be used by the generator. Experience has shown that the gearbox in a turbine is a problematic component. This is due to the fact that the energy in the wind does not remain constant for a relatively acceptable length of time. It continuously fluctuates, because of the nature of wind. This causes the gear teeth to undergo overload and hammering stress that leads to fatigue and failure. In addition, the gearbox is a heavy item in the nacelle on the top of a turbine.

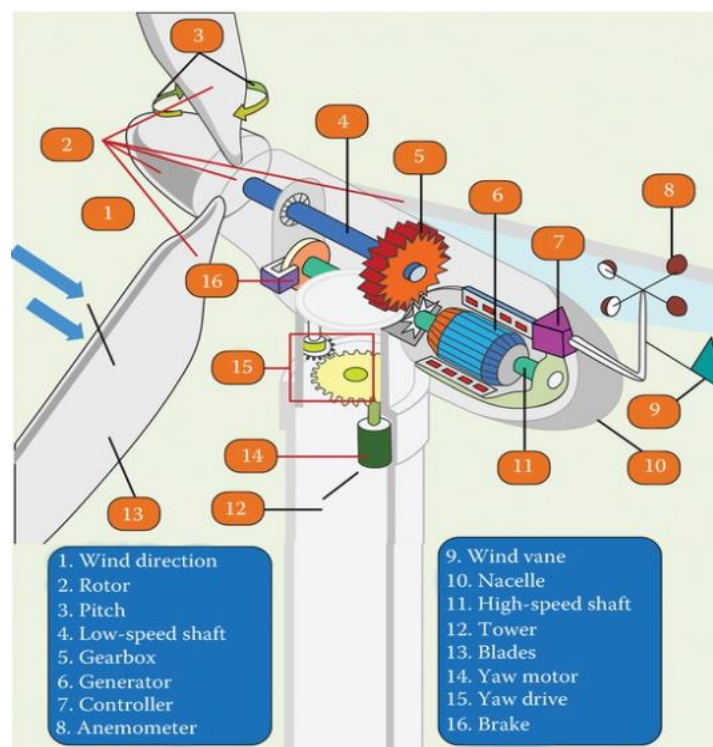


Figure 2-4. Wind turbine components, source [Electrical Academia, Wind Turbine Parts and Functions, 2015]

2.3.4 Offshore and onshore wind turbines

Both onshore and offshore wind farms provide two options for bulk wind electricity generation, and there exist different trade-offs for both types of installations. Onshore wind

farms are the most popular type of wind farm in the world today, but there is growing interest in the developed countries to construct offshore wind farms. [Zheng et al., 2016]

Offshore wind power, also referred to as offshore wind energy, is when wind over open water, usually in the ocean, is used to generate power. Wind farms are constructed in bodies of water where higher wind speeds are available. The advantages of offshore wind farms can be listed as follows:

- Windmills can be built that are larger and taller than their onshore counterparts, allowing for more energy collection.
- They tend to be far out at sea, meaning they are much less intrusive to neighboring countries, allowing for larger farms to be created per square mile.
- Typically, out at sea, there is a much higher wind speed/force allowing for more energy to be generated at a time.
- Wind farms seem to have a relatively neutral impact on their surrounding environment. They are not built-in shipping lanes, fishing areas or in delicate environments.
- There are no physical restrictions such as hills or buildings that could block the wind flow.

The general disadvantages of offshore wind farms are:

- The biggest disadvantage of an offshore wind farm is the cost. Offshore wind farms can be expensive to build and maintain and because of their hard-to-reach locations, they are susceptible to damage from very high-speed winds during storms or hurricanes which is expensive to repair.
- The effect of offshore wind farms on marine life and birds are not yet fully understood.
- Offshore wind farms that are built closer to coastlines (generally within 26 miles) can be unpopular with residents as it can affect property values and tourism.



Figure 2-5. Example of offshore wind farm, source [DNV, 2018]

Onshore wind power refers to turbines that are located on land and use wind to generate electricity. They are generally located in areas where there is low conservation or habitat value. The advantages of onshore wind turbines can be listed as follows:

- The cost of onshore wind farms is relatively cheap, allowing for mass wind turbine farms.
- The shorter distance between the windmill and the consumer allows for less voltage drop off on the cabling.
- Wind turbines are very quick to install. Unlike a nuclear power station, which can take over twenty years, a wind turbine can be built in a matter of months.

The disadvantages of onshore wind turbines are:

- One of the biggest issues of onshore wind farms is that many deem them to be an eyesore on the landscape.
- They don't produce energy all year round due to often poor wind speed or physical blockages such as buildings or hills.
- The noise that wind turbines create can be compared to that of a lawnmower, often causing noise pollution for nearby communities.



Figure 2-6. Onshore wind farm example, source [Roxtec Global, 2013]

2.3.4.1 Comparison of offshore and onshore wind turbines

Offshore wind turbines have many advantages over onshore wind turbines. In addition, there are some difficulties in the application of offshore wind turbines. The strong wind potential in the offshore is at a level that can offset the high installation and operating costs. The noise of wind turbines becomes inaudible after 1.5 km. Establishing it away from the coast prevents negative effects such as visual impact and noise. On land, obstacles create turbulence in front of the turbine and cause energy losses. Since the offshores are wide and unobstructed areas, turbulences are at minimum level. On land, transporting turbine parts with large rotor diameters to the installation site poses a problem. Wind turbines with much larger rotor diameters can be transported on offshore by ships. [Van Bussel, G.J.W., Zaaier, M.B., 2001]

In addition to the advantages of offshore wind turbines, there are also some disadvantages. The pre-installation planning phase takes longer than those on land. Seabed and depth surveys are laborious and costly operations. Another disadvantage is the maintenance and repair work

of turbines. Repair times for malfunctions that may occur as a result of unusual weather conditions that may occur on the offshore are longer and more costly than those on land. Stopping turbines during this repair maintenance process means a waste of money. [Van Bussel, G.J.W., Zaaijer, M.B., 2001]. The disadvantages of offshore wind turbines are generally their cost. The difficulties encountered in the design phase can be overcome with engineering solutions; but they also increase the cost. Generally, they must be economically viable as they are made for commercial purposes.

2.4 Wind turbine mechanical design matters

A wind turbine cannot function in the first place if it cannot stand straight in the wind. At the same time as the energy from wind is harnessed, the wind exerts forces on the body of a turbine that push the tower and can topple the turbine.

The power capacity of a turbine has a direct relationship with its size. Nevertheless, as the size grows, so does the magnitude of the force from wind. A wind turbine, thus, must be capable of withstanding the forces it is subjected to. In the same way, all the mechanical parts in a turbine must stand the forces and loads that can break those parts if they are not sufficiently strong to handle the forces and loads to which they are subjected.

The forces exerted by wind on a turbine and its components can be different in magnitude and nature when a turbine is running and when it is stopped. These forces can also induce vibrations in the blades and in the turbine tower. Vibrations are not desirable in any machine and can damage or break a vibrating component much earlier than expected.

The loads on the major components of a turbine, other mechanical concerns such as vibration and fatigue can affect the components. The discussion here is only intended to bring to the reader's attention the reasons why a turbine can mechanically fail and how important are mechanical issues such as vibration and fatigue. [A. Hemami, 2011, Wind Turbine Technology]

2.4.1 Loads on the rotor

The rotor consists of the blades and the hub. The blades are subject to a number of loads. The hub transfers all of the loads from the blades to the nacelle. Thus, the variation of the loads on the hub is directly dependent on the loads from the blades. The hub has a shell-like structure (is not solid) and accommodates the mechanisms for blade pitch control. From a mechanical point of view, all the rotor forces must ultimately be transferred to the ground through the nacelle and the tower. The body of the hub, therefore, must be capable of handling the forces coming from the blades and transferred to the nacelle. Blade loads are transferred to the hub through a number of bolts holding the blade bearing in variable pitch machines (in fixed blades there is no bearing, and the blades are bolted directly to the hub). The bolts and the bearing between each blade and the hub, therefore, must take the loads. At the rear end of the hub there is another bearing between the rotor and the nacelle. Since the rotor (the assembly of hub and blades) rotates with respect to the nacelle, this bearing must take all the loads from the rotor.

In order to study the loads from the rotor to the rest of the turbine we examine the various loads on a blade. These are mainly the aerodynamic force, the weight, and the centrifugal forces when a turbine is running at a constant speed. During start-up and shutdown, inertial force comes into the picture as well. Some other forces may also come to existence, but their effects can be small or only for a short period of time. Aerodynamic force is the force from wind on the turbine blades. Centrifugal force is what any rotating object experiences: it is a force pushing out an object that rotates about an axis or moves on a curved path. You can feel it in a vehicle when it turns. Inertial force is the force required to accelerate an object. To change your car's speed from stop to any speed or from 40 to 50 m/h, for example, it is necessary to overcome the inertial force. Also, to do the reverse action of slowing down a moving object, the inertial force opposes the deceleration. In the example of your car, the brakes effort is used to cancel the inertial force.

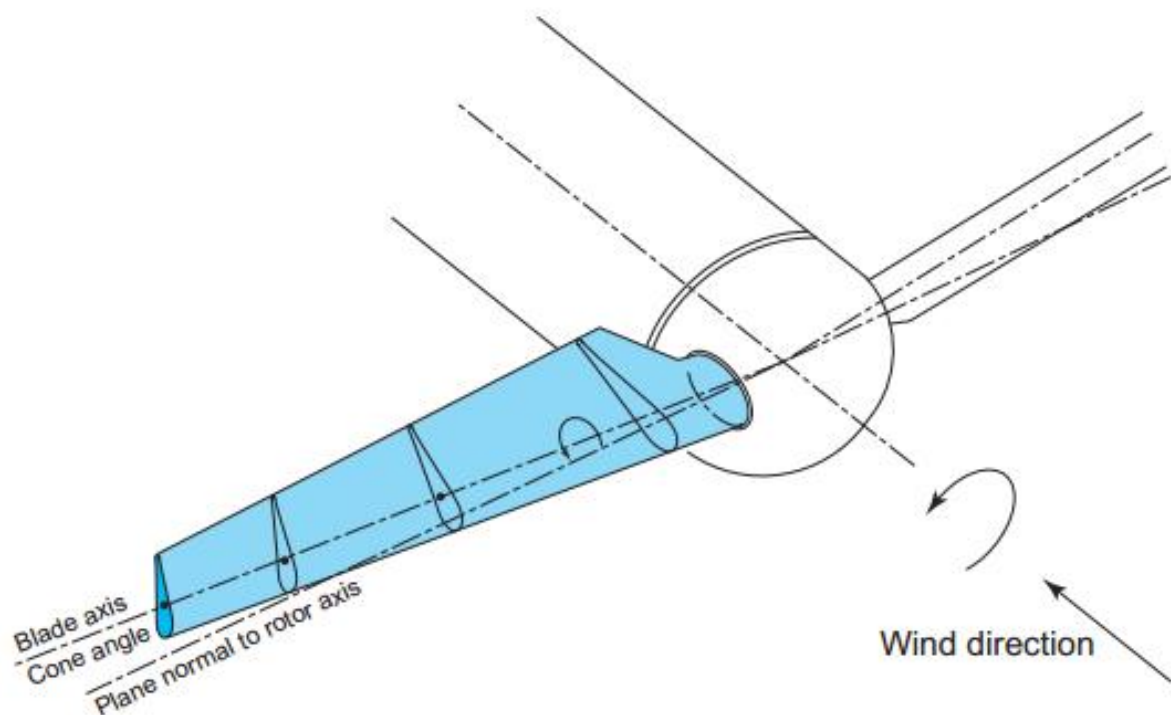


Figure 2-7. Blade configuration with respect to rotor hub, source [Cengage Learning, 2012]

Figure 2-7 depicts a blade and a hub. Note that the blade axis, about which the blade pivots, is normally not perpendicular to the rotor axis; there is a small angle between the blade axis and the perpendicular direction. This angle is called the cone angle. This angle changes when a blade bends due to aerodynamic forces. Some rotors are designed such that the cone angle is not initially zero and leans toward the front of the turbine; thus, when aerodynamic forces bend the blade back, this angle becomes smaller. [A. Hemami, 2011, Wind Turbine Technology]

2.4.1.1 Aerodynamic loads on the blade

Each blade of a turbine is subject to aerodynamic forces from the wind. The airstream has a relatively fixed direction for the area swept by the blades, at an instant, but since blades are

twisted the relative direction of wind with respect to a blade is not the same for various segments of the blade. Moreover, whereas the windstream has a constant speed (for a short period under consideration), the speed of air as a result of the blade rotation is smaller for the segments of the blade closer to the hub than the segments closer to the tip of the blade. Consequently, the relative motion of air with respect to the blade as a result of wind and blade motion varies along the length of a blade. The resulting aerodynamic force, thus, varies in both magnitude and direction along the blade span. The typical force for a segment is shown in Figure 2-8.

The force on each blade segment consists of two components: one component along the direction of wind (the drag force, almost in the horizontal direction) and one perpendicular to wind (the lift component, in a near vertical plane). These forces are depicted for a two-blade turbine in Figure 2-9.

A two blade-turbine is more appropriate to demonstrate the fact that all the components along the wind direction have the same force direction in the two blades, whereas the forces normal to the wind have opposite directions in the two blades, since the blades are symmetric to each other. The forces shown correspond to when the blade is feathered and does not catch much energy (the lift components are smaller than the drag components). This is just for the sake of clarity of the figure. This implies, also, the fact that the horizontal force on the blades is greater when a turbine is parked than when it is working.

It is easy to verify that the resultant of the two sets of forces is a push on both blades in the wind direction and a torque about the turbine shaft axis. In other words, all those force components along the wind direction contribute to a backward push on the blades, and do not generate any rotational motion. However, those force components that are in the opposite direction in a (near) vertical plane are the only ones that generate a torque that makes the turbine rotate.

Note that the just mentioned aerodynamic forces are functions of wind speed, rotational speed, and pitch angle. Therefore, they are not the same for different operating conditions and for when the turbine is parked. A blade must be able to withstand these forces in the harshest condition; that is, when these forces are at their highest. All the forces on a turbine must ultimately be transferred to the ground through the tower. [A. Hemami, 2011, Wind Turbine Technology]

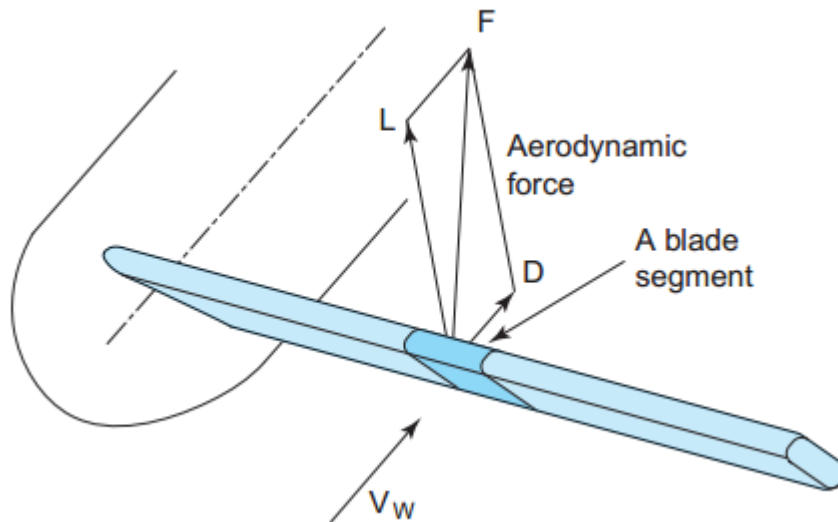


Figure 2-8. Aerodynamic force on a blade segment, source [Cengage Learning, 2012]

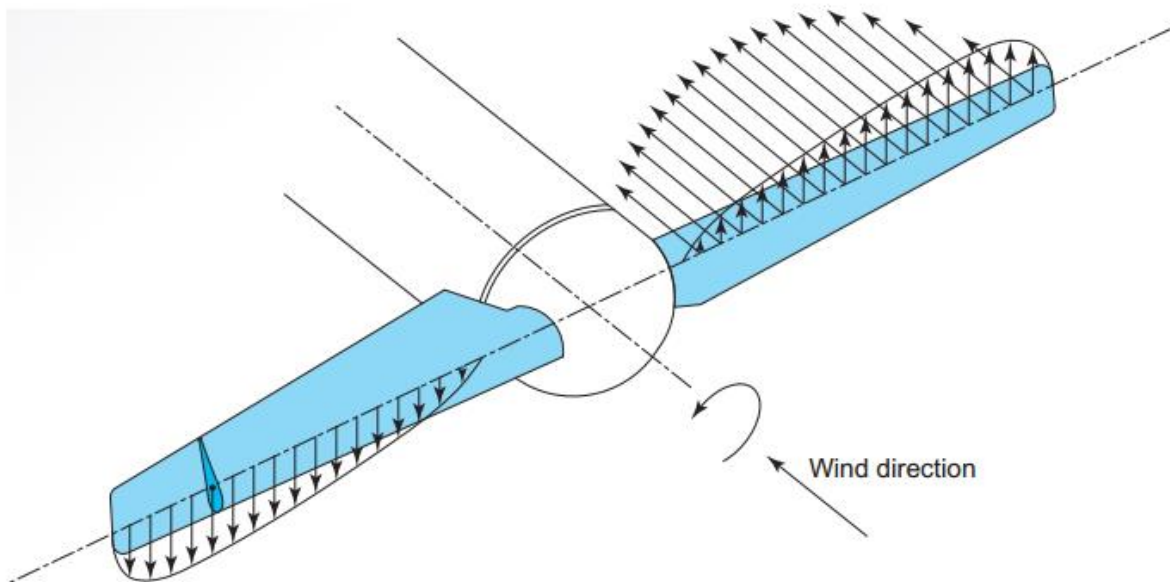


Figure 2-9. All the aerodynamic force on two symmetric blades, source [Cengage Learning, 2012]

2.4.1.2 Other blade loads

In addition to the preceding forces, a blade is subject to its own weight and when rotating at a constant speed a longitudinal force; that is, a force along the length of the blade. The latter is the centrifugal force. The magnitude of the blade weight force is always constant; its direction is also always the same, in the vertical direction and downward. Thus, during rotation this force changes with respect to the blade. The centrifugal force is, on the other hand, always along the blade. Its magnitude, however, is a function of the blade rpm. The faster the blade rotates the larger is this force. Its magnitude is normally more than the force of the weight, even for turbines with a low rotational speed of 12–14 rpm. For example, for a 6150 kg (13,576 lb) turbine blade, 44 m (144 ft) long, running at 12 rpm, the centrifugal force can be 145,000 N (32,955 lb).

During start-up and shutdown there is a speed change, and an additional force comes into effect: the inertial force. The inertial force is lateral to the blade direction. Its magnitude depends on how fast the turbine resumes its normal speed of rotation from start-up, or how fast it stops during a shutdown. The direction of the inertia force is in the opposite direction to the rotation during start-up, and in the same direction as rotation during shutdown. The inertial force has the effect of bending the blades in the plane of rotation, and it directly affects the bolts and the bearing at the root of the blades. Like other forces on the blade, this force is transferred to the hub. This force can be very high, especially during an emergency shutdown that the speed is abruptly dropped from operating speed to zero.

The centrifugal force is always in the radial direction and outward from the center of rotation. In this sense, when a blade is hanging downward the centrifugal force and the force of weight add together, and when the blade is in the upright position (tip up), the centrifugal force and the weight are in different directions and subtract from each other. The inertia force, when it exists (that is, during speeding up and slowing down motion of rotor), is always lateral to the blade. The direction of the force of weight varies with respect to the blade direction, since it is always vertical. These forces are shown in Figure 2-10.

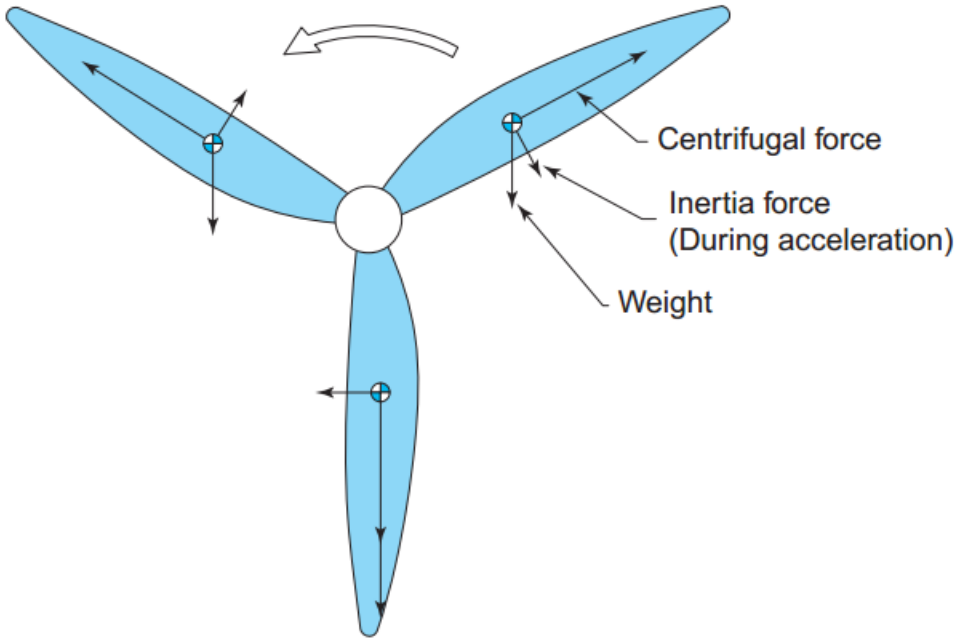


Figure 2-10. Centrifugal, inertial and weight force at three positions of a blade, source [Cengage Learning, 2012]

In those positions of the blade between horizontal and vertical, the weight force can be decomposed into two parts, one along the blade and one perpendicular to the blade, as shown in Figure 2-11.

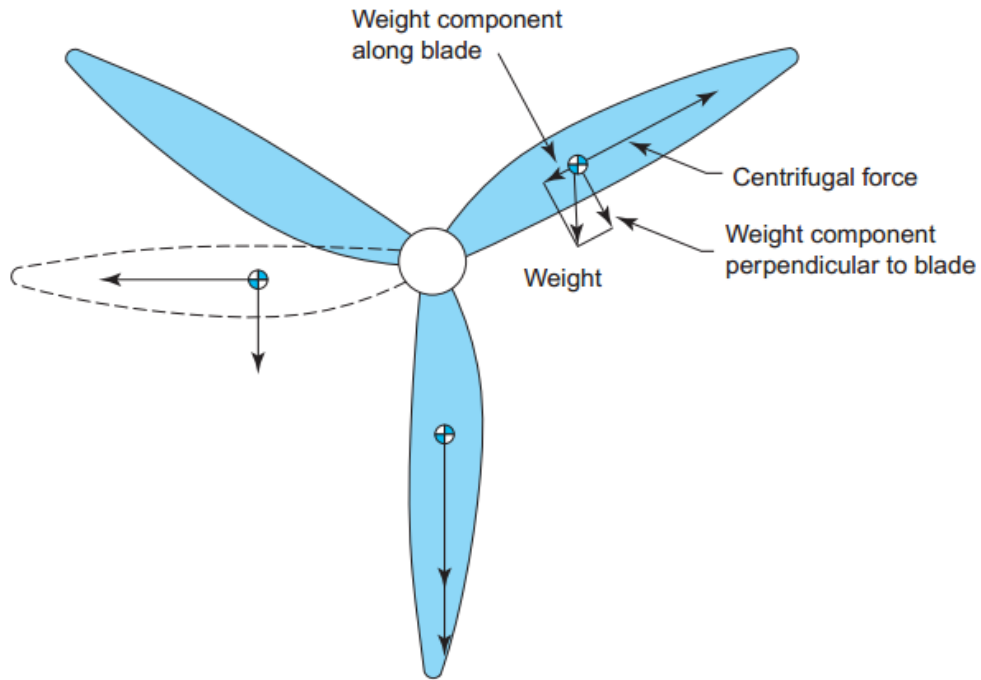


Figure 2-11. Decomposition of force of blade weight when at an angle, source [Cengage Learning, 2012]

As can be realized, the effects of the forces thus far studied are a lateral load (a component of weight force, and inertial force when present) and a longitudinal load (the other component of the weight and the centrifugal force). The blade is, therefore, subject to a combined stress: tensile stress as a result of longitudinal forces as well as tensile and compression stress due to lateral forces that tend to bend the blade. Note that the drag component of aerodynamic forces acts at a 90° angle from the lateral and centrifugal forces. The blade is, therefore, bending in two directions. This is illustrated in Figure 2-12. Note also that the lateral forces just described do not cause the blade to always bend to the same side, as their direction can switch; for instance, the weight force effect switches direction by crossing a vertical position.

The loads on a turbine blade have a periodic nature. As the blade turns one revolution, the aerodynamic forces change from a maximum value to a minimum value.

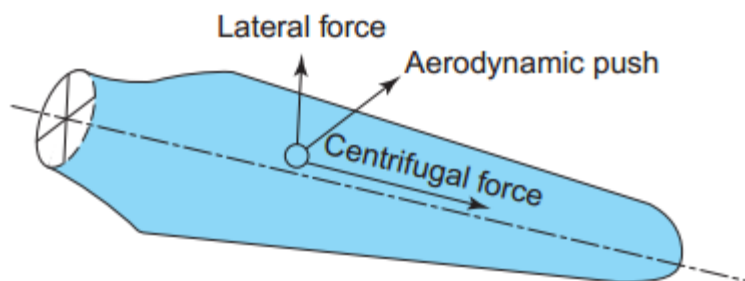


Figure 2-12. A blade can bend in two directions 90° from each other, source [Cengage Learning, 2012]

Another load on the blade is due to the fact that the mass center of the blade is not necessarily on the blade axis. This causes additional load, such as moments. Mass center is a point that all the mass can be assumed to be accumulated there. Consider when a blade is bent due to aerodynamic forces. Then the mass center, even if initially on the blade axis, displaces from its original position. The centrifugal force consists of many smaller forces all over the blade, but the resultant of all these forces can be shown as a sole force at the mass center of the blade. The direction of the centrifugal force is perpendicular to the rotor shaft axis. As a result of displacement of the mass center, the centrifugal force that must be along the blade axis is now at a distance from it. It is also at an angle to the blade axis.

Figure 2-13 shows a possible position of the centrifugal force with respect to the blade axis. As shown, the centrifugal force can be decomposed into three components, one parallel to the blade axis, one intersecting the axis, and the third one perpendicular to and at a distance from the axis. The only component that generates a moment is this third one. Whereas it would not create a moment if the mass center was exactly on the blade axis, now the centrifugal force generates a moment that tends to twist the blade about its axis. As a result, the blade is subject to torsion. Torsion introduces another stress, shear stress, which tends to tear an object.

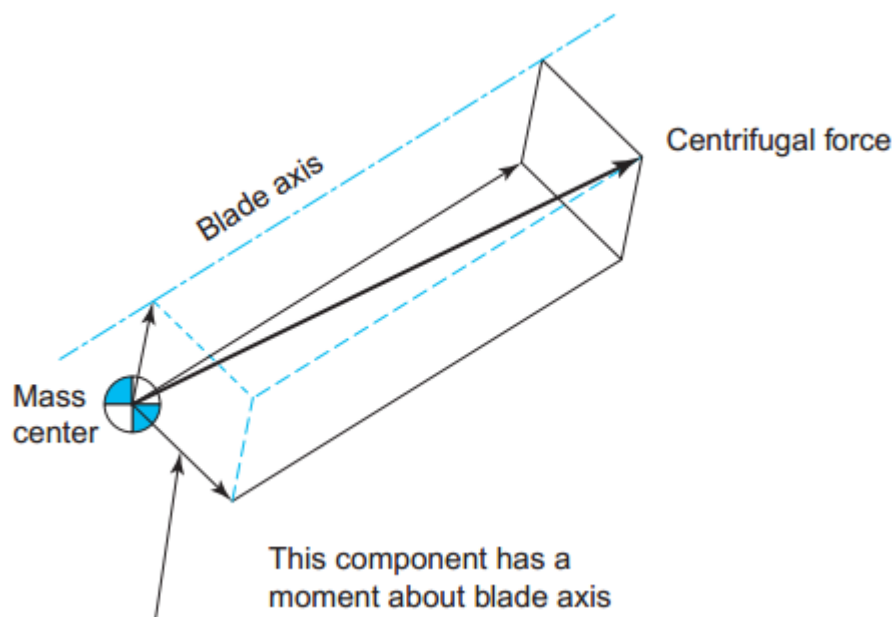


Figure 2-13. Position of the centrifugal force with respect to blade axis, source [Cengage Learning, 2012]

As we can see, any blade, no matter whether or not the turbine is working, is subject to various loads. The magnitude of these loads varies based on:

- The aerodynamic forces (which depend on wind speed, blade surface area, blade length, and the angle of attack which corresponds to the pitch angle—and the rotational speed)
- The position of the blade in its 360° course of rotation

- The rotational speed of the turbine
- The weight of the blade (which depends on its size and design and the material used)
- The inertial force during speed change, which can be significant in many cases. These loads are not constant, and each one can continuously fluctuate between a maximum and minimum range of values. [A. Hemami, 2011, Wind Turbine Technology]

2.4.1.3 Vibrations

For any mechanical component, a constant (or nearly constant) force is better than a force whose magnitude, direction, or both vary. A component subject to variable force must be designed to be stronger than if it was subject to a constant force. In addition, vibration may be induced in mechanical systems and parts, which is a basis for rapid destruction and failure. A cyclic force that is, a force whose magnitude changes, but repeats the same values with time can lead to vibration.

Consider the rotor of a wind turbine. When a blade is at its top position it is subject to stronger aerodynamic forces than it experiences at a lower position, because the wind speed is higher at a higher altitude. For instance, in a turbine with 50 m (165-ft) blades, the difference between the highest and the lowest points through which a blades passes are 100 m. The speed of wind is not the same between these two points, and therefore, there are more aerodynamic forces on each blade when it sweeps the top part of its course during rotation. In addition, in the lower course of rotation, a blade crosses the shadow of the tower. A 3 m(10-ft) diameter tower has sufficient effect on the wind flow that it can significantly reduce the wind speed in front of it all along its length. A mechanical component subject to variable force must be designed to be stronger than if it was subject to a constant force.

With a constant speed of rotation, the preceding phenomena lead to a cyclic variation of the forces to the blades and the rotor. Th is cyclic alteration of the force magnitudes leads to vibration of the blades as well as vibration of the rotor. When these vibrations have a small amplitude, no harm is done, but if the vibrations have a frequency the same as or near the natural frequency of the blade, then undesirable results can follow.

Vibration in machine parts is a “killer,” since the vibrating element undergoes a repeated alteration of stress, say from tensile stress to compression stress. A mechanical component that normally can handle a fixed load for a long time fails in much less time (hundreds or even thousands of times smaller) if the load is switching direction in a repeated manner. Vibration is not desirable in any machine part.

In order to prevent vibration buildup in the rotor, the blades must be designed such that their natural frequency is sufficiently away (usually higher than) from the rotor rpm. Also, they must not be an integral multiplier (that is, 2 times, 3 times, etc.) of the rotor rpm. For example, if a rotor rotates at 14 rpm, the natural frequency of the blades must not be equal to 14, 28, 42, or any other multipliers of 14. This is for possible vibration of the blades about their point of connection to the hub. The rotor bearing is subject to another vibration of the rotor assembly. If the operating speed is 14 rpm, since there are three blades and each blade passes the same course 14 times per minute, the rotor is subject to a varying force with a frequency of $14 \times 3 = 42$ cycles per minute (which is 0.7 Hz).

The variation of aerodynamic and other forces in the blades, thus, can induce severe vibrations both in each blade and in the rotor. Note that, in general, the vibration of a long piece like a blade can occur about three axes, as shown in Figure 2-14. Those about x- and y-axes are in conjunction with the bending of a blade; they affect the body of the blade and the bolts attaching it to the hub, as well as its bearing in a pitch-controlled turbine. Another possible vibration in blades is about the blade axis (the z-axis in figure 2-14); it is in conjunction with blade torsion due to the moments of this axis (see figure 2-13). This type of vibration is called flutter.

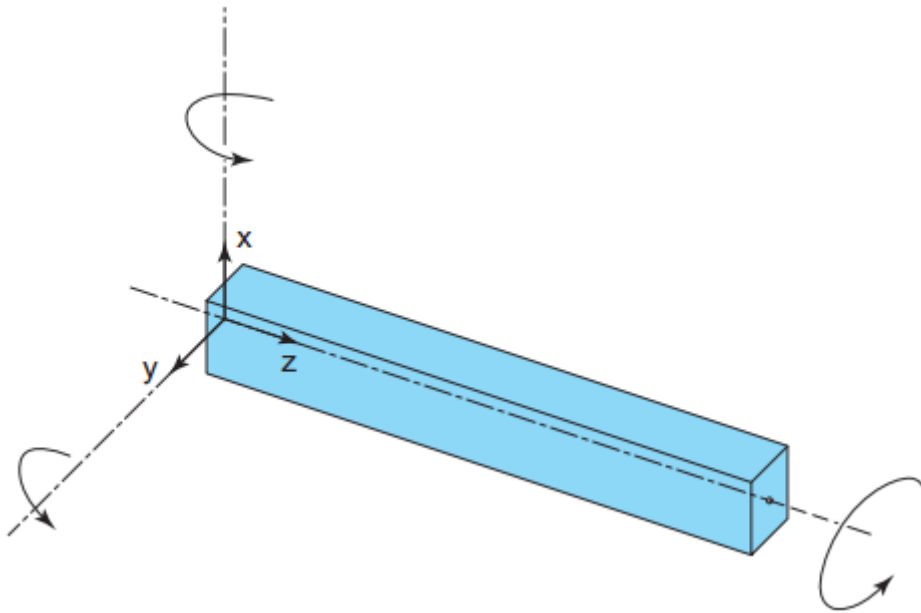


Figure 2-14. Possible vibrations in a turbine blade, source [Cengage Learning, 2012]

Vibrations in the entire rotor affect the bearings on the main shaft and are transferred to the gearbox. The effect of vibrations is never desirable, and if vibration is detected, its source must be found and corrected as soon as possible.

Another source of vibration of a rotor is an imbalance in the blades. The three blades must be completely uniform, similar in design, and have the same weight and their mass centers be the same distance from the rotor axis. Any deviation from these requirements causes an imbalance in the rotor and leads to vibration. [A. Hemami, 2011, Wind Turbine Technology]

2.4.1.4 Blade fatigue

Fatigue is a term used for the stress effect of cyclic loads on a mechanical component. A part of a machine that is under a continuously varying load, either due to vibration or the nature of load, can fail much faster than expected. This failure is called fatigue failure. In fact, this is a way that we use to break a piece of metallic bar by hand, repeated bending in opposite directions.

All the rotating components in machinery, including wind turbine blades, are subject to fatigue even if there is no vibration. In the presence of vibration, a machine part may fail after a week. But even if there is no vibration, a blade of a turbine running at 14 rpm undergoes alternating stresses approximately 7 million times per year.

A machine part subject to fatigue must be designed based on fatigue test data. These data usually show the expected life for a material (more for metals) under various stress values. A typical curve can look like that in Figure 2-15, where the horizontal axis shows the number of cycles, and the vertical axis shows the stress. These data are used extensively for the design of airplane propellers and blades in blowers, compressors, and so on. For wind turbines, because it is a relatively young and limited industry, such data do not exist. Compared to blades in other machines, the rotational speed of a rotor in a wind turbine is much lower and the loads are much smaller. Under fatigue stress a mechanical component in a machine can break much faster than it should.

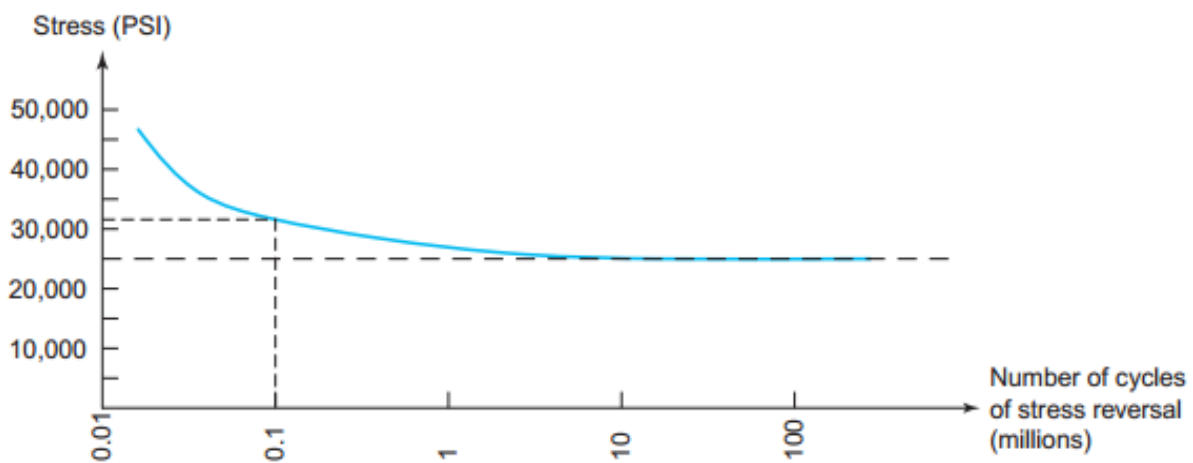


Figure 2-15. A typical fatigue curve, source [Cengage Learning, 2012]

The curve in figure 2-15 shows that if the stress is, say, 32,000 psi, the specimen tested failed after 100,000 cycles, but for a stress of 25,000 psi the specimen did not fail through 100 million cycles. Thus, based on these test results, the stress for the part must not exceed 25,000 psi (25 kips) if subject to stress reversals. [A. Hemami, 2011, Wind Turbine Technology]

2.5 Blade construction

Wind turbine blades are hollow; otherwise, their weight would be tremendous, even with a lightweight material, and their use would be impossible. They might not even start to move the rotor. It is, however, necessary that they have a sturdy structure to withstand all the stress from various loads, and work for the useful life of a turbine. The blades of a turbine spinning at 14 rpm must go through 175 million cycles in 25 years.

Blade shells are made from composite material that is light and strong. Inside, they must have structural support for the shell. The internal structure can be made from wood or a similar lightweight material.

One of the important issues in new blades is the integration of a lightning rod in the blade structure. The lightning rod is a strip of copper along the blade. At some point at the tip of a blade it is exposed to the outside by a small disk. At the other end, it is connected to a metallic counterpart in the hub. Through a number of metal connectors, the strip in the blade ultimately makes a connection to the ground through the tower.

If a blade becomes damaged in operation, it must be repaired. Normally the broken parts must be cut, replaced by pieces of the same size, and glued together by the proper material. Depending on the severity of damage, this can be done while the blade is in the air, or it may have to be brought down to the ground. Any repair work on the blades is a costly job and involves loss of production. [A. Hemami, 2011, Wind Turbine Technology]

2.6 Gearbox

All the power collected from wind by the rotor goes to the generator through the gearbox. And all the power transferred by a gear is concentrated on each tooth of that gear. This explains how much load is on the teeth of the gears.

We also learned that during rotation the rotor is subject to a periodic force due to the nonuniformity of the aerodynamic forces at the top position of a blade and when it passes across the tower shadow at the bottom position. All this variation leads to a pulsating torque on the rotor shaft that is transferred to the gearbox. This pulsating vibration causes fatigue in the teeth of a gear.

In addition to the preceding, another phenomenon has an undesirable effect on a turbine gearbox. This is due to the nature of wind, which does not blow uniformly. Gusts of wind can generate sudden power fluctuation on the rotor, which ends up as shocks on the gearbox. In industrial machinery, a flywheel usually smooths out the load variation and reduces the effect of uneven loads. In a wind turbine, the rotor itself plays the role of a flywheel. At the same time, however, it is the source of the uneven load. In other words, the smoothing effect of the rotor on the shaft is smaller than the disturbance that it injects to the shaft. With all these fluctuations carried to the gearbox, we can see that the gearbox in a wind turbine is subject to very hostile loading conditions.

Presently one of the major shortcomings of wind turbines is the uncertainty about the gearbox and its behavior. Some wind turbine gearboxes have given up and failed after 6–7 years of service. Changing or repairing a wind turbine gearbox is a major cost and it changes the whole scenario of the economics of a wind turbine. Six or seven years are much less than an expected life of 20-plus years. Proper gearbox maintenance is one of the key issues in prolonging its service life.

One of the major shortcomings of present wind turbines is the uncertainty about the gearbox and its behavior during its life expectancy. [A. Hemami, 2011, Wind Turbine Technology]

2.7 Nacelle

Nacelle is the room-size box on the top of the tower. Its main role is to house all the components that are to be on the top of the tower, such as the gearbox and the generator. In most wind turbines, the nacelle consists of a floor, called the bed plate, on which the equipment is installed, and the roof, which is a shell-type cover to enclose the equipment. In another type of nacelle, the floor is a part of the structure of the gearbox body.

The force of the weight of all the components, including the rotor, and the aerodynamic forces are transferred through the body of the nacelle to the tower. In addition to the force of weights of the rotor and the components inside the nacelle, the nacelle must transfer the

torque received from the rotor to the tower. In this sense, the nacelle must be sufficiently strong for all of these loads.

It is the bedplate (or its equivalent) that takes the loads, and the roof must support only its own weight plus any other item that goes on the top of the nacelle, such as anemometers, oil coolers, and so on (Each wind turbine has a flashing beacon that is normally installed on top of the nacelle.) [A. Hemami, 2011, Wind Turbine Technology]

The magnitudes of the weights and rotor shaft torque depend on the size of a turbine. They are also dependent on the design and the material used. Just to have an idea about typical values, the following data are for Gamesa G87, a 2-MW turbine with 87-m (290-ft) blade diameter turbine:

Weight of blade: 6150 kg (13,576 lbs.)

Rotor weight: 37 ton (metric) (81,000 lbs.)

Total tower top mass: 107 ton (235,000 lbs.)

Four-section tower: 203 ton (446,000 lbs.)

2.8 Tower

The tower is like a vertical slender bar fixed at one end (cantilever beam) subject to:

- A compression load due to the weight of the rotor and nacelle, at its free end.
- A lateral force due to the aerodynamic forces from wind on the rotor, at the free end.
- A moment at its free end, as shown in Figure 2-16.
- Aerodynamic forces on the nacelle.
- Aerodynamic forces on the tower.
- Weight of any other item attached to the tower.
- Its own weight.

The forces from wind and the torque have variable values and have a periodic nature as well as being impulsive when gusts of wind hit a turbine. Depending on a turbine's geographic location, and its design, a tower consists of three to four segments. A rule of thumb is that the height of the tower is the same as the diameter of the blades. But this is not always the case.

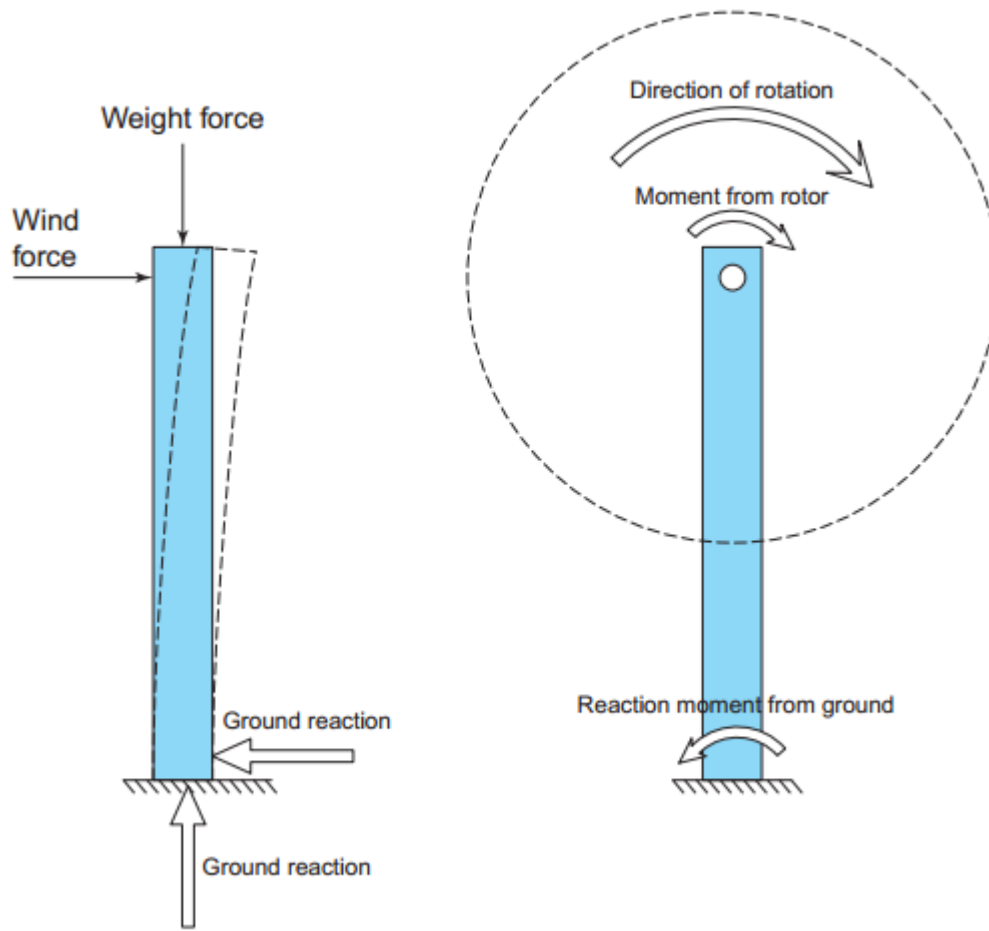


Figure 2-16. Force and moment on the top of the tower, source [Cengage Learning, 2012]

The aerodynamic force on the tower is only a drag force, pushing the tower in the direction of wind. Assuming a linear graduation from zero (at the ground level) to a maximum on the top of the tower, it can be substituted by a horizontal force at the 2/3 height of the tower from ground. The magnitude of the force of wind on the tower is given by:

$$F = \frac{1}{2} c \rho v^2 A$$

where ρ is the air density, v is the wind velocity, and A is the surface area blocking the wind flow. Thus, A is the projection of the shape of the object in the direction perpendicular to the wind flow. Also, c is the drag coefficient, a factor that depends on the shape of the object. For instance, for a rectangular prism c is larger than for a circular pipe. [A. Hemami, 2011, Wind Turbine Technology]

2.9 Safety issues

A wind turbine must operate safely for operators working for maintenance, for people around, and for itself. All risks and hazards must be minimized in order for it to work in an orderly and efficient manner. It is possible to obtain a long-lasting and sustainable wind turbine life by minimizing these risks.

In the previous titles, the loads and dangers that wind turbines are exposed to were mentioned. Under this title, the effects of environmental conditions on wind turbines and

typical faults are mentioned. Blades, generator, yaw system, and gearbox come to the fore as the most common failure components of wind turbines. These failures cause extra maintenance costs and preventive approaches in physical designs. These faults occur as a result of the mentioned loads.

2.9.1 Blade failures

Reliability is extremely important in wind turbine blades. The blades are responsible for using the mechanical energy of the wind and are exposed to the mentioned loads during operation. In addition, they may be exposed to abrasion or higher loads, due to environmental conditions such as wind, rain, snow, and storm etc. These problems are the ones that need to be solved at the design stage of the blades, and a delicate balance must be found between durability, aerodynamic properties and noise.

It can be said that the starting point of the failure in the blades is the transport stage. While the wind turbine blade, which is out of production, is transported to the operation area, minor or major damage may occur in certain parts of the blade. These damages may increase with the assembly and may fail quickly with the loads it is exposed to during use. Another reason is the blade size. Making the blade larger to use more of the mechanical energy in the wind also causes rotor imbalances, corrosion and greater loads on the blade.

2.9.2 Generator failures

Generators are the parts used to convert the energy obtained into electrical energy. There are many types of generators used. The most commonly used generator type is the double-fed asynchronous generator. There are wind turbines that have become unusable due to generator failures.

Failures in generators can be divided into mechanical and electrical failures. Mechanical failures are mostly caused by misalignment or bearing failures. Electrical faults are caused by stator and rotor winding faults and slip ring faults.

2.9.3 Yaw system failures

Yaw system is the system used to position the blades according to the desired angle. In Yaw systems, shaft cracks, gear failures, bearing failures and damage to these parts are encountered. These damages occur in case of bad weather conditions and exposure to heavy loads. Failure in the yaw system can lead to larger failures, for example, damage to incorrectly positioned blades or excessive load on the blades.

2.9.4 Gearbox failures

The gearbox is a system consisting of gear wheels that bring the rotational speed of the low-speed shaft to a suitable level for electricity generation. In wind turbines, fixed and variable gear ratios can be used between the turbine rotor and the electric generator. The use of variable gear ratios can result in more stable and stagnant electricity and provide higher aerodynamic efficiency. In gearboxes that are under heavy operating conditions for a long time, shaft misalignment, bearing damage, gear damage, shaft damage, etc. failures occur.

2.9.5 Effect of temperature and environmental changes

Wind turbines are installed in a variety of different geographical areas, from a hot and dry climate to a humid and cold climate. In addition, the installed wind turbine is exposed to different climatic conditions and seasonal changes throughout the year. These seasonal and climatic changes have an impact on wind turbines. For example, in the selection of the lubrication and grease used in the gearbox, it is important to choose it according to the region where the wind turbine will be installed. With the change of seasons, the wind turbine is subject to different conditions. The manufacturer must take into account the climatic conditions of the region where the wind turbine will be installed.

Different components are used to cool the engine section of a wind turbine in summer and to heat it in winter. These parts can be fans, blowers and heaters. In summer, blowers that circulate the outside air inside are used to cool the gearbox and generator located in the nacelle part. In winter, if the temperature inside the nacelle is not sufficient, the heaters give warm air in order to keep the interior at the desired temperature. Nonetheless, if the wind turbine is shut down for a long time, the gearbox lubricate may decrease to ambient temperature and cause damage.

In some regions, the temperature difference between summer and winter may not be much. In these regions, the gearbox lubricates selected for the wind turbine can be used in both seasons, but it is important that the manufacturer chooses considering these temperatures throughout the year.

Temperature change is not only important for lubrication. At the same time, bad weather conditions can affect the maintenance work, resulting in longer maintenance time and downtime. Another effect is on anemometers. The anemometer measures the wind speed and maintains turbine control. Extremely cold weather, freezing rain may stop the anemometer from working and the wind speed may be zero, in which case the control orders given will be wrong, resulting in time, cash and damage.

For offshore and coastal installations, the effect of sea salt on various components must be taken into consideration, whereas the onshore wind farms are immune from these effects. On the other hand, in dusty regions a turbine eventually gets dirty. A cleaning of the blades and tower, although relatively expensive, may prolong the useful life as well as the efficiency of operation of a turbine. As a matter of fact, the inside of a turbine nacelle, hub, and tower must always be kept clean from oil spills, grease, and other materials used by a turbine or for maintenance works. It is the responsibility of an operator to make sure that after maintenance work, everything is back to normal, and no pieces of tools or extra stuff are left behind.

2.9.6 Lightning

Lightning is the discharge of millions of volts of static electricity between the clouds and the ground in a very short time with intense light, thunder and a great destructive power. As the size of the wind turbines increases and the blade length increases, the blades become much more open to lightning and attract lightning just like a lightning rod. The impact of this destructive power on any metal or non-metal part on the wind turbine can cause irreversible

damage to the wind turbine. Especially the damage it causes on the blades can prevent the wind turbine from working. Figure 2-17 shows how lightning damages a wind turbine blade.

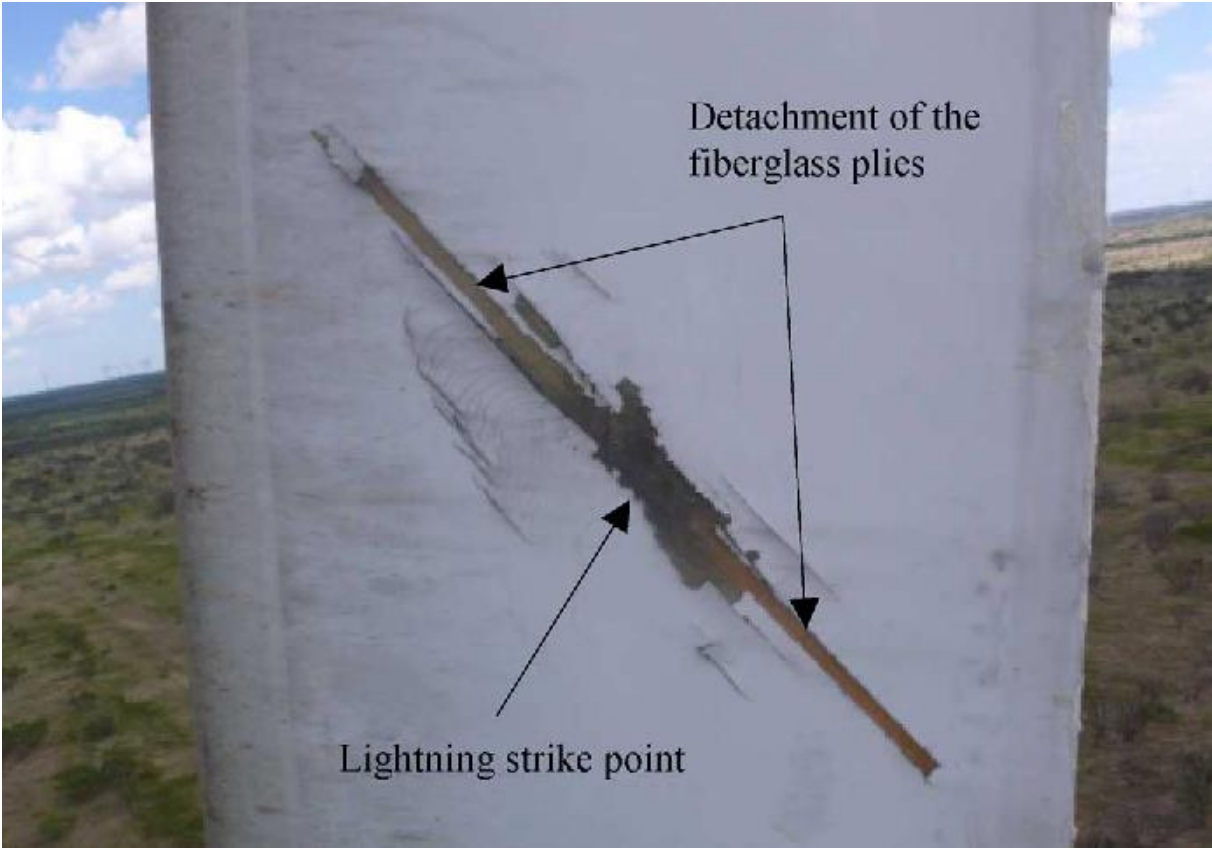


Figure 2-17. Damage from lightning to a turbine blade, source [A. Garolera et al., 2016]

“Today, all wind turbine blades have a lightning rod embedded inside them along the blade. It is a copper wire or strip that through connections in the hub and nacelle it finally makes a connection to the body of the tower. The rod is exposed to the outside somewhere near the blade tip so that if lightning hits, the rod catches the discharge. The tower is metallic and transfers any electrical charge to the ground. A lightning rod inside a blade is a preventive device. In case of lightning, a blade without a rod is more likely to be damaged. On the contrary, if lightning strikes a blade with a lightning rod, it is not 100% sure that it gets to the metallic rod at the point of exposure to outside; thus, although the chances are smaller, the lightning may still damage the blade, but to a much less extent.” [A. Hemami, 2011, Wind Turbine Technology]

2.9.7 Ice forming on the blades

Ice formation can be observed on the blades of wind turbines that are freezing cold and operating at temperatures close to the freezing point. The temperature of the air, which is not at the freezing point, but passing through the blade edge at a temperature close to it, may reach the freezing point. Different amounts of ice may be formed due to rain or humidity in the air. The ice layer formed on the blade edges changes the blade profile and causes the drag and lift coefficients to change. The power capture capacity of the blade decreases, causing less energy to be obtained. Depending on the weight of the ice in the area, it may even disrupt the balance of the blades.

At the same time, in much freezing rain and cold, the entire airfoil can freeze, resulting in high losses. Another issue is the falling of ice pieces from a height. It can damage the surrounding structures, living things or settlements. In such cases, extra attention should be paid when performing maintenance work.

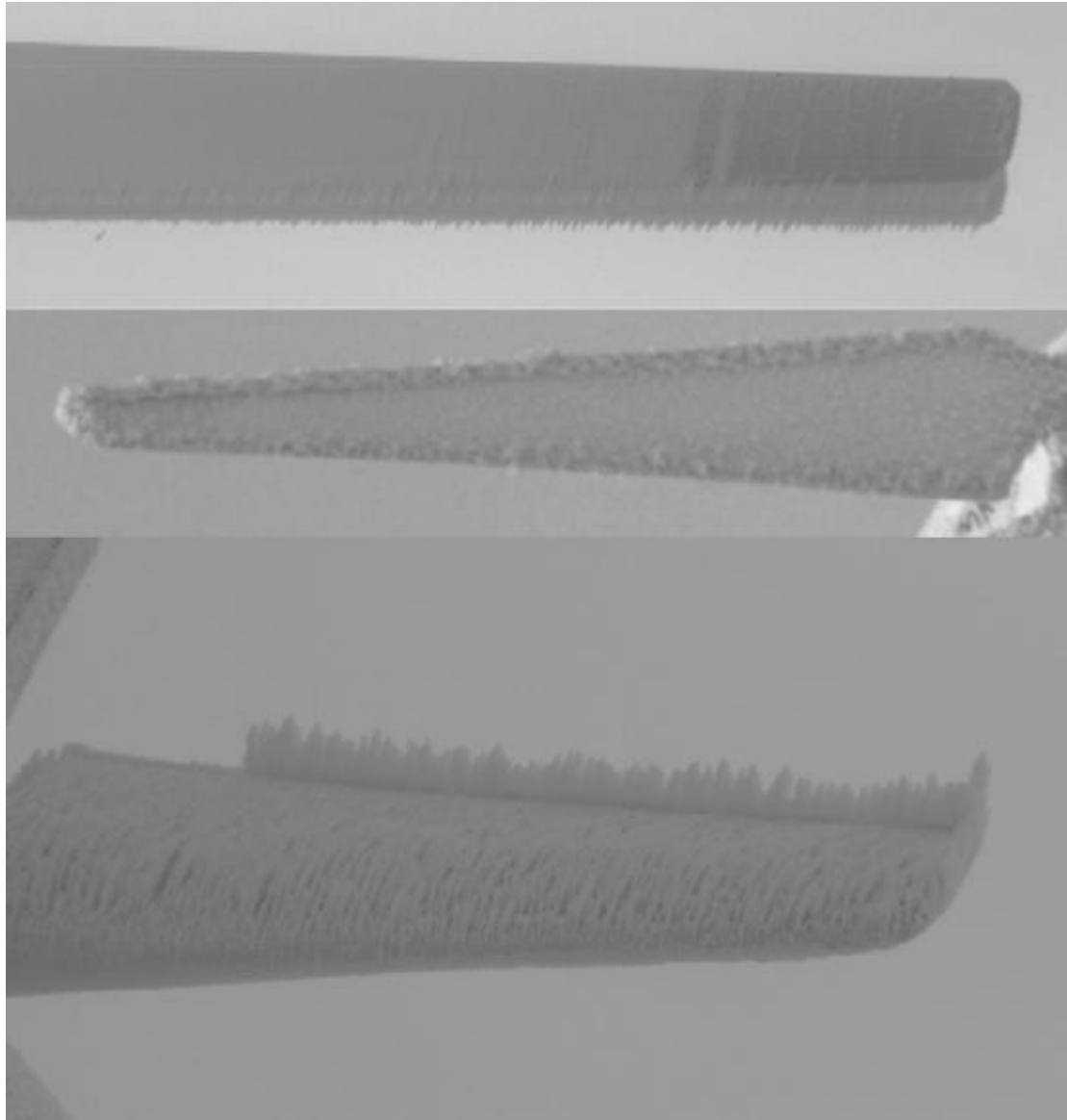


Figure 2-18. Icing on a wind turbine blade, source [Haaland, Estimating Production Loss due to Icing on Wind Turbines, University of Tromsø, 2011]

2.9.8 Structural failures

Another type of failure is structural failure. These failures are results such as collapse, fracture, or blade fracture. There are two main causes, extreme winds and the ground where the wind turbine is located.

Extreme winds can be very dangerous to the structural integrity of wind turbines. Especially in regions where natural disasters such as typhoons and hurricanes occur, damage to wind turbines is inevitable in some cases, and blade fracture and simple failures are considered acceptable. However, this is not exactly the case. In the previous titles, design standards and operating modes were mentioned. When the wind speed is more than 25 m/s wind speed, the operation mode of the turbine is changed to "standstill" or "idling" state. In these cases, the blades return to the feather position and the turbine is free to yaw. This allows the nacelle to turn in the direction of the wind. In this case, it is ensured that both the blades and the tower carry the minimum wind loads.

However, in case of any power loss, mechanical failure, electrical imbalance or instability (likely to be seen in extreme typhoons and hurricanes), the operating mode is "fault parked" or "emergency stop". In these operating states, the blades return to the feather position, but the yaw system is locked. As a result, the turbine has to maintain the wind coming from any direction without changing its position. In such cases, exposure to high forces as well as weakness in the ground cause wind turbines to collapse or get damaged easily.

Due to the design, reductions in shell wall thickness and bending stiffness may appear in certain parts of the wind turbine. Composite materials used to provide structural integrity in wind turbines are of great importance. For example, blade composite materials used at a certain height may be prone to fracture. An example of a structural failure is shown in Figure 2-19.



Figure 2-19. An example structural failure of onshore wind turbines, source [Tallbloke's Talkshop, 2014]

Chapter 3

3 Wind Turbine Design Aspects

3.1 Stages of wind turbines

There are a number of design requirements made to ensure that wind turbines are properly designed to resist damage from hazards within their planned lifetime. These design requirements are determined by international standards or standards prepared by certification companies. These standards, prepared by certification companies, are generally determined on the basis of international standards. These international standards relate to many aspects of turbine life, from turbine components that are tested, installed, and operated under site conditions prior to construction. Wind turbines are capital intensive and are usually purchased before they are installed and commissioned. Some of these standards provide technical terms that can be verified by an independent third party and are therefore necessary to enter into business deals so that wind turbines can be financed and installed. Before these standards are explained, some conditions that should be considered in the installation of wind turbines are mentioned under certain headings.

3.1.1 Conditions to be considered in wind farm construction

Since manufacturers produce turbines with different technologies and features, the investor should analyze the system they need in detail before choosing a turbine brand. As a result of examining the economic, technical, social and environmental factors with a certain technical-economic approach, it is expected that the most suitable wind energy conversion system will be selected for the field. It is extremely important to determine the most suitable brand that can implement the system determined considering its financial conditions. [A. Sarucan et al., 2010]. While choosing the wind turbine brand, model and power, the selection is made according to the following criteria, which are more prominent.

- Wind class of the site according to the land structure and micro-deployment results
- Determination of the capital expenditures (CAPEX) and operational expenditures (OPEX) of the turbine
- Service support and material supply
- Annual energy production of turbine, loss production factor and power curve performances etc.

The above criteria are of decisive importance when choosing a wind turbine, while the following criteria may be important in order to determine the location of the wind farm and the appropriate location for the turbines.

- Before the wind turbine construction, licensing procedures must be completed, and adequate feasibility studies must be carried out.
- Reviewing local regulations
- Site selection and detailed analysis

- Land ownership and transportation
- Analyzing the capacity factor
- Determination of wind speed and power density
- Land structure and distance to transformer center
- Local and environmental acceptability
- Actual feasibility report after licensing
- Initial investment cost
- Purchasing, financial transactions, assembly-acceptance and commissioning
- Operation period costs and technology change processes
- Sales price scenarios

3.1.1.1 Field work

The installation of wind turbines and the infrastructure works in the field should be carried out in certain sequences.

- Opening the roads for access to the turbine site
- Excavation works at the turbine site, opening the turbine foundations,
- Opening the high voltage (HV) lines between turbines and placing the cables
- Laying the turbine foundation and completing the steel base on which the tower will sit
- Construction of switchgear for grid connection
- Placing cubicles in the switchgear and making connections with turbine breakers
- Making the high voltage connection between the power plant and the electricity distribution center



Figure 3-1. Wind turbine foundation work, source [Creamer Media's Engineering News, 2014]

3.1.1.2 Transport of wind turbine equipment

Wind turbine equipment needs to be transported from the port or production centers to the site. Special organizations and plans should be made especially for the transportation of long and heavy equipment to the field.

- Pre-shipping route survey
- Transport of Nacelle, Drive Train, Hubs and Towers
- Transport of blades

3.1.1.3 Construction of wind turbine

Since turbine parts used in wind turbine assembly are large in weight and size, it is an operation performed with heavy-duty machinery. For this, attention should be paid to technical safety rules and weather conditions. There are specific safety rules for this work in the wind turbine assembly sector. For example, rotor assembly is not recommended when the air is charged with lightning or if the wind speed is over 6 m/s. Each turbine part has separate attachment points and lifting instructions for lifting. Each piece of equipment connected to each other has torque values according to the bolt diameter and quality. On the other hand, information such as by which element and at how many Nm the tightened bolt was tightened and with which tool it was made is recorded. Record reports and checklists related to this should be kept separately. [O. Kunt et al., 2013]. Construction steps can be listed as follows:

- Main crane and auxiliary crane installations
- Tower Assembly
- Nacelle Assembly
- Drive Train Assembly
- Hub Assembly
- Assembly of blades



Figure 3-2. Tower assembly, source [Betontec, Clean Energy Structures, 2019]



Figure 3-3. Blade assembly, source [Power Technology, Lake winds energy parks, Mason County, Michigan, 2017]

3.1.1.4 Starting to use wind turbine

After the assembly process of the wind turbine main equipment is completed, the following operations are carried out sequentially.

- Making high voltage (HV), low voltage (LV) and communication connections between nacelle and tower processor
- Making cabling, hydraulic and cooling system connections inside Nacelle
- Gearbox and Generator alignment
- Downloading the software to the turbine processor
- Completion of turbine tests

- Making the necessary configuration for Scada connection

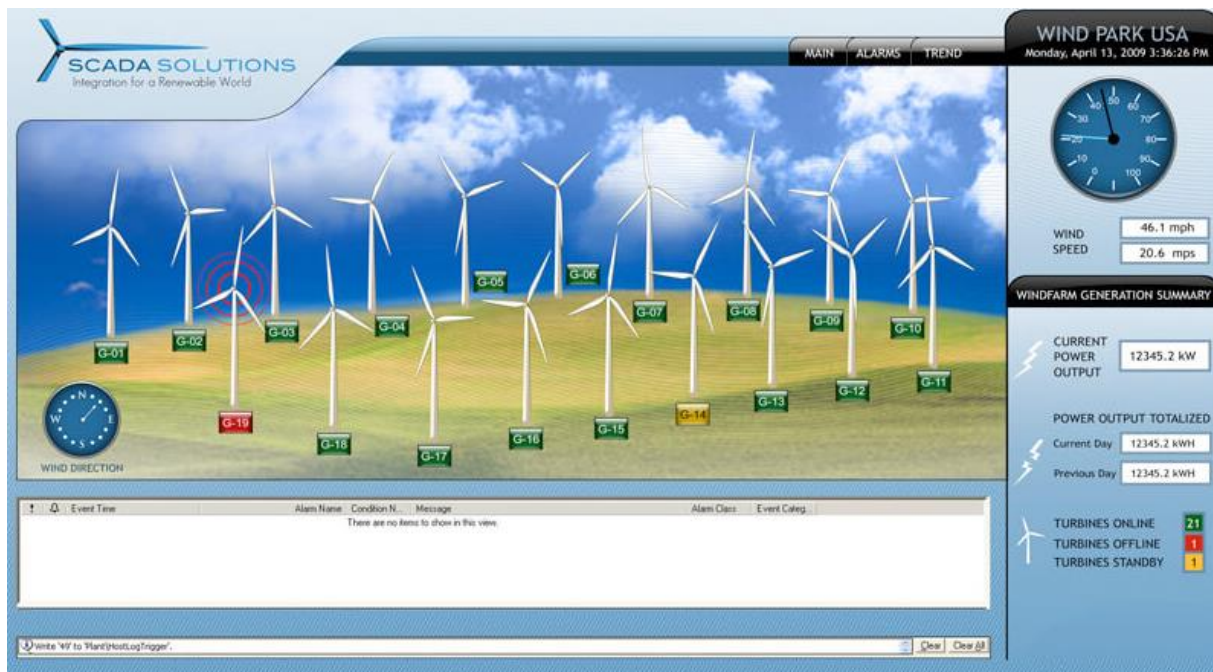


Figure 3-4. Scada sample interface image, source [Windpower Engineering & Development, 2009]

3.1.1.5 Service process of wind turbines

The planned and unplanned maintenance periods of wind turbines differ depending on the wind turbine technology and turbine type. The decrease in energy unit prices day by day creates pressure on producer and investor companies to reduce maintenance and breakdown costs. For this reason, various researches and applications are made for the ideal maintenance period. Although it varies according to the turbine brand and type, the maintenance period of an average turbine can be considered as 50-70 man-hours. However, if the turbine is gearless or the pitch system is electric, these times will differ. The content of maintenance activities can be generalized as follows.

- Visual Care
- Lubrication Maintenance
- Electrical maintenance
- Mechanical Maintenance
- Cleaning

While the operations of wind turbines are carried out by investor companies, maintenance and breakdown works are generally provided by turbine manufacturers. However, companies that own turbines can provide these services by establishing their own maintenance teams. The most important issue to be considered in this regard is that if the turbine manufacturer is completely disabled in order to reduce maintenance costs, it should be taken into account that longer downtimes may occur in case of malfunctions and there may be problems in the supply of spare parts. It is extremely important for wind farm owners to make an agreement

according to the model that will achieve maximum profit when making turbine maintenance contracts.

3.2 Standards and design requirements of wind turbines

International standards for wind turbines have been compiled by Technical Committee 88 of the International Electrotechnical Commission since 1988. Technical Committee 88; There are working groups, project teams, and update teams that create or revise standards, technical reports, and technical specifications. In addition to the standards established by the IEC, CENELEC's Technical Committee 88 has its own EN standards compiled by various European working groups.

A standardization body is defined as an organization that produces technical standards aimed at somehow meeting the needs of the industry. An international standards body produces international standards, and examples are the International Electrotechnical Commission (IEC) and the International Organization for Standardization (ISO). A special group of standards bodies consists of classification societies, which are non-governmental organizations that establish and maintain technical standards. There are also several industry-based standards bodies such as the Institute of Electrical and Electronics Engineers (IEEE).

There are also regional standardization bodies such as the European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELEC), both of which are recognized by the EU to provide European Standards (EN), and national standardization bodies such as the British Standards Institute (BSI) in the UK, Deutsches Institut für Normung (DIN) in Germany, Danish Standards (DS) in Denmark, Standard Norge and Norsk Electrotechnical Committee (NEK) in Norway, etc. These organizations are responsible for developing, maintaining and publishing relevant standards. Typically, standards are developed and maintained by relevant committees. Committees are usually made up of a group of experts across countries and companies. [DNV-GL, Overview of offshore wind standards and certification requirements in selected countries, 2020-1194, Rev. 01]

Wind turbine standards address design requirements and considerations as well as cover relevant components, systems and technologies that have an impact on the reliable operation of wind turbines. These standards help design and manufacture reliable and long-lasting wind turbines so that they can reliably remain in service throughout their planned life and realize both environmental and economic benefits. The following table provides standardization bodies and a brief description of them.

Type	Organization	Providing specific standards developed for the wind industry
International standard organizations	International Organization for Standardization (ISO)	ISO is an independent, non-governmental international organization with a membership of 165 national standards bodies. Provides more than 23 000 international standards covering almost all aspects of technology and manufacturing, however, no standard specific for wind turbines. Standard Norge is the Norwegian member of ISO.
	International Electrotechnical Commission (IEC)	IEC is an organization for preparation and publication of international standards for all electrical, electronic and related technologies. Technical committee TC88 of IEC is responsible for development of wind related standards. The national standardization organizations have the opportunity to participate in TC88 by nominated individuals. The IEC 61400-series includes a set of standards wind turbines. NEK is the Norwegian member of IEC.
Regional standard organizations	EU: European Committee for Standardization (CEN)	CEN is an association bringing together the National Standardization Bodies of EU. European Standards (EN) used for wind turbine structures are e.g. EN 1993-1-series. Standard Norge is the Norwegian member of CEN.
	EU: European committee for Electrotechnical Standardization (CENELEC)	CENELEC is responsible for standardization in the area of electrotechnical engineering. European Standards (EN) used for wind turbines are e.g. EN 61400-series. NEK is the Norwegian member of CENELEC.
National standardization organizations	UK: British Standards Institute (BSI)	BSI is the national standards body of the UK and develops technical standards such as the BS EN 61400-series.
	US: American Petroleum Institute (API)	API provides standards for the petroleum industry (originally developed for US conditions). API standards were among the first to be developed for this industry and have been the basis for other standards developed later e.g. the NORSOK standards. API has no offshore wind specific standards
	Norway: Standard Norge	Standard Norge has the responsibility for standardization in all areas except for electrical and postal- and telecommunications standardization. Standard Norge has exclusive rights to decode on and publish "Norsk Standard" (NS). There are no wind specific standards within the NS series. The NORSOK ("the Norwegian shelf's competitive position") standards are developed by the Norwegian petroleum industry. Standard Norge are managing the NORSOK standards. There are no wind specific NORSOK standards.
	Norway: Norsk Elektroteknisk Komite (NEK)	NEK deliver and are responsible for the completion of international standards from IEC and CENELEC. In addition, NEK translate international standards and create national standard collections. NEK is also responsible for a number of manuals and technical specifications and sell regulations from "Direktoratet for samfunnssikkerhet og beredskap" (DSB) based on national regulations. NEK is a Norwegian supplier of regulations and standards for the electrotechnical area.
National authority	Germany: Bundesamt für Seeschifffahrt und Hydrographie (BSH)	The BSH is a higher federal authority within the portfolio of the Federal Ministry of Transport and Digital Infrastructure (BMVI). It is the public institution for maritime tasks. This concerns tasks such as averting dangers at sea, issuing official nautical charts and surveying tasks in the North Sea and Baltic Sea, as well as forecasting tides, water levels and storm surges. In addition, the BSH is responsible for the surveying of ships, flag law, the testing and approval of navigation and radio equipment and the issue of certificates for seafarers. With regard to construction projects in the North and Baltic Seas, the BSH is responsible for spatial planning and for the testing and approval of power generation systems (offshore wind turbines), cables and other systems within the scope of federal responsibility.
	Norway: Petroleum Safety Authority (PSA)	Responsibility for the safety of renewable energy generation on the Norwegian Continental Shelf (NCS) has been added to the PSA's supervisory responsibilities (since 17 August 2020). A dedicated regulatory regime covering HSE in the offshore wind sector will be developed. The starting point will be the HSE regulations for petroleum operations, with performance-based requirements and a risk-based approach.

Classification societies/Certification bodies	American Bureau of Shipping (ABS)	Three offshore wind specific documents. ABS Guide for Building and Classing Bottom-Founded Offshore Wind Turbine Installations. ABS Guide for Building and Classing Floating Offshore Wind Turbine Installations. Guidance Notes on Global Performance Analysis for Floating Offshore Wind Turbine Installations (technical guidance in addition to applicable industry standards and regulations).
Classification societies/Certification bodies	Bureau Veritas (BV)	Delivering testing, inspection and certification services. One floating offshore wind specific document. NI572 Classification and certification of floating offshore wind turbines.
	Nippon Kaiji Kyokai (ClassNK)	Delivering classification of ships, certification and technical advisory services. One floating offshore wind specific document. Guideline for offshore floating wind - turbine structures.
	DNV GL	Delivering classification, certification and advisory services for the maritime, petroleum and renewables industry. Complete set of standards and recommended practices for wind power plants including turbines, bottom-fixed and floating support structures, cables and offshore substation. Certification scheme for both type and project certification.

Table 3-1. Standardization bodies, source [DNV-GL, Overview of offshore wind standards and certification requirements in selected countries, 2020-1194]

3.2.1 IEC Standards

IEC standards are the most important standards worthy of attention in this sector and subject, as they have international validity and other international, national organizations and certification organizations adapt and modify these standards by taking these standards into account. The IEC has a wide range of applicable and noteworthy standards, from the design, operation, safety and sustainable maintenance of onshore and offshore wind turbines. Table 3-2 shows the applicable standards for IEC onshore and offshore wind turbines, and in particular the scope of the IEC 61400 standard directly related to wind turbines.

The main standards related to IEC covering wind power generation systems are the IEC 61400 series. IEC 61400-1 Design requirements is the main standard used by turbine manufacturers for wind turbine design (Rotor Nacelle Assembly). The standards in the 61400 series are provided by the IEC Technical Committee (TC) 88. Other IEC standards are also applied in the wind energy sector. The standards focus on electrical components, but also include requirements for the support structure. [DNV-GL, Overview of offshore wind standards and certification requirements in selected countries, 2020-1194, Rev. 01]

Document code	Title
IEC 60076 series	Power transformers
IEC 60227 series	Polyvinyl chloride insulated cables of rated voltages up to and including 450/750 V
IEC 60335-2-40	Household and similar electrical appliances - Safety - Part 2-40: Particular requirements for electrical heat pumps, air-conditioners and dehumidifiers
IEC 60364 series	Low-voltage electrical installations
IEC 60502 series	Power cables with extruded insulation and their accessories for rated voltages from 1 kV (Um= 1,2 kV) up to 30 kV (Um= 36 kV)
IEC 60751	Industrial platinum resistance thermometers and platinum temperature sensors
IEC 60870 series	Telecontrol equipment and systems
IEC 60947 series	Low-voltage switchgear and controlgear
IEC 60947-3	Low-voltage switchgear and controlgear - Part 3: Switches, disconnectors, switch-disconnectors and fuse-combination units
IEC 61131 series	Programmable controllers
IEC 61400-1	Wind energy generation systems- Part 1: Design requirements
IEC 61400-11	Wind turbines - Part 11: Acoustic noise measurements techniques
IEC 61400-12-1	Wind energy generation systems - Part 12-1: Power performance measurements of electricity producing wind turbines
IEC 61400-12-2	Wind turbines - Part 12-2: Power performance of electricity-producing wind turbines based on nacelle anemometry
IEC 61400-13	Wind turbines - Part 13: Measurement of mechanical loads
IEC 61400-14	Wind turbines - Part 14: Declaration of apparent sound power level and tonality values
IEC 61400-21	Wind turbines - Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines
IEC 61400-21-1	Wind turbines - Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines
IEC 61400-22	Wind turbines - Part 22: Conformity testing and certification of wind turbines
IEC 61400-23	Wind turbines - Part 23: Full-scale structural testing of rotor blades
IEC 61400-24	Wind turbines - Part 24: Lightning protection
IEC 61400-25 series	Wind energy generation systems - Communications for monitoring and control of wind power plants
IEC 61400-26-1	Wind energy generation systems – Part 26-1 IECRE Availability for wind energy generation systems
IEC 61400-27-1	Wind turbines - Part 27-1: Electrical simulation models - Wind turbines
IEC 61400-3-1	Wind energy generation systems - Part 3-1: Design requirements for fixed offshore wind turbines
IEC 61400-3-2	Design requirements for floating offshore wind turbines
IEC 61400-4	Wind turbines - Part 4: Design requirements for wind turbine gearboxes
IEC 61400-5	Wind energy generation systems - Part 5: Wind turbine blades
IEC 61400-6	Wind energy generation systems - Part 6: Tower and foundation design requirements
IEC 61508 series	Functional safety of electrical/electronic/programmable electronic safety-related systems
IEC 61511 series	Functional safety - Safety instrumented systems for the process industry sector
IEC 62040 series	Uninterruptible power systems (UPS)
IEC 62053 series	Electricity metering equipment (a.c.) - Particular requirements
IEC 62271 series	High-voltage switchgear and control gear
IEC 62305 series	Protection against lightning
IEC 62477-1	Safety requirements for power electronic converter systems and equipment - Part 1: General
IEC 62610	Mechanical structures for electronic equipment - Thermal management for cabinets in accordance with IEC 60297 and IEC 60917 series
ISO/IEC 13273-1	Energy efficiency and renewable energy sources - Common international terminology - Part 1: Energy efficiency
ISO/IEC 13273-2	Energy efficiency and renewable energy sources - Common international terminology - Part 2: Renewable energy sources

Table 3-2. IEC Wind turbine relevant standards, source [DNV-GL, Overview of offshore wind standards and certification requirements in selected countries, 2020-1194]

3.2.1.1 IEC 61400-1 Design Requirements Standard

The IEC 61400 standard is an international standard for wind energy and wind turbines. As can be seen in Table 3-2, the IEC 61400 series are detailed standards for wind energy and wind turbines before and after the application by examining many aspects.

This part of IEC 61400 specifies the basic design requirements to ensure the structural integrity of wind turbines. Its purpose is to provide an appropriate level of protection against damage from all hazards throughout its planned lifetime. [IEC 61400-1, Edition 4.0 2019-02]

The International Electrotechnical Commission (IEC) 61400-1 design standard specifies the design requirements for wind turbines. The design standard is important for the analysis of the resulting loads and structural integrity. It allows designers to optimize low-cost wind turbines that provide appropriate performance and maintain structural integrity. Analysis involving a range of design conditions determines the expected operational modes over the economic life of the structure. These design conditions cover the basic design driving conditions such as normal operating conditions, start-up events, shutdown events, and parked or idle conditions, and appropriate normal and extreme external conditions and possible failure scenarios.

Within the IEC 61400-1 design standard, the main elements, external conditions, determining the wind turbine class depending on these external conditions, structural design and the loads to which the wind turbine will be exposed depending on this design, the design of mechanical systems and the design of electrical systems are included.

For example, regarding the structural design of a wind turbine, the integrity of the load-bearing components of the wind turbine structure will be verified and an acceptable level of safety determined in order to maintain its structural integrity and minimize the loads to which it will be subjected. The ultimate and fatigue strength of structural members should be verified by calculations, tests or both to demonstrate the structural integrity of a wind turbine with the appropriate level of safety. For design purposes, the life of a wind turbine can be represented by a set of design situations that cover the most critical conditions the wind turbine may encounter. The load cases will be determined from the combination of operating modes or other design conditions, such as specific installation, assembly or maintenance conditions, with external conditions. All relevant load cases with a reasonable probability of occurrence shall be considered together with the behavior of the control system. [ACP (American Clean Power Association) 61400-1-202x, Modified Adoption of IEC 61400-1]

3.2.2 Structural design

In order to ensure the structural integrity of wind turbines, the structural design requirements have been examined under this title, and the IEC 61400-1 Design Requirements standard and the ACP 61400-1-202x standard are based. A total of 8 design situation have been created depending on the loads that the turbine is exposed to, and depending on these conditions, the analysis type and safety factors have been determined by these standards.

Based on international standards, the integrity of the load-carrying components of the wind turbine structure shall be verified and an acceptable safety level shall be ascertained. The

ultimate and fatigue strength of structural members shall be verified by calculations, tests or both to demonstrate the structural integrity of a wind turbine with the appropriate safety level.

Tower, rotor, and drive train resonances shall be identified for the frequency range up to and including 2 times the blade passing frequency excitation. Possible resonances shall be investigated at turbulence levels of 30 % of the NTM (Normal Turbulance Model) category C design turbulence for DLC 1.2 (Table 3-3). If high resonant loads are found at low turbulence, means shall be taken to avoid the resonances or they shall be included in the design loads. [ACP (American Clean Power Association) 61400-1-202x, Modified Adoption of IEC 61400-1.]

The structural loads to which the wind turbine is exposed are briefly given below depending on the design conditions. These loads are effective in setting standards, and these loads explained in more detail in the chapter 2.

3.2.2.1 Gravitational and inertial loads

Gravitational and inertial loads are static and dynamic loads that result from gravity, vibration, rotation and seismic activity.

The allowable tolerances in tower verticality shall be stated in the design documentation and shall include initial and long-term effects due to permanent soil subsidence. The effect of tower verticality on gravitational loads shall be taken into account separately during the structural analysis of tower and foundation. [ACP (American Clean Power Association) 61400-1-202x, Modified Adoption of IEC 61400-1.]

3.2.2.2 Aerodynamic loads

Aerodynamic loads are static and dynamic loads that are caused by the airflow and its interaction with the stationary and moving parts of wind turbines.

The airflow is dependent upon the average wind speed and turbulence across the rotor plane, the rotational speed of the rotor, the density of the air, and the aerodynamic shapes of the wind turbine components and their interactive effects, including aeroelastic effects.

It is not required in the aerodynamic load calculations to account for geometric tolerances in tower verticality of less than or equal to 3°. [ACP (American Clean Power Association) 61400-1-202x, Modified Adoption of IEC 61400-1.]

3.2.2.3 Actuation loads

Actuation loads result from the operation and control of wind turbines. They are in several categories including torque control from a generator or inverter or both, yaw and pitch actuator loads and mechanical braking loads. In each case, it is important in the calculation of response and loading to consider the range of actuator forces available, including friction. In particular, for mechanical brakes, the range of friction, spring force or pressure as influenced by temperature, and ageing shall be taken into account in checking the response and the loading during any braking event. [ACP (American Clean Power Association) 61400-1-202x, Modified Adoption of IEC 61400-1.]

3.2.2.4 Other loads

Other loads such as wake loads, impact loads, ice loads, tower loads resulting for example from vortex-induced vibrations might occur and shall be considered where appropriate. [ACP (American Clean Power Association) 61400-1-202x, Modified Adoption of IEC 61400-1.]

3.2.3 Design load cases

For design purposes, the life of a wind turbine can be represented by a set of design situations covering the most significant conditions that the wind turbine may experience.

The load cases shall be determined from the combination of operational modes or other design situations, such as specific assembly, erection or maintenance conditions, with the external conditions. All relevant load cases with a reasonable probability of occurrence shall be considered, together with the behavior of the control system. The design load cases used to verify the structural integrity of a wind turbine shall be calculated by combining the following:

- normal design situations and appropriate normal or extreme external conditions.
- fault design situations and appropriate external conditions.
- transportation, installation and maintenance design situations and appropriate external conditions.

If correlation exists between an extreme external condition and a fault situation, a realistic combination of the two shall be considered as a design load case.

Within each design situation, several design load cases shall be considered. As a minimum, the design load cases in Table 3-3 shall be considered. In that table, the design load cases are specified for each design situation by the description of the wind, electrical and other external conditions.

If the wind turbine controller can, during design load cases with a deterministic wind model, cause the wind turbine to shut down prior to reaching maximum yaw angle and/or wind speed, then it shall be shown that the turbine can reliably shut down under turbulent conditions with the same deterministic wind condition change.

Other design load cases shall be considered, if relevant to the structural integrity of the specific wind turbine design.

For each design load case, the appropriate type of analysis is stated by "F" and "U" in Table 3-3. "F" refers to analysis of fatigue loads, to be used in the assessment of fatigue strength. "U" refers to the analysis of ultimate loads, with reference to material strength, blade tip deflection and structural stability.

The design load cases indicated with "U" are classified as normal (N) or abnormal (A). Normal design load cases are expected to occur frequently. The turbine is in a normal state or may have experienced minor faults or abnormalities. Abnormal design situations are less likely to occur. They usually correspond to design situations with severe faults that result in the activation of system protection functions. The type of design situation, N or A, determines the partial safety factor to be applied to the ultimate loads. [ACP (American Clean Power Association) 61400-1-202x, Modified Adoption of IEC 61400-1]

Design situation	DLC	Wind condition	Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	<u>NTM</u> $V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	<u>NTM</u> $V_{in} < V_{hub} < V_{out}$		F	*
	1.3	<u>ETM</u> $V_{in} < V_{hub} < V_{out}$		U	N
	1.4	<u>ECD</u> $V_{hub} = V_r - 2 \text{ m/s}, V_r, V_r + 2 \text{ m/s}$		U	N
	1.5	<u>EWS</u> $V_{in} < V_{hub} < V_{out}$		U	N
2) Power production plus occurrence of fault	2.1	<u>NTM</u> $V_{in} < V_{hub} < V_{out}$	Normal control system fault or loss of electrical network or primary layer control function fault	U	N
	2.2	<u>NTM</u> $V_{in} < V_{hub} < V_{out}$	Abnormal control system fault or secondary layer protection function related fault	U	A
	2.3	<u>EOG</u> $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	<u>NTM</u> $V_{in} < V_{hub} < V_{out}$	Control system fault, electrical fault or loss of electrical network	F	*
	2.5	<u>NWP</u> $V_{in} < V_{hub} < V_{out}$	Low voltage ride through	U	N
3) Start-up	3.1	<u>NWP</u> $V_{in} < V_{hub} < V_{out}$		F	*
	3.2	<u>EOG</u> $V_{hub} = V_{in}, V_r \pm 2 \text{ m/s}$ and V_{out}		U	N
	3.3	<u>FDC</u> $V_{hub} = V_{in}, V_r \pm 2 \text{ m/s}$ and V_{out}		U	N
4) Normal shutdown	4.1	<u>NWP</u> $V_{in} < V_{hub} < V_{out}$		F	*
	4.2	<u>EOG</u> $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}		U	N
5) Emergency stop	5.1	<u>NTM</u> $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}		U	N
6) Parked (standing still or idling)	6.1	<u>EWM</u> 50-year return period		U	N
	6.2	<u>EWM</u> 50-year return period	Loss of electrical network connection	U	A
	6.3	<u>EWM</u> 1-year return period	Extreme yaw misalignment	U	N
	6.4	<u>NTM</u> $V_{hub} < 0,7 V_{ref}$		F	*
7) Parked and fault conditions	7.1	<u>EWM</u> 1-year return period		U	A
8) Transport, assembly, maintenance and repair	8.1	<u>NTM</u> V_{maint} to be stated by the manufacturer		U	N
	8.2	<u>EWM</u> 1-year return period		U	A

Table 3-3. Design load cases (DLC), source [ACP (American Clean Power Association) 61400-1-202x, Modified Adoption of IEC 61400-1]

Key	
DLC	Design load case
ECD	Extreme coherent gust with direction change
EDC	Extreme direction change
EOG	Extreme operating gust
EWM	Extreme wind speed model
EWS	Extreme wind shear
NTM	Normal turbulence model
ETM	Extreme turbulence model
NWP	Normal wind profile model
Vr ± 2 m/s	Sensitivity to all wind speeds in the range shall be analysed
F	Fatigue
U	Ultimate strength
N	Normal
A	Abnormal
*	Partial safety for fatigue

Table 3-4. Design load cases keys, source [ACP (American Clean Power Association) 61400-1-202x, Modified Adoption of IEC 61400-1]

3.2.3.1 Power production (DLC 1.1 to 1.5)

In this design situation, a wind turbine is running and connected to the electric load. The assumed wind turbine configuration shall take into account rotor imbalance. The maximum mass and aerodynamic imbalances (e.g., blade pitch and twist deviations) specified for rotor manufacture shall be used in the design calculations. In addition, deviations from theoretical optimum operating situations such as yaw misalignment and control system tracking errors shall be taken into account in the analyses of operational loads.

Design load cases (DLCs) 1.1 and 1.2 embody the requirements for loads resulting from atmospheric turbulence that occurs during normal operation of a wind turbine throughout its lifetime (NTM). DLC 1.3 embodies the requirements for ultimate loading resulting from extreme turbulence conditions. DLC 1.4 and 1.5 specify transient cases that have been selected as potentially critical events in the life of a wind turbine. [ACP (American Clean Power Association) 61400-1-202x, Modified Adoption of IEC 61400-1]

3.2.3.2 Power production plus occurrence of fault or loss of electrical network connection (DLC 2.1 to 2.5)

This design situation involves a transient event triggered by a fault or by the loss of electrical network connection while the turbine is producing power. Any fault in the control system, or internal fault in the electrical system, significant for wind turbine loading (such as generator short circuit) shall be considered. This design situation is considered to be relevant for fatigue analysis as well.

A failure mode and effect analysis (FMEA) or equivalent fault analysis shall be carried out to determine fault events relevant for the wind turbine loading.

The azimuth position for the rotor at the time of a fault may have significant influence on the load level. The azimuth position at time of occurrence for the fault should be random. [ACP (American Clean Power Association) 61400-1-202x, Modified Adoption of IEC 61400-1] The azimuth is the angle between North, measured clockwise around the observer's horizon, and a celestial body (sun, moon). It determines the direction of the celestial body.

3.2.3.3 Start-up (DLC 3.1 to 3.3)

This design situation includes all the events resulting in loads on a wind turbine during the transients from any standstill or idling situation to power production. The number of occurrences shall be estimated based on the control system behavior.

For DLC 3.2, at least four different timing events between the EOG and the start-up event shall be considered for each wind speed. The first timing shall be chosen so that the beginning of the EOG occurs when the power production reaches 50 % of maximum power. The last timing shall be chosen so that the beginning of the EOG occurs when the power production reaches 95 % of maximum power. At least two additional timings shall be chosen, evenly distributed within the interval from 50 % to 95 % of maximum power.

For each wind speed, the characteristic value of the load may be computed as the average value of the extreme computed transient value for the four defined distinct points of time. [ACP (American Clean Power Association) 61400-1-202x, Modified Adoption of IEC 61400-1]

3.2.3.4 Normal shutdown (DLC 4.1 to 4.2)

This design situation includes all the events resulting in loads on a wind turbine during normal transient situations from a power production situation to a standstill or idling condition. The number of occurrences shall be estimated based on the control system behavior.

For DLC 4.2, the timing of the gust and the shutdown event shall be chosen such that the EOG gust starts at different times relative to the shutdown, with minimum six events evenly distributed from 10 s before the beginning of the shutdown, till the power reaches 50 % of the initial power production level.

At least four evenly distributed rotor azimuth positions shall be applied for each distinct point of time. For each wind speed, the characteristic value of the load may be computed as the mean value of the extreme computed loads among all timings and azimuth positions considered. [ACP (American Clean Power Association) 61400-1-202x, Modified Adoption of IEC 61400-1]

3.2.3.5 Emergency stop (DLC 5.1)

Loads arising from activation of the emergency stop button shall be considered.

The azimuth position for the rotor at the time of a fault may have significant influence on the load level. The azimuth position at time of occurrence for the fault should be random. [ACP (American Clean Power Association) 61400-1-202x, Modified Adoption of IEC 61400-1]

3.2.3.6 Parked (standstill or idling) (DLC 6.1 to 6.4)

In this design situation, the rotor of a parked wind turbine is either in a standstill or idling condition. In DLC 6.1, 6.2 and 6.3, this situation shall be considered with the extreme wind speed model (EWM). For DLC 6.4, the normal turbulence model (NTM) shall be considered.

In DLC 6.1, for a wind turbine with an active yaw system, a yaw misalignment of up to $\pm 15^\circ$ using the steady extreme wind model or a mean yaw misalignment of $\pm 8^\circ$ using the turbulent extreme wind model shall be imposed, provided restraint against slippage in the yaw system can be assured.

In DLC 6.2, a loss of the electrical power network at an early stage in a storm containing the extreme wind situation shall be assumed. Unless power back-up is provided for the control and yaw system with a capacity for yaw alignment for a period of at least 6 h, the effect of a wind direction changes of up to $\pm 180^\circ$ shall be analyzed.

In DLC 6.3, the extreme wind with a 1-year return period shall be combined with an extreme yaw misalignment. An extreme yaw misalignment of up to $\pm 30^\circ$ using the steady extreme wind model or a mean yaw misalignment of $\pm 20^\circ$ using the turbulent wind model shall be assumed. If for the cases DLC 6.1 with steady extreme wind model, DLC 6.2 and DLC 6.3, yaw misalignment is evaluated using discrete values, the increment in yaw misalignment shall be not more than 10° in the sector of the maximum lift force on the blades.

In DLC 6.4, the expected number of hours of non-power production time at a fluctuating load appropriate for each wind speed where significant fatigue damage can occur to any components (e.g., from the weight of idling blades) shall be considered. [ACP (American Clean Power Association) 61400-1-202x, Modified Adoption of IEC 61400-1]

3.2.3.7 Parked plus fault conditions (DLC 7.1)

Deviations from the normal behavior of a parked wind turbine, resulting from faults on the electrical network or in the wind turbine, shall require analysis. As a minimum, failures in the following systems shall be evaluated: brake system, pitch system, and yaw system. The fault condition shall be combined with EWM for a return period of one year. Those conditions shall be either turbulent or quasi-steady with correction for gusts and dynamic response.

In case of a fault in the yaw system, yaw misalignment of $\pm 180^\circ$ shall be considered. If for the cases DLC 7.1 with fault in the yaw system, yaw misalignment is evaluated using discrete values, the increment in yaw misalignment shall be not more than 10° in the sector of the maximum lift force on the blades. For any other fault, yaw misalignment shall be consistent with DLC 6.1.

If slippage in the yaw system can occur at the characteristic load found in DLC 7.1, the largest unfavorable slippage possible shall be considered. [ACP (American Clean Power Association) 61400-1-202x, Modified Adoption of IEC 61400-1]

3.2.3.8 Transport, assembly, maintenance and repair (DLC 8.1 to 8.2)

For DLC 8.1, the manufacturer shall state all the wind conditions and design situations assumed for transport, assembly on site, maintenance and repair of a wind turbine. The maximum stated wind conditions shall be considered in the design if they can produce significant loading on the turbine. The manufacturer shall allow sufficient margin between the stated conditions and the wind conditions considered in design to give an acceptable safety level. Sufficient margin may be obtained by adding 5 m/s to the stated wind condition.

In addition, DLC 8.2 shall include all transport, assembly, maintenance and repair turbine states which may persist for longer than one week. This shall, when relevant, include a partially completed tower, the tower standing without the nacelle and the turbine without one or more blades. In the case of a tower standing without a nacelle, appropriate means shall be taken to avoid critical wind speeds for vortex generated transverse vibrations, or the appropriate fatigue design load case shall be added. It shall be assumed that the electrical network is not connected in any of these states. Measures may be taken to reduce the loads during any of these states as long as these measures do not require the electrical network connection. [ACP (American Clean Power Association) 61400-1-202x, Modified Adoption of IEC 61400-1]

Chapter 4

4 Data and Method

4.1 Wind turbine failures

In the previous chapters, detailed information about wind turbines is given, and at the same time, failures, damages and risks that may occur are specified and the parameters and conditions affecting these concepts are explained. In this chapter, malfunctions, risks and faults that occur in wind turbines are collected and their causes are stated. Case data were collected by specifying the previous failures, hazards and risks and their causes. In this chapter, some typical faults and risk situations are examined under specific headings in order to inform about them, similar failure and risk situations and all collected data are shown in the table in Appendix-A.

It should also be noted that in some of the data that resulted in the fire, as listed in the Appendix-A table, the cause of the fire was not specified as the reason was not stated by the data sources or the authorities. However, these cases cover some fire data, not all fire data as stated. For example, statements such as "the wind turbine engine caught fire, the nacelle caught fire even though there was no storm, the engine cover started to burn even though there was no lightning or storm, and the reason is unknown" were found in the source. In these cases, if there is no lightning or storm, the failure type is specified as generator failure in this study. The date of completion of the failures investigations was May 4, 2022. Additionally, although the sample identified is very large and suitable for careful assessment, it should be noted that there may be other failures that are not identified and recorded.

4.1.1 USA Washington Klickitat; wind turbine fire

On July 19, 2019, in a two phases wind farm with a total of 128 wind turbines in the southern region of Washington, USA, one of the wind turbines started to catch fire due to mechanical misalignment in the generator, Figure 4.1. In fact, since the land where the farm is located was barren and dry, the flames in the wind turbine spread to the nature and caused a huge fire. This fire was brought under control at the end of the 4th day. [in the Appendix-A, turbine number:1]



Figure 4-1. Wind turbine fire in USA, Washington, source [Newsradio 610Kona, 2019]

4.1.2 USA California Tehachapi; idle wind turbine blades

On May 2, 2009, the blade rotation speed got out of control due to a fault in a wind turbine gearbox at a wind farm located in Tehachapi, California, USA. With the effect of the increasing wind, the wind turbine blades started to rotate at a speed that cannot be seen with the eye, posing a danger to the environment and other wind turbines in the environment. Due to these blades with very high rotational rotation, the highway was closed for a certain period of time in the region where it is located. Since it was not possible to fix the wind turbine easily and quickly or to shut it down immediately, repair had to wait until the high wind speed ceased. [in the Appendix-A, turbine number:2]

4.1.3 Denmark Roedsand-2 Offshore Wind Park; ice forming on blades

On December 23, 2010, Roedsand-2 offshore wind farm with a capacity of 207 megawatts was operated with a capacity of 130 megawatts due to cold weather. Roedsand-2 offshore wind farm located 9 km off coast of Rødbyhavn, between the German island of Fehmarn and the Danish Island of Lolland. Ice formation was observed on the blades due to cold weather and the system was stopped. [in the Appendix-A, turbine number:10]

4.1.4 USA Ohio Perkins; wind turbine blade fall

On November 30, 2010, Perkins Schools officials shut down the wind turbines on school property after a mechanical failure. Bolts on one of the blades broke, which released the blade. The blade fell to the base of the turbine. [in the Appendix-A, turbine number:21]

4.1.5 Netherland Medemblik Lely; wind farm blades fall

On December 26, 2014, authorities shut down the four-turbine Lely nearshore wind farm in the Netherlands after the rotor head and blades fell off one of its Nedwind N40/500 machines, see Figure 4.2. The hub and rotors from the twin-bladed turbine were lying around a meter beneath the water's surface and the area was marked with buoys so that there was no danger to shipping. [in the Appendix-A, turbine number:108]



Figure 4-2. Wind turbine blades fell in Netherlands, Lely Wind Farm, source [National Wind Watch, 2014]

4.1.6 Sweden Yttre Stengrund; Offshore Wind Farm to be scrapped

On September 19, 2014, Yttre Stengrund was an offshore wind farm in Sweden, operated by Vattenfall. Vattenfall has abandoned plans to repower its 10MW Yttre Stengrund offshore wind farm in the Kalmar Sound, Sweden because of difficulty finding spare parts. It was a long-running problem at the wind farm. [in the Appendix-A, turbine number:122]

4.1.7 UK Anglesey; wind turbine fire

On February 13, 2014, wind turbines in Anglesey burst into flames in gale force winds that hit North Wales. Anglesey is an island off the north-west coast of Wales. The wind turbine generator malfunctioned due to the increase in the wind speed and the wind speed exceeding 108 mph, causing the turbine to catch fire. [in the Appendix-A, turbine number:143]

4.1.8 Germany Nordsee-Ost Wind Farm; blade fall

On June 25, 2015, just over a month after it was inaugurated, German 295MW Nordsee Ost wind farm encountered a problem. Authorities was forced to shut down the wind farm after one of Senvion 6.2M126 wind turbines suffered a blade loss. Several ships and a helicopter were used in the salvage operation, after which the recovered parts were taken to Senvion's production site in Bremerhaven. [in the Appendix-A, turbine number:167]

4.1.9 Norway Fitjar Midtfjellet; Vindkraft generator fire

On October 31, 2015, a wind turbine in Midtfjellet Vindkraft was shut down and cordoned off due to a fire. According to an eyewitness, a "big fire" was observed at the top of the wind turbine. Erik Mortensen, managing director of Midtfjellet Vindkraft, confirmed that a wind turbine had caught fire. He knew nothing but that there was a fire, and the area was secured. The generator house was completely burned in the fire at the wind farm in Midtfjellet Vindkraft in Fitjar, Figure 4.3. After the fire, a part of the wind turbine fell to the ground and the perimeter was cordoned off. [in the Appendix-A, turbine number:176]



Figure 4-3. Norway Fitjar Midtfjellet Vindkraft turbine fire, source [Haugesund Avis, 2015]

4.1.10 UK Shrewsbury; unstable wind turbine

On June 13, 2016, a wind turbine had to be taken down by firefighters and engineers after concerns about its stability during storm weather. Firefighters from Shrewsbury helped engineers to take the turbine down at Shrewsbury Road in Cressage, near Much Wenlock. A spokeswoman from Shropshire Fire and Rescue said: "One wind turbines was reported as unstable from the stormy weather so was lowered using straining wires and man power." [in the Appendix-A, turbine number:203].

4.1.11 USA New Hampshire Balsams; wind turbine ice forming

On December 1, 2016, researchers who worked near the 400-foot-high wind turbines on peaks above the proposed Balsams ski area said there was reason to be worried about people getting too close, Figure 4.4: They saw chunks of ice being thrown and found ice craters and broken saplings 930 feet from a turbine. Concerns included a mechanical failure that could send pieces of metal flying or under some conditions in winter, the huge blades collecting and then shedding ice. Both are rare, but they could be deadly, experts say. When the weather indicates that ice could form on the blades, the wind turbines would be shut down. [in the Appendix-A, turbine number:218]



Figure 4-4. The wind turbines above the Balsams, source [IndepthNH, 2016]

4.1.12 Germany Bavaria Zultenberg-Seubersdorf; wind farm gearbox oil leak

On March 16, 2017, a wind turbine at the Zultenberg-Seubersdorf wind farm came to a standstill after oil leaked from a gearbox malfunction. A high amount of oil leakage occurred from the gearbox and the wind turbine operation was stopped. [in the Appendix-A, turbine number:237]

4.1.13 Antarctica Mawson research station; wind turbine rotor fall

On November 8, 2017, the rotor fell off a wind turbine at an Australian research station in Antarctica, Figure 4.5. Nobody was injured. The cause of the accident, which happened in normal gusty conditions, was investigated. The fact that the wind intensity was not high in this event and the moderate weather before and after the event makes the event more interesting. [in the Appendix-A, turbine number:253]



Figure 4-5. Rotor has fallen off a wind turbine in Antarctica, source [Pedestriangroup, 2017]

4.1.14 USA Iowa Highway 65; wind turbine blade bent

On July 25, 2018, one of the blades of a wind turbine in the U.S. state of Iowa was bent like a rabbit's ear (Figure 4.6) due to high winds from a storm from Central Iowa. Strong winds will damage wind turbines. [in the Appendix-A, turbine number:318]



Figure 4-6. USA Iowa wind turbine blade bent, source [Times-Republican, 2018]

4.1.15 USA Block Island Wind Farm; exposed cable

On August 8, 2018, the sea2shore transmission cable, installed by National Grid as part of the Block Island Wind Farm project, could be seen about 25 feet from Town Beach at low tide. The cable, which was yellow and black, was getting some attention, Figure 4.7. The cable connects Block Island to the mainland. There are 34,500 volts running through the cable. Although the cable is fully armored and insulated, it can be dangerous for the area. [in the Appendix-A, turbine number:319]



Figures 4-7. USA Block Island Wind Farm exposed cable, source [TheBlockIslandTimes, 2018]

4.1.16 Spain Bilbao Saitec; floating wind turbine

On November 4, 2020, ten-meter-high waves broke and capsized a wind turbine prototype as a storm crashed into northern Spain causing damage along the coast. The impact of the severe storm caused the wind turbine offshore of Bilbao to collapse. [in the Appendix-A, turbine number:400]

4.1.17 Denmark Horns Rev 1 Wind Farm; turbine fire

On May 22, 2021, A wind turbine at the 160 MW Horns Rev 1 wind farm offshore Denmark caught fire and burned. Located in the North Sea 20 kilometers from the west coast of Jutland, the Horns Rev 1 wind farm comprises 80 Vestas V80 2 MW turbines which have been in operation since 2002. Given that the incident was limited to a single turbine, the overall supply of electricity from the wind farm was not affected. [in the Appendix-A, turbine number:422]

4.1.18 Germany Oberwolfach Hohenlochen Wind Farm; cracks on blades

On January 30, 2022, two of the four systems at the Hohenlochen wind farm on the ridge above Oberwolfach and Hausach were dormant and awaiting repair, with cracks in the rotor blades cited as the cause. The operation was stopped due to cracks in the blades. Cracks in the rotor blades were discovered during routine maintenance work on two turbines. [in the Appendix-A, turbine number:444]

4.1.19 Belgium Offshore; Wind Farms shut down wind turbines operation

On February 18, 2022, For the first time since they were placed there, all wind turbines at sea were shut down as a result of storm Eunice, which officially became a Belgian storm. However, all the turbines, even the oldest ones, were said to be storm proof, meaning the heavy gusts of wind shouldn't cause any damage. The blades of the wind turbines were blocked by authorities, which resulted in the turbines automatically shutting down. Although there were no malfunctions, severe storms hindered the operation of the wind turbines and cause production to stop, Figure 4.8. Therefore, this example is included in the study. [in the Appendix-A, turbine number:451]



Figure 4-8. Belgian Offshore Wind Farm, source [TheBrusselsTimes, 2022]

Chapter 5

5 Data Analysis and Assessment

Data analytics refers to the analysis of data collected in order to extract patterns, discover the desired information, and create knowledge in line with the determined purpose. These terms are presented in the light of visualization and summary of statistical information. Data analysis is done according to the data collected in the project, the structure of the data, the audience receiving the analysis, and the experience of the analyst.

In this study, statistical information has been prepared in the light of the data obtained, and during the operation of offshore and onshore wind turbines, the failure and risk situations were determined, and the data obtained were analyzed.

5.1 Data

5.1.1 Data collection and cleaning

The dataset analyzed in this study is a compilation of 458 news reports from 2010 to 2022. The data source was created using the results obtained from the Google search engine using the search terms "wind turbine failures", "wind turbine accidents", "wind turbine collapse", etc., and the results of many articles and literature studies reviewed throughout the study. In many of the resulting news articles, irrelevant, repetitive, and unverifiable news were eliminated. Only news reports that provided a certain level of detail were included, and a most reliable data was created. All the data obtained are listed in detail in "Appendix A".

This analysis is based on publicly failures and risks news. Without full access and detail to all wind turbine failures and accidents, it is impossible to say that the data used in this study or similar studies are representative of all wind turbines. Because it will not be possible to convince all wind turbine manufacturers to share all their data on accidents, let alone convince one manufacturer. The data in this study is reliable as the data base was created with extreme precision and meticulousness regarding data collection and examination, but it should not be forgotten that there are different types of failures that are not recorded.

Most of the sources of the data obtained are in English. The last time non-English news sources were checked using Google Translate in May 2022, and complete data analysis was conducted again. In terms of analysis quality, data quality, and study reliability, it has been validated more than once, with special emphasis on the translation of technical terms in addition to high translation quality.

All of these data, obtained from 2010 to 2022 about failures, risks, damages, and dangerous situations were related to the operation of offshore and onshore wind turbines. Therefore, failure and risk factors during construction or transportation are not included in the data. Much effort was required in a short time to expand the framework and collect potential, reliable and large amounts of data.

Details such as location, date, type of failure, cause of failure, type of wind turbine and more features have been carefully and painstakingly manually generated by reading each news reports in detail and understanding the content and researching online the information to complement any missing information. Data sources have been recorded in order to ensure originality and scientific reproducibility.

5.1.2 Data attributes

The attributes in the structured dataset (Appendix A) are the following:

- Turbine No : Turbine number defined for each failure
- Year, month, day : Year, month, and day of failure reporting
- Wind turbine location: The specific location of the turbine and name
- Location : State, province, county in which the failure occurred
- Country : Country where the failure occurred
- Failure location : Section showing which part of the wind turbine fails
- Failure type : Section showing the type of fault
- Failure cause : Section that explains the reason for the failure
- Failure effect : Section showing damage and result of the wind turbine failure
- Type : Offshore or onshore wind turbine classification

5.2 Analysis and Results

This section summarizes the data collected and generated during the research, such as failure rates, country distributions, risk factors, with table and graphic analyzes.

The first analysis in this research was the analysis of the collected data showing the rate distribution of the failure types of the datasets. The Figure 5.1 chart below shows the failure rates.

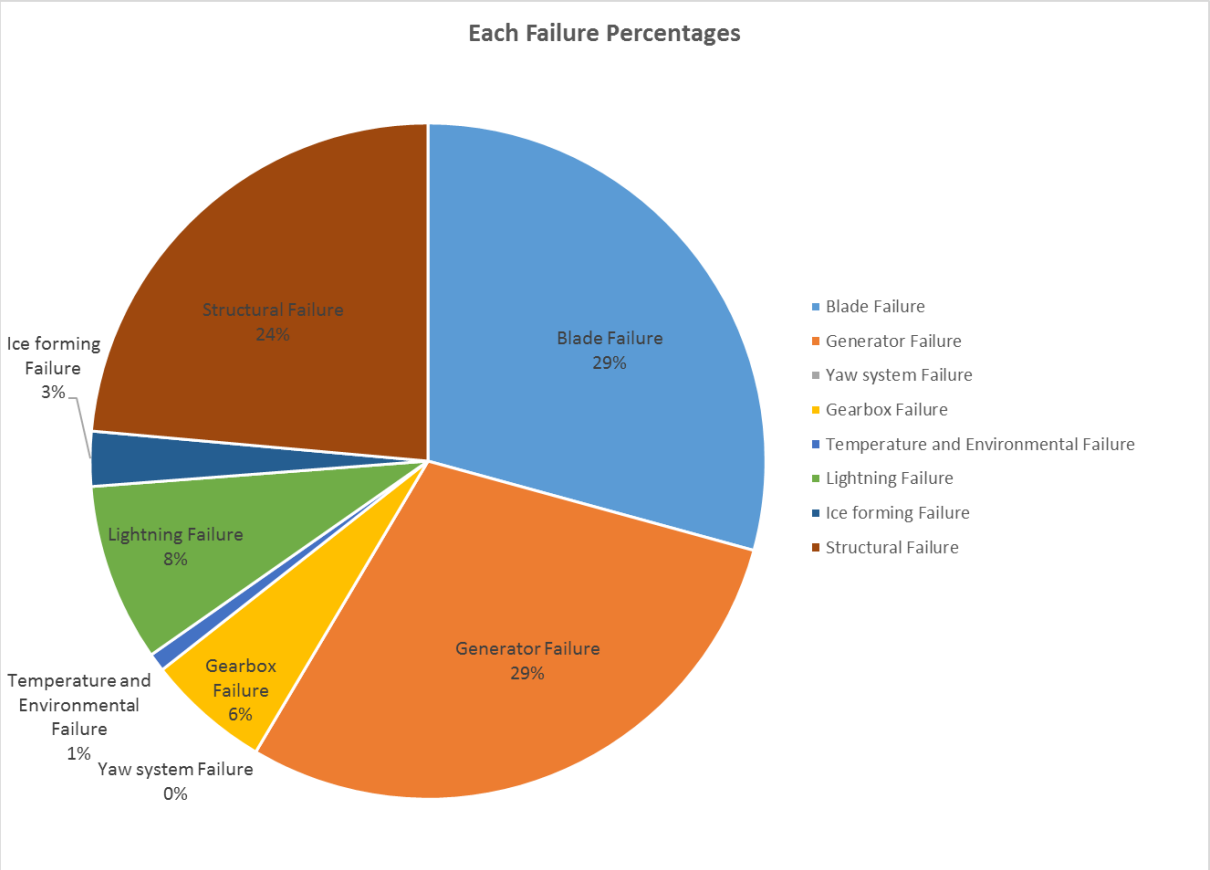


Figure 5-1. Graph showing failure percentages

The first analysis focused on the distribution of failure rates as shown in the above figure. As can be seen from the graph, blade and generator failures cover offshore and onshore wind turbines failures and risks with a 29% percentile each. Structural failures follow with 24%. There are lightning failures with 8%, gearbox failures with 6%, ice forming in turbines 3% and faults caused by temperature and environmental effects of 1%. Yaw system failures were not found in the collected data, this detail is evaluated as a comment in the next chapter. Table 5.1 failure rates are shown below for easier assessment of the graphic results.

Failure Type	Failure Percentage (%)
Blade Failure	29
Generator Failure	29
Structural Failure	24
Lightning Failure	8
Gearbox Failure	6
Ice forming Failure	3
Temperature and Environmental Failure	1

Table 5-1. Failure percentages

The percentage shares of the causes of blade failures, which have a high rate of overall failure, are shown Figure 5.2 below.

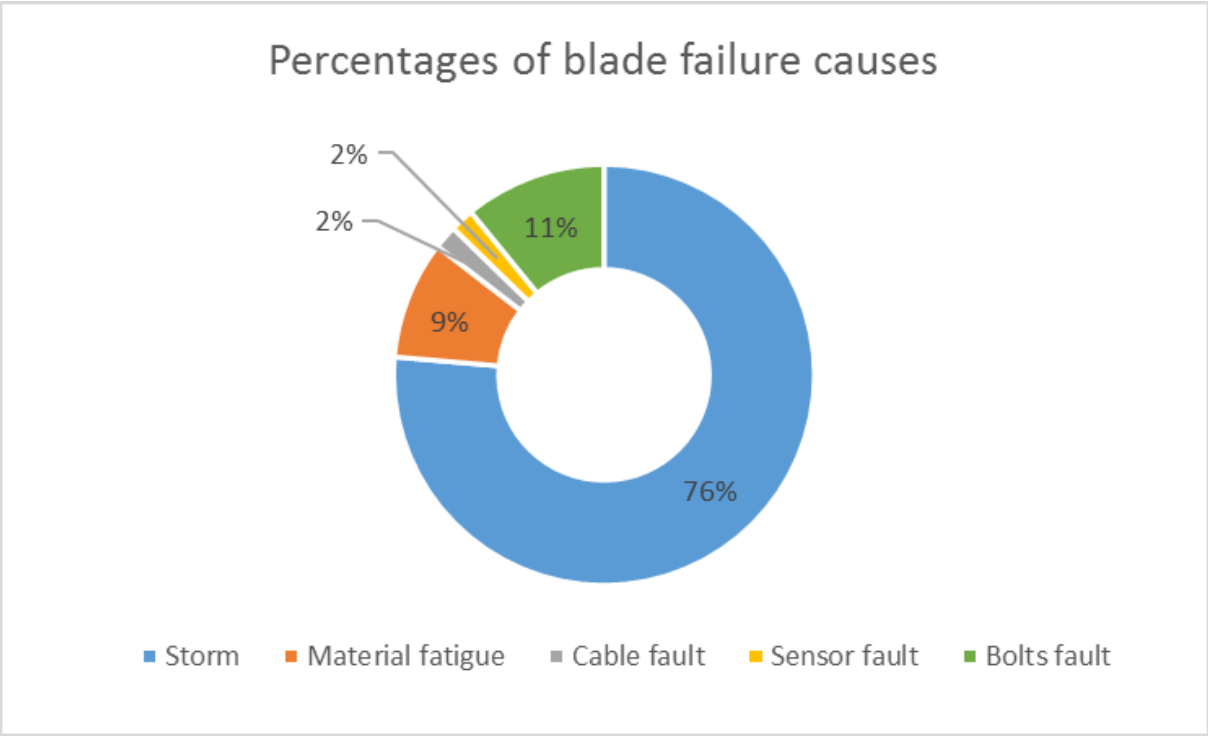


Figure 5-2. Percentages of blade failure causes

Considering the known causes of blade failures, which account for 29% of the overall failure rate, it is seen that 76% are due to storm, 11% are bolt and fastener faults, 9% are due to material fatigue, and 2% are cable and sensor faults. As a result of these failures and risks, results such as blade break, falling, damage to the blade, bending of the blade were encountered.

The percentage shares of the causes of generator failures are shown Figure 5.3 below.

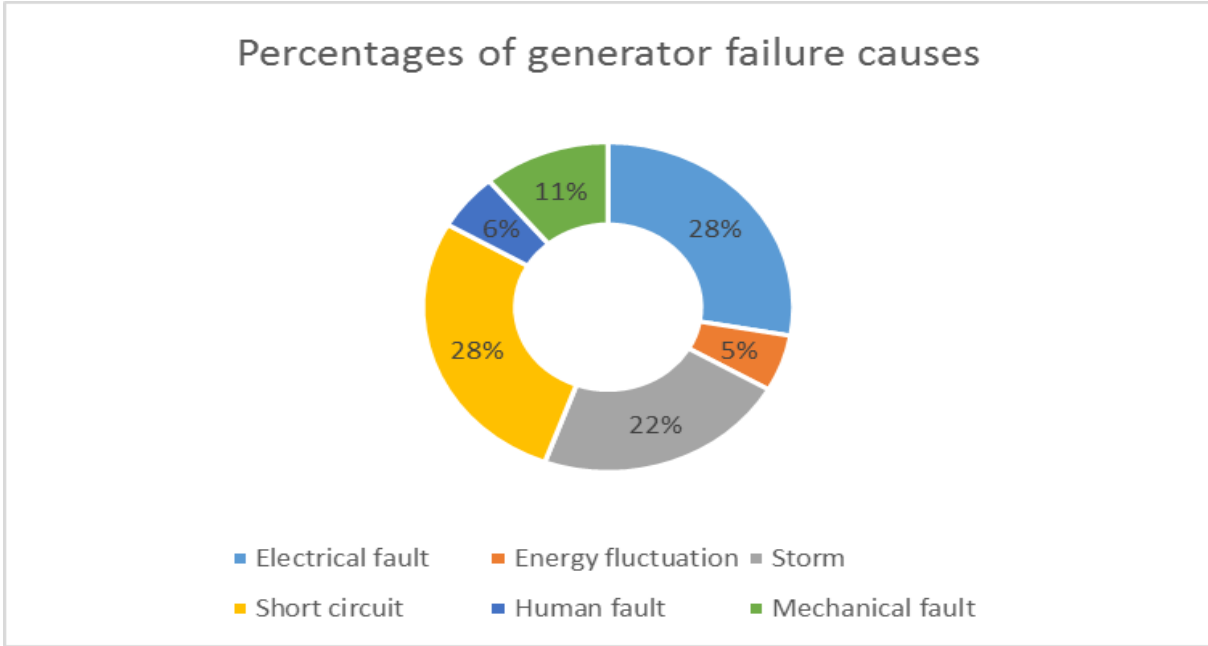


Figure 5-3. Percentages of generator failure causes

When the known causes of the generator failure data obtained are examined, the percentage of failure causes is as seen in figure 5.3. Short circuit and electrical faults are seen to contribute with 28%. Electrical faults include faults made in the electrical panel, voltage conditioning fault, converter fault, for more detailed information, see Appendix-A. It is seen that the failure rate in the generator due to storms is 22%, mechanical faults represent 11%, human faults are 6% and energy fluctuations are 5%. The vast majority of generator failures result in fire.

The failure cause percentages of structural failures with overall failure percentage of 24% are shown in Figure 5.4 as follows.

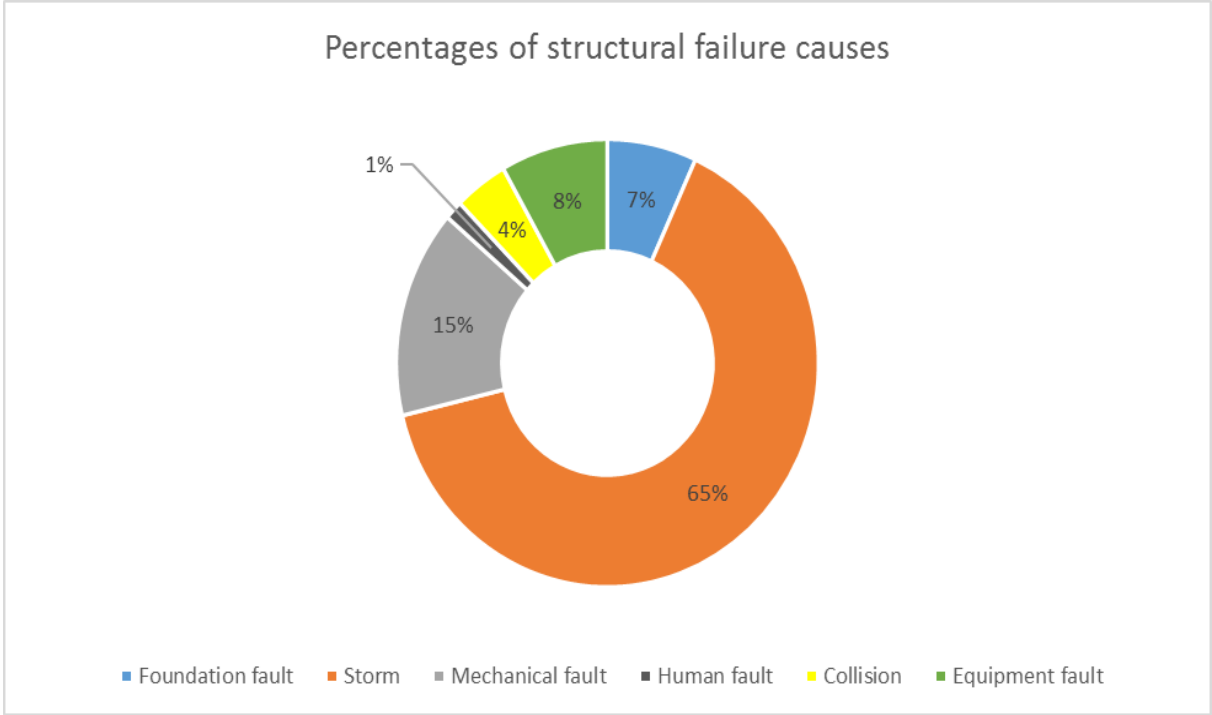


Figure 5-4. Percentages of structural failure causes

When the percentiles of the known causes of structural failures are examined, wind turbines were damaged due to storm with 63% in the first place, mechanical failures such as misalignments and stabilization faults are 15%, high maintenance costs, faults such as missing mechanical parts are equipment failures 8%. 4% is collision and 1% is human fault. More detailed information can be seen in Appendix-A. The vast majority of structural failures result in the collapse of wind turbines.

In Figure 5.5, percentiles of the causes of gearbox failures, which constitute 6% of general failures, are shown. There was no need to show the causes of ice form failure, lightning, and temperature and environmental failures that make up the remainder of the faults.

The main problem of gearbox failure causes is oil leakage with 40%. It was seen that the braking system and material fatigue represents 20%, the faults in the bearing 15%, and the failure and risk situations as a result of the storm with 5%.

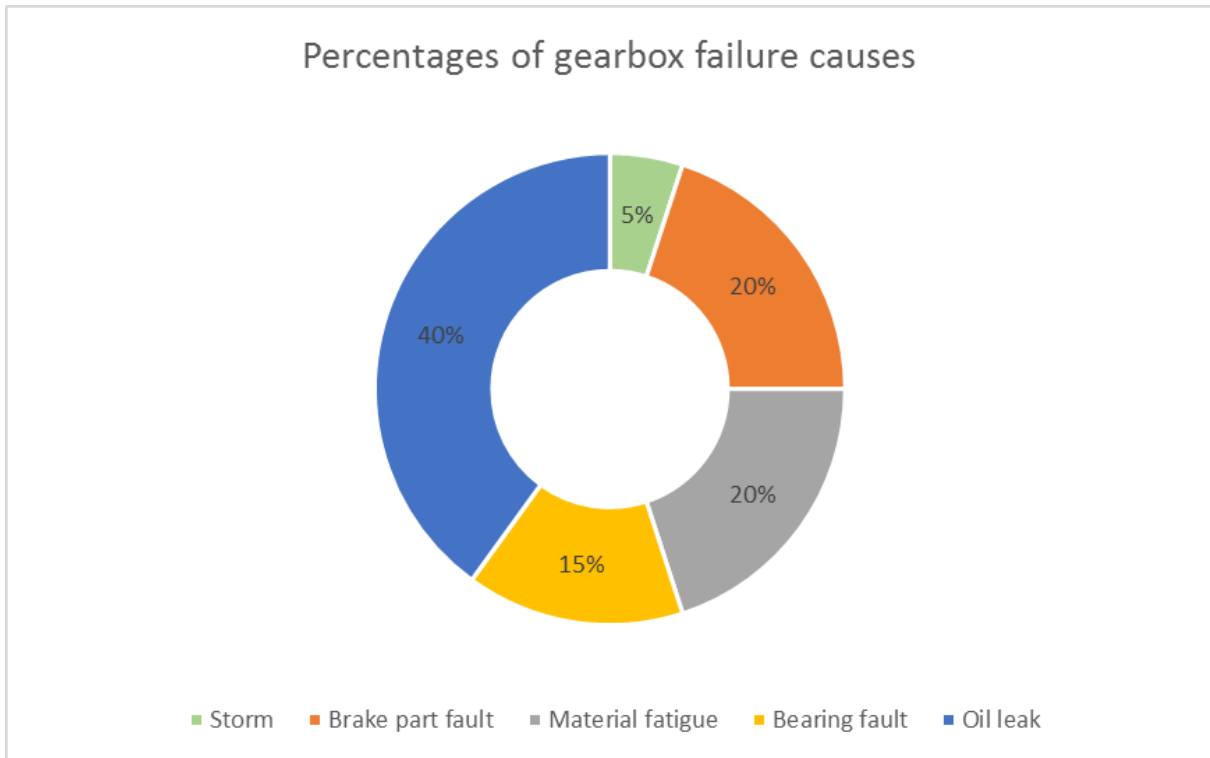


Figure 5-5. Percentages of gearbox failure causes

Another analysis focused on the distribution of failures by country, as shown in Figure 5.6. The countries USA, Germany, UK and Canada constitute the majority of the failures in the dataset. Because the research is conducted and reported in English and the search terms are in English, it is likely that there will be a large number of English-speaking countries represented in the full dataset. However, it was not possible during the study period to extend the search to other languages.

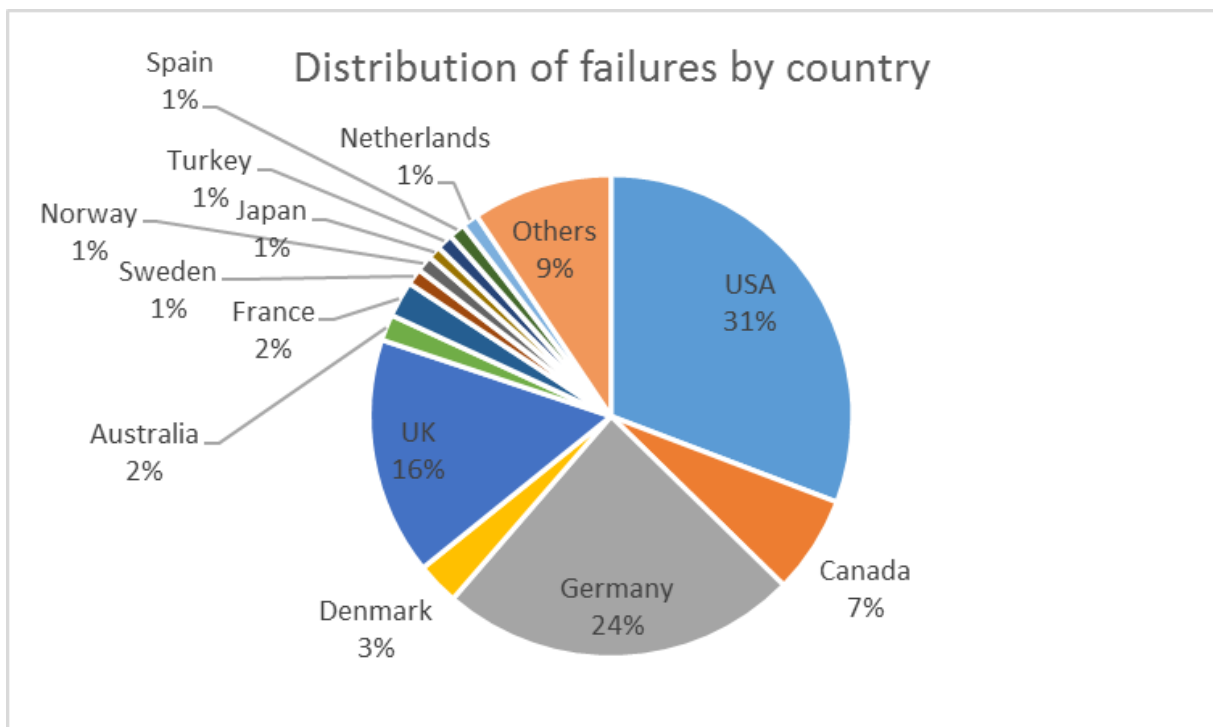


Figure 5-6. Distribution of failures by country

Considering the distribution of faults by country, USA is in the first place with 31%, in the second place by Germany with 24%, in the third place by the UK with 16%, in the fourth place by Canada with 7%, and in the fifth place by Denmark with 3%. More detailed information can be found in Appendix A.

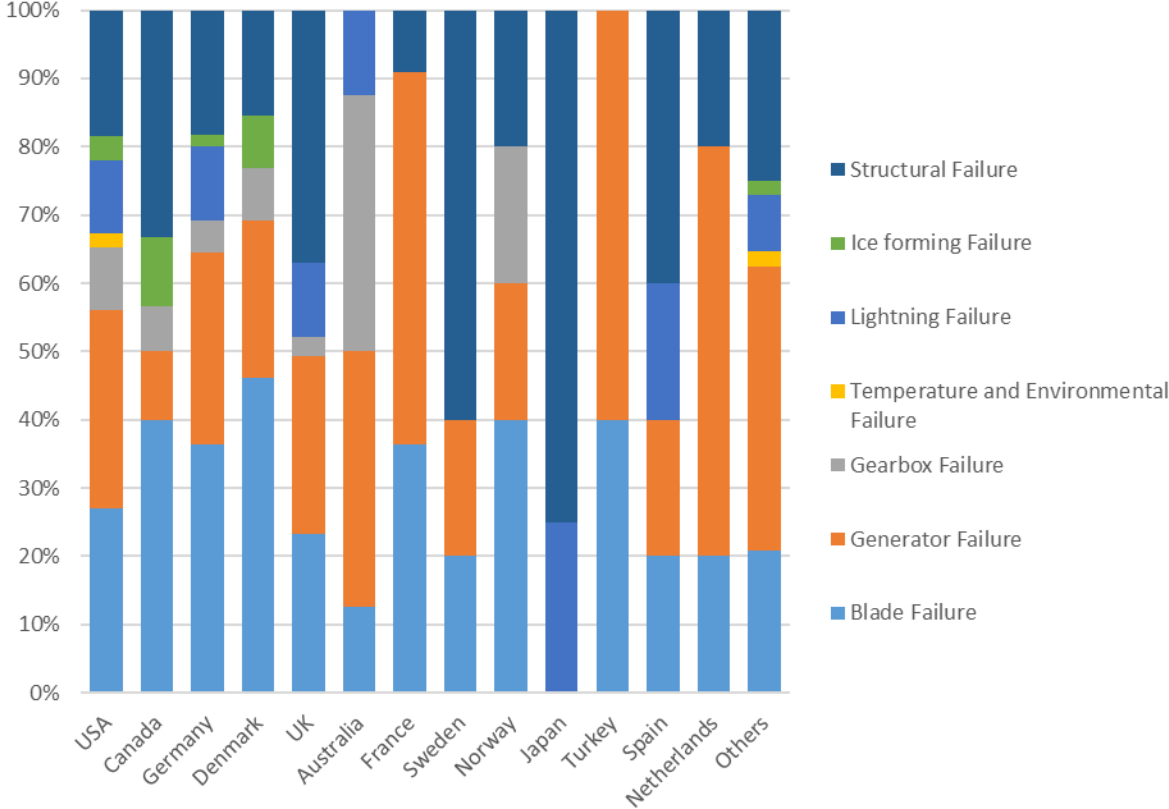


Figure 5-7. Failure types of rates by country

According to the collected and analyzed data, the distribution ratio of the failure types according to the countries is given in Figure 5.7.

Countries (Total Cases)	Blade Failure	Generator Failure	Gearbox Failure	Temperature and Environmental Failure	Lightning Failure	Ice forming Failure	Structural Failure
USA (141)	27%	29%	9%	2%	11%	4%	18%
Canada (30)	40%	10%	7%	0%	0%	10%	33%
Germany (110)	36%	28%	5%	0%	11%	2%	18%
Denmark (13)	46%	23%	8%	0%	0%	8%	15%
UK (73)	23%	26%	3%	0%	11%	0%	37%
Australia (8)	13%	38%	38%	0%	13%	0%	0%
France (11)	36%	55%	0%	0%	0%	0%	9%
Sweden (5)	20%	20%	0%	0%	0%	0%	60%
Norway (5)	40%	20%	20%	0%	0%	0%	20%
Japan (4)	0%	0%	0%	0%	25%	0%	75%
Turkey (5)	40%	60%	0%	0%	0%	0%	0%
Spain (5)	20%	20%	0%	0%	20%	0%	40%
Netherlands (5)	20%	60%	0%	0%	0%	0%	20%
Others (43)	21%	42%	0%	2%	8%	2%	25%

Table 5-2. Percentages of failure types by countries

In Table 5.2, the distributions by country are examined in detail. Blade failures, generator and structural failures seem to be leading as a result of examining the distributions in countries with high number of data, such as USA, Germany and the United Kingdom.

Another analysis is the failure rates of wind turbine types. There are 29 offshore wind turbines and 429 onshore wind turbines in the dataset with covers 458 cases, this detail is evaluated as a comment in the next chapter. Failure rates of offshore and onshore wind turbines are shown in Figure 5.8.

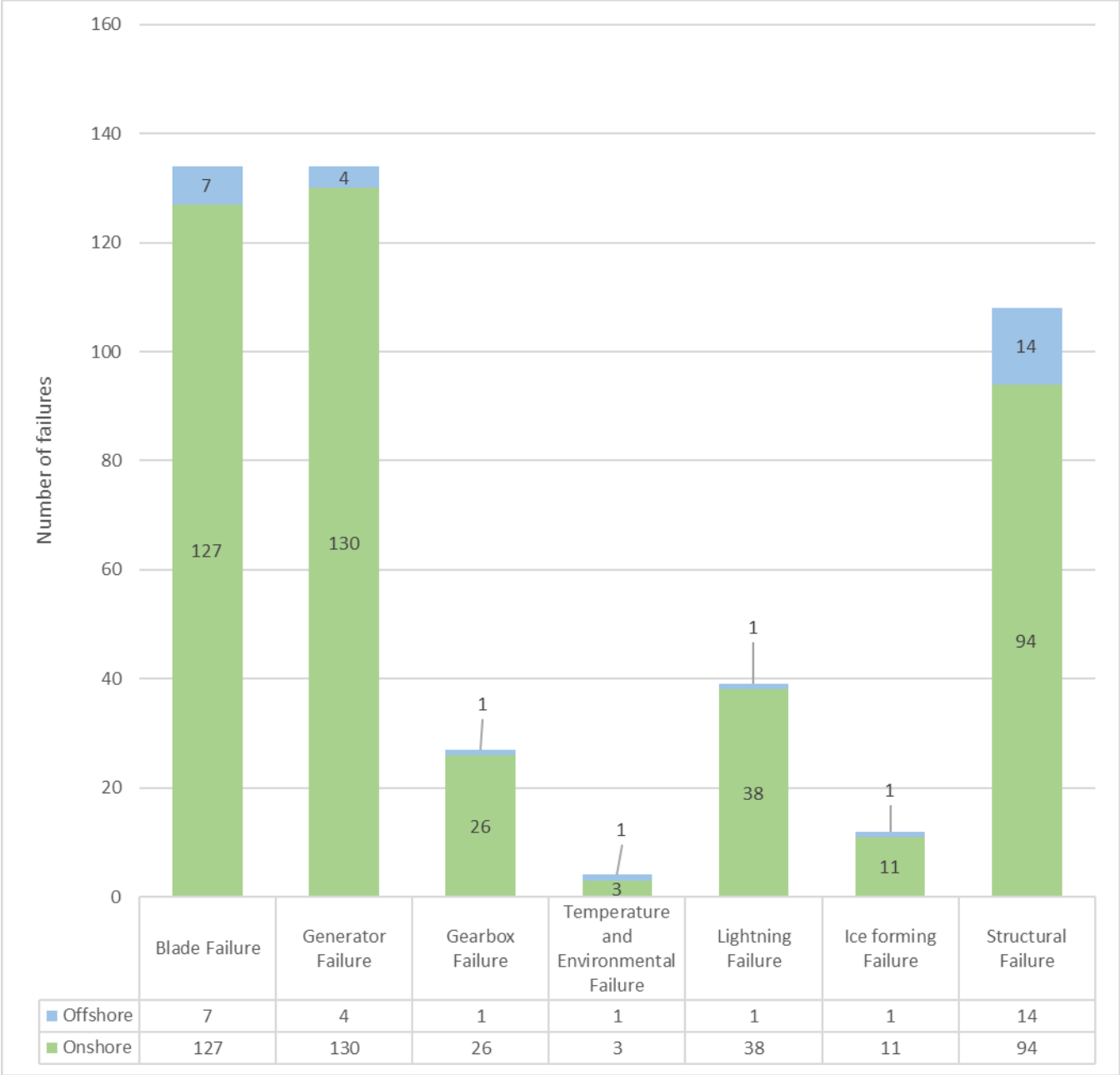


Figure 5-8. Failure rates of offshore and onshore wind turbines

Types of failures of offshore wind turbines are followed by firstly structural failures with 14 cases, blade failures with 7 cases, and generator failures with 4 cases. In other failure types, there is 1 case each.

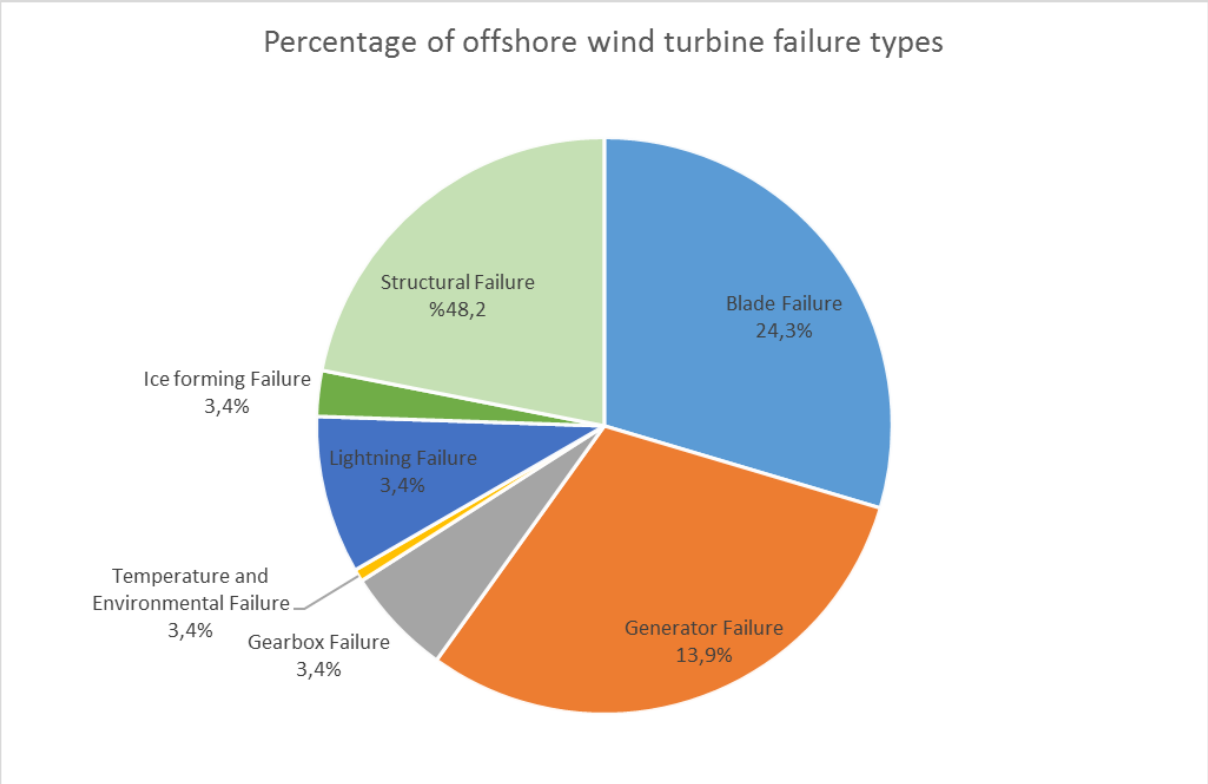


Figure 5-9. Percentage of offshore wind turbine failure types

The percentage of offshore wind turbine failure types is shown in Figure 5.9. Structural failures take the biggest share with 48.2%, followed by blade failures with 24.3% and generator failures with 13.9%. The remaining faults represent 3.4% each.

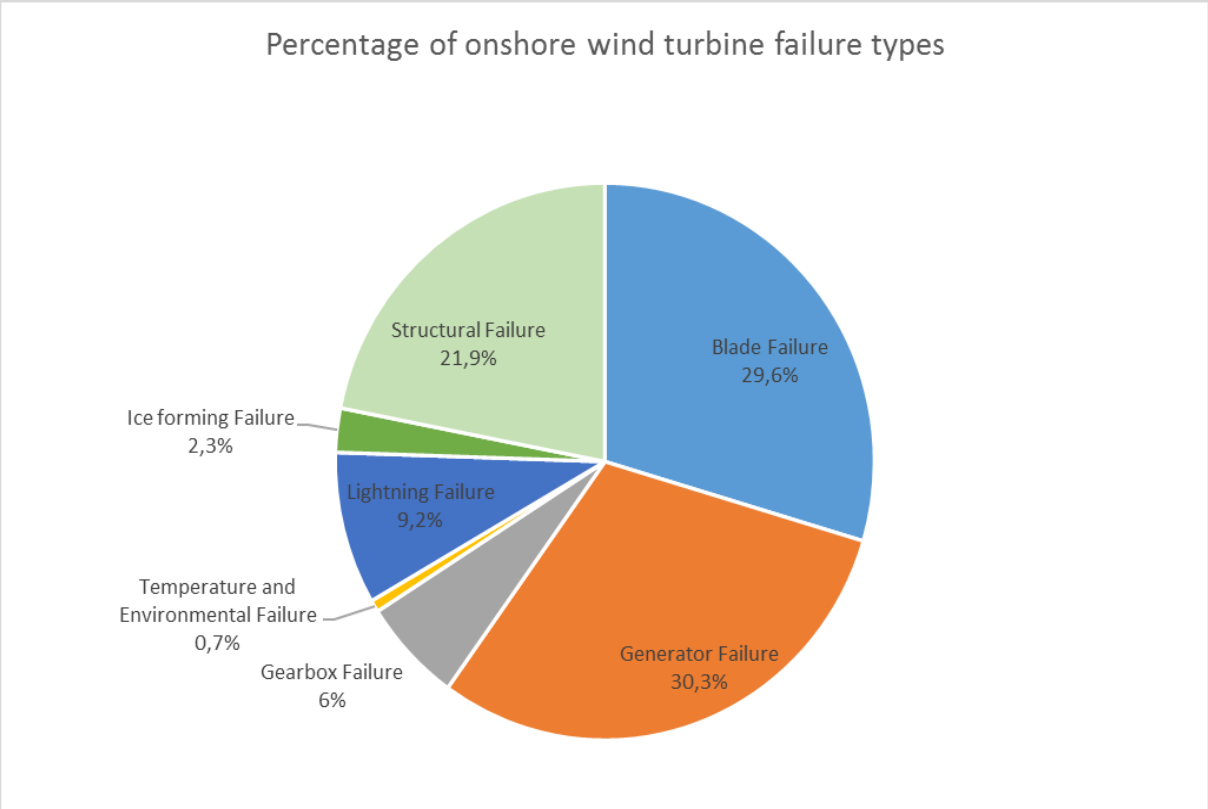


Figure 5-10. Percentage of onshore wind turbine failure types

The percentage of onshore wind turbine failure types is shown in Figure 5.10. Generator failures ranked first with 30.3%, followed by blade failures with 29.6%, structural failures with 21.9%, lightning with 9.2%, gearbox failures with 6%, ice forming failure with 2.3% and finally temperature and environmental failures are included with 0.7%.

Failure Type	Failure Cause	Failure Effect
Blade Failure	<ul style="list-style-type: none"> • Storm • Material fatigue • Cable fault • Sensor fault • Bolt fault 	<ul style="list-style-type: none"> • Fall down • Bend • Crack • Break • Stop operation
Generator Failure	<ul style="list-style-type: none"> • Electrical fault • Storm • Energy fluctuation • Short circuit • Human fault • Mechanical fault 	<ul style="list-style-type: none"> • Fire • Noisy operation • Stop operation • Oil leak • Explosion
Gearbox Failure	<ul style="list-style-type: none"> • Storm • Brake part fault • Material fault • Bearing fault • Oil leak 	<ul style="list-style-type: none"> • Idle blades with high rotation speed • Stop operation • Fire • Blade and gearbox fall down • Gearbox break
Temperature and Environmental Failure	<ul style="list-style-type: none"> • Cold weather • Storm • Sudden weather changes 	<ul style="list-style-type: none"> • Stop operation • Oil leak • Expansion
Lightning Failure	-	<ul style="list-style-type: none"> • Fire • Stop operation • Crack on blades • Damage to turbine
Ice forming Failure	<ul style="list-style-type: none"> • Minus temperature 	<ul style="list-style-type: none"> • Ice forming on blades
Structural Failure	<ul style="list-style-type: none"> • Foundation fault • Storm • Mechanical fault • Human fault • Collision • Equipment fault 	<ul style="list-style-type: none"> • Collapse • Stop operation • Parts fall down • Damage to turbine • Tower bend • Unstable • Remove to turbine • Fire

Table 5-3. Causes and consequences of failure types

In the light of the data obtained, the causes and consequences of the failure types are shown in Table 5.3. Failures represent various risks and damages. These summary statistics, based on

the recent decade of failures, can be used in many ways, including where to focus on reducing failures and in the calculation of rates for risks.

Chapter 6

6 Conclusions and Recommendations

In this chapter, interpretation, recommendation, limitations of the study and measures that can be taken to limit failures are stated according to the results of the analysis. In this study, the failure and risk situations of offshore and onshore wind turbines during operation were examined and an analysis of failures was carried out for the benefit of wind energy research. The applicability of this study should be well demonstrated by a comprehensive processing of wind turbine failure and risk news between 2010 and 2022, collected during the research process.

Discussion on the best mitigating measures that can be taken based on the analysis results in Chapter 5 are presented below.

The vast majority of blade failures are caused by storms. In addition, results such as falling, bending, and cracking of blades as a result of material fatigue, wiring and assembly faults, and sensor faults were observed. It should, however, be noted that data about the age of failed blades is not known and aero-elastic considerations have recently become much more important during the design phase of modern wind turbines to avoid blade failures. Aerodynamic and structural modeling should be integrated according to the location of the offshore and onshore wind turbines, and climatic conditions should be among the main factors to be considered in wind turbine design. Especially in today's wind turbines with large rotor diameters, this issue is of vital importance in order to solve the interaction of fluid and structure and to minimize excessive loads. In addition, the selection of aero-elastic materials should be made under these conditions, and structural health monitoring by using online feedback sensors should be implemented in wind turbine blades that are quite long. In order to avoid these failures and associated risks, regular and routine maintenance work should be carried out, and the time between maintenance should be decreased if necessary.

The main causes of generator failures are electrical faults which include short circuits and energy fluctuation, storms, and mechanical failures. The majority of generator failures result in fire, causing the entire turbine to be out of service. Since it is difficult to intervene in a wind turbine that has started to burn, the fire is expected to burn out. This type of fire not only damages the turbine, but it also damages the environment. Therefore, electric stability analysis of all turbines or wind turbines in the wind farm should be done in order to minimize and overcome generator failures. Thus, energy fluctuations, current differences, and electrical faults that wind turbines are exposed to can be detected. Spectral analysis method can be used to detect winding faults, which are frequently encountered in generator failures, in this method the fault sidebands of a signal in the frequency dimension are looked at. In this way, failures can be detected and tracked. A dynamic state space model can be created to detect short-circuit faults in the stator windings. More information on these methods can be found in the literature. In addition, there are methods that use generator output power to detect and prevent mechanical faults in the generator, such as axial misalignment. Vibration and

generator current analysis can be performed for bearing failures. This situation should be prevented by simultaneous current monitoring and time-frequency monitoring.

The majority of structural failures are caused by storms. In addition, mechanical faults such as assembly and misalignment and foundation faults are among the causes. As a result of these faults, the wind turbine collapses, turbine parts fall, the turbine tower bends or becomes unstable. In order to prevent structural failures, aerodynamic and structural models should be developed, just like for blade failures. The response of the wind turbine to excessive loads should be determined beforehand. This involves collection of wind-data at site to ensure the turbines are designed to withstand the actual wind velocities and the wind turbulence at the site with a low probability of exceedance (normally the design is to withstand the wind conditions having an annual probability of exceedance of 2×10^{-2}). During the wind turbine construction phase, the tower foundation should be made stable and solid. The most suitable wind turbine should be designed in accordance with climatic and environmental conditions, that is, according to the location. With the monitoring of the latest model sensors providing online feedback, the wind turbine should be kept under constant control and routine maintenance should be carried out and the frequency of maintenance periods should be increased if necessary. At the same time, maintenance activities should be considered in order to prevent assembly faults. Assembly faults can be detected by vibration analysis.

The main causes of gearbox failures are oil leakage, braking mechanism faults, and material fatigue. For these reasons, results such as from idle wind turbine blades rotating at high speed and then abruptly stopping the operation, have been encountered. Gearbox diagnostics are difficult. Vibration analysis is performed for fault detection in the gearbox communication chain, but due to the working principle of the gearbox, fault detection with vibration analysis may not always be successful. Therefore, it has been seen that a common amplitude and frequency demodulation analysis method based on the energy separation algorithm has been proposed in the literature. This method can be used to detect wear and damage in the gearbox. In order to detect gearbox failures, apart from routine maintenance, performing these analyses at regular intervals by experts can prevent oil leakage, healthy functioning of the braking system, and material fatigue.

Regarding temperature and environmental failures and ice formation failures, the region where the wind turbines are located is very important. Especially if the seasonal differences in the region where the wind turbines are located are high, it is possible for the wind turbine to be affected by these seasonal differences. It is seen that temperature difference damages turbine parts and the lubrication oil. In order to prevent this situation, it is important to choose the materials and the lubrication suitable for the climatic conditions of the region where the wind turbine is located. The wind turbines operating in the offshore are affected by salt water and salty sea-spray, and all parts are negatively affected. Regular and frequent maintenance is required to prevent this situation. In addition, decrease in the air temperature to minus or close to minus causes ice formation on the blades. In order to prevent this situation, regular maintenance should be done, and operational activities should be stopped, especially in certain seasonal conditions.

Fire and associated damage occur as a result of lightning strikes to wind turbines. There are two different suggestions for mitigating effects of lightning. The first is to protect from lightning, the second is to reduce the effect of lightning. Firstly, a strong grounding system should be established to protect against lightning. It is possible for wind turbines to attract lightning due to their size. For such cases, lightning rods should be used, and the high energy voltage obtained should be removed from the system by grounding. Thus, energy fluctuations, current changes, etc. faults are avoided. Maintenance work should be increased, especially after stormy weather. The second method is to use coordinated surge protection units for power supply systems to prevent lightning damage. These lightning surge arrester systems are effective in the coordinated protection of wind turbine components and in reducing the consequences of sudden voltage differences.

Yaw system failures were not found in the data set. In the obtained data and news sources, the cause of the failure was not specifically stated as yaw system failures. Among the main reasons for this is the indication of such failures as structural failures, technical failures or failures in the engine part. Although this type of failure is rare compared to other types of failures, and the fact that the owners of the companies did not specify the reasons for the failures made it difficult to find a yaw system failure.

As can be seen from the data analysis, the number of offshore wind turbine failures are less than the number of onshore wind turbine failures. Apart from the fact that there are fewer offshore wind turbines and that these turbines represent a newer technology, factors such as the high installation and maintenance costs, the absence of an infrastructure that every country can establish, and the inaccessibility of the place where they will be located explain this situation.

In addition, in this study, it is desired to draw attention again to generator failures. As can be seen from the dataset, generator failures are common, and most generator failures result in fire. A blade can be obtained at a certain, and perhaps high cost as a result of a blade failure, but there is no another choice to wait for the entire turbine to be dismantled by a generator failure resulting in a fire. It is very common to wait for the fire to burn out on its own by taking the surroundings under control.

While obtaining the data, many cases were evaluated, and the appropriate ones were included in this study. While collecting the data, the study period is limited, every case does not overlap with the study, the background reasons for the failures are not specified, the transportation and construction phases (other than the operation) are not included because failures during these phases are not related to the operation of the wind turbines or the subject of this study. Furthermore, processing the data is difficult and time consuming. There are such limitations when collecting data, but the database includes many failures, and all cases have been obtained as a result of serious investigation. According to the results of all this study and analysis, the database should represent the general failure rate in the industry.

This study revealed recurring themes and patterns. This study, which provides new insights, has created clear and unambiguous statements as the results of the analysis. This study and dataset can be used by wind energy industry stakeholders, governments, academic

universities, and communities to make data-driven plans and decisions. Different stakeholders can create information flow and innovations by presenting different views and ideas. In addition, when analyzing these data, results such as downtime, cost, total operational hours or age of defective wind turbines were not evaluated. There is a need, and it is necessary to record all datasets and failures in an international database so that it will be a source that can be used by all mentioned stakeholders and future work.

Although governments, academic universities, communities and non-governmental organizations, and all other stakeholders, have their own reasons for adopting green energy, they should focus more on the issue of wind turbine failures. This study can support different stakeholders by facilitating discussions and interactions, giving ideas on this issue. It can be the inspiration to create a large database and additional insights for future studies. Similar analysis can shed light on offshore and onshore wind power. Preventive actions can be adopted to reduce the occurrence and negative consequences of these failures. The research can be a reference for studies such as which measures can be taken in which region, and which measures can be taken in which country. In our increasingly digitalized age, it may be possible to avoid such risks and failures by using much more digital and robotic monitoring systems for the future.

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Appendix-A Failures Data

Turbine No.	Year	Month	Day	Wind Turbine Location	Location	Country	Failure Location	Failure Type	Failure Cause	Failure Effect	Type
1	2019	July	23	Klickitat Wind Turbine	Washington	USA	Generator	Generator failure	Mechanical misalignment in the generator	Wind turbine fire	Onshore
2	2009	May	4	Tehachapi Wind Turbine	California	USA	Gearbox	Gearbox failure	Failure of braking in the gearbox that regulates the rotational speed	Idle blades with high rotation speed	Onshore
3	2010	February	15	RCMP, Amherst	Nova Scotia	Canada	Electrical Panel	Generator failure	Storm	Fire in electrical panel	Onshore
4	2010	February	18	Caribou Wind park, Bathurst	New Brunswick	Canada	Blades	Ice forming failure	Cold weather	Ice forming on blades	Onshore
5	2010	March	8	Hennickendorf	Brandenburg	Germany	Rotor	Blade failure	Storm	Collapse of the rotor in construction step	Onshore
6	2010	April	10	Bostrup	Nedergård	Denmark	Nacelle	Generator failure	-	Wind turbine fire	Onshore
7	2010	September	18	Lincoln County	Nebraska	USA	Blade	Lightning failure	Ligtining	Blade break	Onshore
8	2010	May	7	Shabbona	Illinois	USA	Blade	Blade failure	-	Bent at the base and split along its length	Onshore
9	2022	April	28	Thorney wind turbine	Thorney	UK	Generator	Generator failure	-	Fire	Onshore
10	2010	December	23	Roedsand-2 offshore wind park	Baltic Sea	Denmark	Blades	Ice forming failure	Cold weather	Ice forming on blades	Offshore
11	2010	June	3	Horns Rev 1 offshore wind park	Offshore North Sea	Denmark	Structural	Structural failure	There is a fault in the wind turbine foundation	Turbine towers to slip	Offshore
12	2010	July	16	Portland, Dorset	England	UK	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
13	2010	July	26	Wotton	England	UK	Electrical Panel	Generator failure	Fault in inverter	Noisy operation	Onshore
14	2010	August	9	Elkhorn Ridge	Nebraska	USA	Nacelle	Lightning failure	Lightning	Fire and stop operation	Onshore
15	2010	August	11	Hobart	Tasmania	Australia	Gearbox	Gearbox failure	Failure of braking in the gearbox that regulates the rotational speed	Idle blades	Onshore
16	2010	August	17	Gunfleet Sands Offshore Wind Farm	England	UK	Gearbox	Gearbox failure	Corroded bearings	Stop operation	Offshore
17	2010	September	14	Willmar	Minnesota	USA	Gearbox	Gearbox failure	Oil leak in gearbox	Stop operation	Onshore
18	2010	September	19	Rocheft-en-Valdaine windpark	Drome	France	Generator	Generator failure	-	Wind turbine fire	Onshore
19	2010	October	28	Wales	Wales	UK	Nacelle	Generator failure	-	Wind turbine fire	Onshore
20	2010	November	19	Starfish Hill Windfarm, Cape Jervis	South Australia	Australia	Generator	Generator failure	Mechanical misalignment in the generator	Wind turbine fire	Onshore
21	2010	November	30	Perkins	Ohio	USA	Blade	Blade failure	Bolts on one of the blades broke	Dropped blade	Onshore
22	2010	December	2	Pigeon	Michigan	USA	Blade	Blade failure	Blades used and worn for many years	Dropped blade	Onshore
23	2010	March	23	Whitelee	Scotland	UK	Blade	Blade failure	-	Dropped blade	Onshore
24	2011	January	6	Nuttby mountain	Nova Scotia	Canada	Structural	Structural failure	The foundations were built wrong	-	Onshore
25	2011	February	15	Bathurst	New Brunswick	Canada	Blade	Ice forming failure	Cold weather	Ice forming on blades	Onshore
26	2011	March	2	St.Cloud	Minnesota	USA	Blade	Blade failure	Blade structure and material	Crack on the blade	Onshore
27	2011	March	16	Willmar	Minnesota	USA	Generator	Generator failure	The failure of voltage conditioning electronics	Stop operation	Onshore
28	2011	March	17	Rugby	North Dakota	USA	Gearbox	Gearbox failure	Failure of braking in the gearbox that regulates the rotational speed	Collapse rotor	Onshore

29	2011	March	25	Forked River	New Jersey	USA	Blade	Blade failure	Three loose blades	Stop operation	Onshore
30	2011	April	11	Western Reserve High School, Berlin Center	Ohio	USA	Structural	Structural failure	Fatigued bolts	Collapse turbine	Onshore
31	2011	April	15	Hardscrabble wind project, Herkimer County	New York	USA	Structural	Structural failure	Weak wind turbine foundation	Stop operation	Onshore
32	2011	April	23	Kahuku	Hawaii	USA	Battery Storage	Generator failure	-	Fire	Onshore
33	2011	April	27	Exhibition Place	Toronto	Canada	Gearbox	Gearbox failure	Bearing that has worn out prematurely	Stop operation	Onshore
34	2011	June	20	Kirtorf	Hesse	Germany	Structural	Structural failure	-	Collapse turbine	Onshore
35	2011	July	6	Lincoln County	Minnesota	USA	Structural	Structural failure	Storm	Tower bent down	Onshore
36	2011	August	3	McBain	Michigan	USA	Nacelle	Generator failure	-	Fire	Onshore
37	2011	August	13	Scout Moor Wind farm	England	UK	Electrical Panel	Generator failure	Fault in electrical panel	Fire	Onshore
38	2011	September	3	Northwood	Iowa	USA	Blades	Blade failure	Storm	Blade break and bend	Onshore
39	2011	September	7	Bay City	Michigan	USA	Gearbox	Gearbox failure	-	Stop operation	Onshore
40	2011	September	8	Southern India	Southern India	India	Blade	Blade failure	Failure of a bolt connecting the rotor assembly to the nacelle	Blade fall down	Onshore
41	2011	October	17	Tom Ridge Environmental Center	Pennsylvania	USA	Structural	Structural failure	Storm	Collapse turbine	Onshore
42	2011	December	9	Ardrossan windfarm, North Ayrshire	Scotland	UK	Structural	Structural failure	Storm	Collapse turbine	Onshore
43	2011	December	1	Scapegoat Hill, Halifax Road	England	UK	Structural	Structural failure	Storm	Collapse turbine	Onshore
44	2011	December	1	Offshore	Bergen	Norway	Structural	Structural failure	Storm	Collapse turbine	Offshore
45	2011	December	8	Coldingham, Berwickshire	Scotland	UK	Structural	Structural failure	Storm	Collapse turbine	Onshore
46	2011	April	14	Galveston	Texas	USA	Blade	Blade failure	-	Blade fall down	Onshore
47	2011	November	4	Sarakitomanai Windfarm, Wakkanai	Hokkaido	Japan	Nacelle	Lightning failure	Lightning	Wind turbine fire	Onshore
48	2012	November	29	California Ridge wind farm, Vermilion and Champaign	Illinois	USA	Blade	Blade failure	-	Broke blade	Onshore
49	2012	October	26	Crofton Bluffs wind farm	Nebraska	USA	Nacelle	Generator failure	-	Wind turbine fire	Onshore
50	2012	September	13	Huaneng	Xinjiang	China	Structural	Structural failure	Storm	Collapse turbine	Onshore
51	2012	August	3	University of Delaware, Lewes	Delaware	USA	Blade	Lightning failure	Lightning	One of the turbine's three blades is damaged	Onshore
52	2012	January	6	Huddersfield	England	UK	Structural	Structural failure	Storm	Collapse turbine	Onshore
53	2012	July	31	Riverside County	California	USA	Generator	Generator failure	-	Fire	Onshore
54	2012	July	30	Tehachapi	California	USA	Gearbox	Gearbox failure	Leak oil	Fire	Onshore
55	2012	June	25	Panagudi	Tamil Nadu	India	Generator	Generator failure	Short circuit	Fire	Onshore
56	2012	June	20	Deutschkreutz Windpark	Burgenland	Austria	Blade	Blade failure	-	Broke rotor blade	Onshore
57	2012	June	19	Rankin Inlet	Nunavut	Canada	Blade	Blade failure	-	Broke rotor blade	Onshore
58	2012	January	13	Llandinam, Powys	Wales	UK	Blade	Blade failure	-	Broke rotor blade	Onshore
59	2012	June	6	Northern Ireland	Northern Ireland	UK	Blade	Blade failure	The nuts that hold the turbine to the hub completely sheared (Design)	Broke rotor blade	Onshore
60	2012	January	20	Shrewsbury	England	UK	Structural	Structural failure	Storm	Collapse turbine	Onshore

61	2012	May	19	Harper County	Kansas	USA	Structural	Structural failure	Storm	Collapse turbine	Onshore
62	2012	January	12	Bathurst	New Brunswick	Canada	Blade	Ice forming failure	Cold weather	Ice forming on blades	Onshore
63	2012	April	25	Van Wert County	Ohio	USA	Blade	Blade failure	-	Broke rotor blade	Onshore
64	2012	April	2	Gross Eilstorf wind farm	Lower Saxony	Germany	Nacelle	Generator failure	-	Wind turbine fire	Onshore
65	2012	March	6	Cowley Ridge	Alberta	Canada	Structural	Structural failure	Mechanical misalignment shaft	Collapse turbine	Onshore
66	2012	January	15	Holmesfield	England	UK	Structural	Structural failure	Storm	Broke blade	Onshore
67	2012	February	25	Göls	Neusiedl am See	Austria	Nacelle	Generator failure	-	Fire	Onshore
68	2013	December	24	Schäcksdorf	Brandenburg	Germany	Blade	Blade failure	Storm	Blade fall down	Onshore
69	2013	December	18	Burradale windfarm, Shetland	England	UK	Blade	Lightning failure	Lightning	Hole in the blade	Onshore
70	2013	December	17	Kumeyaay	California	USA	Nacelle	Generator failure	-	Fire	Onshore
71	2013	December	6	Vlatten energy park	North Rhine-Westphalia	Germany	Structural	Structural failure	Storm	Collapse tower	Onshore
72	2013	December	7	Döhlen	Saxony	Germany	Structural	Structural failure	Storm	Collapse nacelle	Onshore
73	2013	December	7	Deining	Bavaria	Germany	Structural	Structural failure	Storm	Blade fall down	Onshore
74	2013	December	6	Corkmore windfarm, Killybegs	Donegal	Ireland	Structural	Structural failure	Storm	Blade fall down	Onshore
75	2013	November	26	Stipa Naya wind power facility	La Ventosa	Mexico	Nacelle	Generator failure	-	Fire	Onshore
76	2013	November	26	Tudela, Fustinana	Navarra	Spain	Nacelle	Generator failure	-	Fire	Onshore
77	2013	December	6	California Ridge windfarm	Illinois	USA	Structural	Structural failure	Storm	Blade fall down	Onshore
78	2013	November	21	Orangeville Windfarm	New York	USA	Blade	Blade failure	-	Broke blade	Onshore
79	2013	November	13	Echo Windpark, Huron County	Michigan	USA	Blade	Blade failure	-	Broke blade	Onshore
80	2013	November	6	Stateline windfarm, Touchet	Washington	USA	Structural	Structural failure	Storm	Collapse turbine	Onshore
81	2013	October	31	Wind 2 Project, Huron County	Michigan	USA	Blade	Lightning failure	Lightning	Damaged blade	Onshore
82	2013	October	31	Piet de Wit windfarm	South Holland	Netherlands	Generator	Generator failure	Short circuit	Fire	Onshore
83	2013	October	11	Belfast Harbour	Northern Ireland	UK	Tower	Structural failure	Human fault	Collapse tower	Offshore
84	2013	September	25	Honghaiwan Windfarm	Guangdong	China	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
85	2013	September	4	Dotlingen	Lower Saxony	Germany	Blade	Blade failure	-	Broke blade	Onshore
86	2013	September	4	Dunhobby, Highlands	Scotland	UK	Structural	Structural failure	Storm	Blade fall down and broke	Onshore
87	2013	August	17	Balikesir	Balikesir	Turkey	Generator	Generator failure	Short circuit	Fire	Onshore
88	2013	August	8	Beidenfleth- Grosskampen	Schleswig-Holstein	Germany	Electrical Panel	Generator failure	-	Fire	Onshore
89	2013	July	14	Forward Energy Windfarm	Wisconsin	USA	Nacelle	Generator failure	-	Fire	Onshore
90	2013	July	16	Genoa	Michigan	USA	Structural	Structural failure	-	Turbine parts break off	Onshore
91	2013	July	8	Kuanyuan wind farm	Taoyuan	Taiwan	Blade	Lightning failure	Lightning	Damaged blade	Onshore
92	2013	July	7	Kochi	Kerala	India	Blade	Blade failure	Bolts on one of the blades broke	Dropped blade	Onshore
93	2013	July	2	Glenconway Windfarm, Limavady	Northern Ireland	UK	Electrical Panel	Generator failure	Electrical fault	Fire	Onshore
94	2013	May	16	Ocotillo Express Windproject, Imperial County	California	USA	Blade	Blade failure	Loose mounting of blades bolts to rotor	Dropped blade	Onshore
95	2013	May	13	Wapsipinicon Wind project, Dexter	Minnesota	USA	Blade	Lightning failure	Lightning	Broke blade	Onshore
96	2013	April	2	Kingsbridge Windfarm, Goderich	Ontario	Canada	Nacelle	Generator failure	-	Fire	Onshore
97	2013	March	23	Maas, Ardara	Donegal	Ireland	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
98	2013	March	15	Tokyo	Kyoto	Japan	Structural	Structural failure	Metal fatigue	Collapse tower	Onshore
99	2013	March	11	Thumb Wind Park, Sigel, Huron County	Michigan	USA	Blade	Blade failure	-	Blade fall down and broke	Onshore
100	2013	February	6	Bodmin Moor, St Clether	England	UK	Blade	Lightning failure	Lightning	Damaged blade	Onshore

101	2013	January	29	East Ash Farm, Bradworthy, North Devon	England	UK	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
102	2013	January	29	Brusseton	England	UK	Blade	Blade failure	Storm	Blade fall down and broke	Onshore
103	2013	October	29	Windpark Wanzleben- Rodensleben, Klein Rodensleben	Saxony-Anhalt	Germany	Nacelle	Generator failure	-	Fire	Onshore
104	2013	October	13	Windpark Sande, Wilhelmshaven	Lower Saxony	Germany	Generator	Generator failure	-	Fire	Onshore
105	2013	September	26	Windpark Regiowind, Lahrer Langenhard	Baden-Württemberg	Germany	Nacelle	Generator failure	-	Fire	Onshore
106	2013	April	12	Gross Bisdorf	Mecklenburg-Vorpommern	Germany	Nacelle	Generator failure	-	Fire	Onshore
107	2014	December	23	Wind Complex Cerro Chato Eletrosul	Rio Grande do Sul	Brazil	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
108	2014	December	29	Lely Windfarm	Medemblik	Netherlands	Blade	Blade failure	-	Blade fall down	Offshore
109	2014	December	20	Rhue Stoer Hall, Highlands	Scotland	UK	Structural	Structural failure	Storm	Collapse turbine	Onshore
110	2014	December	16	Kossdorf Windfarm	Brandenburg	Germany	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
111	2014	December	8	Amayo Complex	Rivas	Nicaragua	Nacelle	Generator failure	-	Fire	Onshore
112	2014	November	21	Howard Township	Ontario	Canada	Blade	Blade failure	-	Blade parts fall down	Onshore
113	2014	November	14	New Deer	Scotland	UK	Structural	Structural failure	-	Collapse wind turbine	Onshore
114	2014	November	11	Little Cheyne Court, Brookland	England	UK	Blade	Lightning failure	Lightning	Blade break and bend	Onshore
115	2014	November	11	Isle of Wight	England	UK	Blade	Blade failure	Storm	Blade fall down	Onshore
116	2014	November	5	Wyoming County	Pennsylvania	USA	Blade	Blade failure	-	Blade fall down	Onshore
117	2014	October	24	Melanos	Island of Chios	Greece	Nacelle	Generator failure	-	Fire	Onshore
118	2014	October	25	Fenner	New York	USA	Generator	Generator failure	-	Fire	Onshore
119	2014	October	23	Rowley Regis	England	UK	Blade	Blade failure	Storm	Blade fall down and broke	Onshore
120	2014	October	23	Roslev	Roslev	Denmark	Blade	Blade failure	-	Blade fall down and broke	Onshore
121	2014	October	20	Senate Wind farm, Cox Mountain	Texas	USA	Nacelle	Generator failure	-	Fire	Onshore
122	2014	September	19	Yttre Stengrund, Offshore	Offshore	Sweden	Structural	Structural failure	Hard to find spare parts	Stop operation	Offshore
123	2014	January	5	Söhre, Kassel	Hesse	Germany	Blade	Lightning failure	Lightning	Blade fall down and broke	Onshore
124	2014	January	9	Antheny	Ardennes	France	Nacelle	Generator failure	-	Fire	Onshore
125	2014	August	14	Off Walney	Offshore	UK	Structural	Structural failure	Collision	Wind turbine damage	Offshore
126	2014	August	8	Thumb Wind Park, Huron County	Michigan	USA	Blade	Lightning failure	Lightning	Blade damaged	Onshore
127	2014	July	22	Ocotillo Wind Express	California	USA	Gearbox	Gearbox failure	Oil Leak	Stop operation	Onshore
128	2014	July	13	Wanzleben-Börde, Seehausen	Saxony-Anhalt	Germany	Nacelle	Generator failure	-	Fire	Onshore
129	2014	July	14	Lowell	Vermont	USA	Blade	Lightning failure	Lightning	Blade damaged	Onshore
130	2014	July	6	Cappaboy Beg Windfarm	Cork	Ireland	Nacelle	Generator failure	-	Fire	Onshore
131	2014	June	24	Boyd	Texas	USA	Nacelle	Lightning failure	Lightning	Fire	Onshore
132	2014	June	21	Horseshoe Bend Windpark	Montana	USA	Blade	Lightning failure	Lightning	Blade bend	Onshore
133	2014	June	15	Ruthton	Minnesota	USA	Nacelle	Lightning failure	Lightning	Turbine damaged	Onshore
134	2014	January	14	Redcar Offshore	England	UK	Blade	Blade failure	-	Stop operation	Offshore
135	2014	May	8	Prairie Breeze Wind Energy farm	Nebraska	USA	Blade	Blade failure	Structural failure	Broke blade	Onshore
136	2014	April	27	Prairie Breeze Wind Energy Center, Boone County	Nebraska	USA	Blade	Blade failure	Storm	Blade fall down	Onshore
137	2014	April	26	Juchen	North Rhine-Westphalia	Germany	Structural	Structural failure	The foundations were built wrong	Stop operation	Onshore
138	2014	January	13	Pheasant Run Windproject, Brookfield	Michigan	USA	Nacelle	Gearbox failure	Oil Leak	-	Onshore
139	2014	March	16	Locust Ridge Windfarm, Mahonoy	Pennsylvania	USA	Nacelle	Generator failure	-	Fire	Onshore
140	2014	February	25	Dunlo	Pennsylvania	USA	Blade	Blade failure	-	Blade break and bend	Onshore

141	2014	February	23	Echtrop	North Rhine-Westphalia	Germany	Generator	Generator failure	-	Fire	Onshore
142	2014	February	12	Lynnway	Massachusetts	USA	Nacelle	Ice forming failure	Cold weather	Ice forming on blades	Onshore
143	2014	February	13	Anglesey	Wales	UK	Generator	Generator failure	Storm	Fire	Onshore
144	2014	January	29	Jutland	Northern Jutland	Denmark	Blade	Blade failure	-	Blade failure	Onshore
145	2014	August	21	Pori	Reposaari	Finland	Blade	Blade failure	Fast wind	Blade damaged and idle	Onshore
146	2014	April	1	Oster-Ohrstedt	Schleswig-Holstein	Germany	Blade	Blade failure	-	Blade break and bend	Onshore
147	2014	November	16	Raposeira Wind Farm, near Budens	Vila do Bispo	Portugal	Electrical Panel	Generator failure	Short circuit	Fire	Onshore
148	2015	January	3	Screggagh Windfarm, Tyrone	Northern Ireland	UK	Structural	Structural failure	-	Collapse wind turbine	Onshore
149	2015	January	5	Woodlawn Windfarm, Lake George	New South Wales	Australia	Gearbox	Gearbox failure	Main bearing failure	Stop operation	Onshore
150	2015	January	8	Tursillagh Wind farm, Tralee	Co Kerry	Ireland	Blade	Blade failure	-	Blade fall down	Onshore
151	2015	December	29	Richfield Windfarm	Bridgetown	Ireland	Blade	Lightning failure	Lightning	Blade damaged	Onshore
152	2015	January	11	Königsmoor wind farm,Aurich, Pfalzdorf district	Lower Saxony	Germany	Nacelle	Generator failure	-	Fire	Onshore
153	2015	January	15	Ocotillo Wind Express Windfarm, Ocotillo	California	USA	Nacelle	Generator failure	-	Fire	Onshore
154	2015	January	16	Morso	Western Jutland	Denmark	Gearbox	Gearbox failure	Storm	Blade and gearbox fall down	Onshore
155	2015	December	28	Lemnhult Windfarm	Jönköping	Sweden	Structural	Structural failure	-	Collapse wind turbine	Onshore
156	2015	February	11	Henry County	Illinois	USA	Blade	Blade failure	-	Blade break	Onshore
157	2015	March	3	El Tablado, Zaragoza	Aragon	Spain	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
158	2015	March	11	East Youlstone, Bradworthy	England	UK	Blade	Lightning failure	Lightning	Blade damaged	Onshore
159	2015	April	10	Tüükri	Viru-Nigula	Estonia	Generator	Generator failure	-	Fire	Onshore
160	2015	April	15	Dillon Road	California	USA	Structural	Structural failure	Failure of braking in the gearbox that regulates the rotational speed	Parts of turbines fall down	Onshore
161	2015	April	22	Mäkikangas Windfarm	Pyhäjoki	Finland	Blade	Blade failure	-	Blade break	Onshore
162	2015	January	19	South Branch Windfarm, Brinston	Ontario	Canada	Gearbox	Gearbox failure	Main bearing failure	Stop operation	Onshore
163	2015	May	15	Westboro	Missouri	USA	Nacelle	Generator failure	-	Fire	Onshore
164	2015	June	1	Ganschendorf, Mecklenburg	Mecklenburg-Vorpommern	Germany	Nacelle	Lightning failure	Lightning	Fire	Onshore
165	2015	June	3	Todmorden Moor, Bacup	England	UK	Nacelle	Generator failure	-	Fire	Onshore
166	2015	June	3	Mittenwalde	Brandenburg	Germany	Nacelle	Generator failure	-	Fire	Onshore
167	2015	June	25	Nordsee Ost Windfarm	Off North Sea	Germany	Blade	Blade failure	-	Blade fall down	Offshore
168	2015	July	10	Demmin, Mecklenburg	Mecklenburg-Vorpommern	Germany	Blade	Blade failure	Storm	Blade break	Onshore
169	2015	July	24	Bayonne	New Jersey	USA	Generator	Generator failure	-	Stop operation	Onshore
170	2015	August	3	Grand Bend	Ontario	Canada	Blade	Blade failure	Storm	Blade bend	Onshore
171	2015	August	7	(Thumb) McKinley Township	Michigan	USA	Blade	Lightning failure	Lightning	Blade damaged	Onshore
172	2015	August	12	Taichung wind farm	Taipei	Taiwan	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
173	2015	August	24	Santilly	Loiret	France	Nacelle	Generator failure	-	Fire	Onshore
174	2015	September	3	Hallet 2 wind farm	South Australia	Australia	Gearbox	Gearbox failure	Material fatigue and failure	Gearbox break	Onshore
175	2015	October	10	Bluewater	Ontario	Canada	Blade	Blade failure	-	Materials Falling	Onshore
176	2015	October	31	Midtjället Vindkraft	Fitjar	Norway	Nacelle	Generator failure	-	Fire	Onshore
177	2015	November	16	Hunsrück	Rhineland-Palatinate	Germany	Blade	Blade failure	Storm	Blade fall down and broke	Onshore
178	2015	December	1	Paludan Flak wind project	Samso	Denmark	Blade	Blade failure	-	Blades fall down	Offshore
179	2015	November	27	Cogar	Oklahoma	USA	Blade	Ice forming failure	Cold weather	Ice forming on blades	Onshore
180	2015	November	13	Ménil-la-Horgne	Meuse	France	Blade	Blade failure	-	Blades fall down	Onshore
181	2015	May	27	Emington	Illinois	USA	Nacelle	Generator failure	-	Fire	Onshore
182	2015	December	3	Heynitz wind farm, Nossen	Saxony	Germany	Blade	Blade failure	-	Blade brake	Onshore
183	2016	January	4	Corme	Coruna	Spain	Blade	Blade failure	-	Blades fall down	Onshore
184	2016	January	20	Bradworthy, North Devon	England	UK	Structural	Structural failure	-	Collapse wind turbine	Onshore
185	2016	January	24	Kremsdorf	Burgenland	Austria	Trafo	Generator failure	-	Fire	Onshore
186	2016	January	27	Paderborn	North Rhine-Westphalia	Germany	Blade	Blade failure	-	Blades fall down	Onshore
187	2016	January	29	Mojave	California	USA	Gearbox	Gearbox failure	-	Idle blades	Onshore
188	2016	February	8	Wales	Wales	UK	Converter	Generator failure	-	Fire	Onshore
189	2016	February	8	Dineault	Brittany	France	Blade	Blade failure	Storm	Blade brake	Onshore
190	2016	February	9	Meenanilta 3 Windfarm	Donegal	Ireland	Blade	Lightning failure	Lightning	Blade damaged	Onshore

191	2016	February	11	Fenner	New York	USA	Blade	Blade failure	-	Blade fall down	Onshore
192	2016	February	19	Sigel Township, Huron County	Michigan	USA	Blade	Blade failure	-	Blade break	Onshore
193	2016	February	22	Dorpen, North Emsland	Lower Saxony	Germany	Blade	Blade failure	Storm	Blade break and bend	Onshore
194	2016	February	25	Harvest Windfarm, Huron County	Michigan	USA	Structural	Structural failure	-	Collapse wind turbine	Onshore
195	2016	April	12	Ferndale	Ontario	Canada	Structural	Structural failure	-	Wind turbine bend	Onshore
196	2016	May	1	Kloster Lehnin	Brandenburg	Germany	Blade	Lightning failure	Lightning	Blade break	Onshore
197	2016	May	10	Ahaus-Graes	North Rhine-Westphalia	Germany	Nacelle	Generator failure	-	Fire	Onshore
198	2016	May	11	Lamar	Colorado	USA	Gearbox	Gearbox failure	Wear and tear on the gearbox	Stop operation	Onshore
199	2016	May	13	University of Minnesota Duluth	Minnesota	USA	Gearbox	Gearbox failure	Failure of braking in the gearbox that regulates the rotational speed	Idle blades	Onshore
200	2016	May	23	Paderborn	North Rhine-Westphalia	Germany	Blade	Blade failure	Storm	Blade fall down and broke	Onshore
201	2016	May	27	Whitewater	California	USA	Nacelle	Generator failure	-	Fire	Onshore
202	2016	May	28	Brookfield Windpark, Sebawaing Township	Michigan	USA	Gearbox	Gearbox failure	Main bearing failure	Stop operation	Onshore
203	2016	June	13	Shrewsbury	England	UK	Structural	Structural failure	Storm	Unstable	Onshore
204	2016	July	2	Hardscrabble Windfarm, Fairfield	New York	USA	Blade	Lightning failure	Lightning	Blade damaged	Onshore
205	2016	July	7	Lathen, Emsland	Lower Saxony	Germany	Gearbox	Gearbox failure	-	Fire	Onshore
206	2016	July	18	Oldersbek, Nordfriesland	Schleswig-Holstein	Germany	Nacelle	Generator failure	-	Fire	Onshore
207	2016	August	1	Juktan	Blaisjön	Sweden	Nacelle	Generator failure	-	Fire	Onshore
208	2016	August	5	Scholen, Diepholz	Lower Saxony	Germany	Nacelle	Generator failure	-	Fire	Onshore
209	2016	August	22	Point Tupper	Nova Scotia	Canada	Structural	Structural failure	-	Collapse wind turbine	Onshore
210	2016	August	28	Isselburg	North Rhine-Westphalia	Germany	Blade	Lightning failure	Lightning	Fire	Onshore
211	2016	October	5	Auwahi Wind project, Maui	Hawaii	USA	Nacelle	Gearbox failure	-	Parts of turbines fall down	Onshore
212	2016	November	4	Deerfield wind project, Bloomfield Township	Michigan	USA	Blade	Blade failure	-	Blade brake and bend	Onshore
213	2016	October	27	Belen	Hatay	Turkey	Nacelle	Generator failure	-	Fire	Onshore
214	2016	October	31	Lynn County	Texas	USA	Nacelle	Generator failure	-	Fire	Onshore
215	2016	November	9	Dreihausen	North Rhine-Westphalia	Germany	Blade	Blade failure	Material fatigue	Blades fall down	Onshore
216	2016	November	11	Bear Creek	Pennsylvania	USA	Nacelle	Generator failure	-	Fire	Onshore
217	2016	November	21	Ocotillo Wind Energy, Ocotillo	California	USA	Structural	Structural failure	Loads	Collapse wind turbine	Onshore
218	2016	December	1	Balsams	New Hampshire	USA	Blade	Ice forming failure	Cold weather	Ice forming on blades	Onshore
219	2016	December	2	Sliabh Bawn	Roscommon	Ireland	Nacelle	Generator failure	-	Fire	Onshore
220	2016	December	2	Block Island	Rhode Island	USA	Generator	Generator failure	Human fault	Stop operation	Offshore
221	2016	December	3	Izmir	Izmir	Turkey	Blade	Blade failure	-	Blade fall down	Onshore
222	2016	December	11	Süderholz, Grischow	Mecklenburg-Vorpommern	Germany	Structural	Structural failure	-	Collapse wind turbine	Onshore
223	2016	December	24	Scar End Farm, Rossendale	England	UK	Blade	Blade failure	Storm	Blades fall down	Onshore
224	2016	December	29	Sitten Windfarm, Döbeln	Saxony	Germany	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
225	2016	April	10	Arecleoch Windfarm, Ayrshire	England	UK	Nacelle	Generator failure	-	Fire	Onshore
226	2016	December	29	Bindesbøl	Tarm	Denmark	Blade	Blade failure	Storm	Blade fall down	Onshore
227	2016	February	10	Embuaca wind farm	Ceará	Brazil	Structural	Structural failure	-	Collapse wind turbine	Onshore
228	2017	January	4	Grand Etang	Nova Scotia	Canada	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
229	2017	March	10	Zichow, Uckermark	Brandenburg	Germany	Blade	Blade failure	Sensor fault	Blade bend	Onshore
230	2017	January	6	Hamina	Kymenlaakso	Finland	Generator	Generator failure	-	Fire	Onshore

231	2017	January	7	Knabs Ridge farm, Harrogate, Yorkshire	England	UK	Nacelle	Generator failure	-	Fire	Onshore
232	2017	January	11	Ringer Hill Windfarm, Elk Lick	Pennsylvania	USA	Blade	Blade failure	-	Blade fall down	Onshore
233	2017	January	18	Nurlu	Hauts-de-France	France	Blade	Blade failure	-	Blade fall down	Onshore
234	2017	January	20	Kilgallioch Windfarm, South Ayrshire	Scotland	UK	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
235	2017	February	24	Laubersreuth,Hof, Munchberg	Bavaria	Germany	Blade	Blade failure	Storm	Blade bend	Onshore
236	2017	March	14	Whiteleehill wind farm, Ayrshire	Scotland	UK	Hub	Structural failure	-	Hub fall down	Onshore
237	2017	March	16	Zultenberg- Seubersdorf wind farm, Kulmbach	Bavaria	Germany	Gearbox	Gearbox failure	Oil Leak	Stop operation	Onshore
238	2017	April	12	Whitelee wind farm	Scotland	UK	Nacelle	Generator failure	-	Fire	Onshore
239	2017	April	15	Fiefbergen,Plön district (near Kiel)	Schleswig-Holstein	Germany	Nacelle	Generator failure	-	Fire	Onshore
240	2017	April	24	Barrow, Cumbrian coast, Irish Sea	Offshore	UK	Structural	Structural failure	Collision	Wind turbine damage	Offshore
241	2017	April	25	Bornish wind farm	Ontario	Canada	Blade	Blade failure	-	Blade damaged	Onshore
242	2017	May	12	Juchitan	Tehuantepec peninsula	Mexico	Generator	Generator failure	Storm	Oil leak	Onshore
243	2017	June	2	Breckinridge wind farm, Enid	Oklahoma	USA	Blade	Blade failure	-	Blade break	Onshore
244	2017	June	8	Endeavor I wind energy centre, Osceola County	Iowa	USA	Generator	Generator failure	-	Fire	Onshore
245	2017	June	13	Steele Flats wind farm, Diller	Nebraska	USA	Structural	Structural failure	-	Collapse wind turbine	Onshore
246	2017	June	27	Shannon Wind Farm	Texas	USA	Structural	Structural failure	-	Collapse wind turbine	Onshore
247	2017	June	22	Norway	Prince Edward Island	Canada	Blade	Blade failure	One of the inside cables detached	Stop operation	Onshore
248	2017	July	17	SPIC Binhai North offshore Wind farm	Off Jiangsu	China	Structural	Generator failure	-	Fire broke out on an offshore substation platform	Offshore
249	2017	July	20	Lincoln County	Kansas	USA	Nacelle	Generator failure	-	Fire	Onshore
250	2017	July	30	Caddo-Comanche County	Oklahoma	USA	Nacelle	Generator failure	-	Fire	Onshore
251	2017	August	1	Windpark Wörbzig, Pfaffendorf, Großwülknitz	Saxony-Anhalt	Germany	Nacelle	Lightning failure	Lightning	Fire	Onshore
252	2017	September	10	Wyoming Energy Center, Evanston	Wyoming	USA	Nacelle	Generator failure	-	Fire	Onshore
253	2017	November	8	Mawson research station	Mawson research station	Antarctica	Hub	Structural failure	-	Hub fall down	Onshore
254	2017	May	16	Dargelin, Greifswald	Mecklenburg-Vorpommern	Germany	Blade	Blade failure	Storm	Blade fall down	Onshore
255	2017	October	31	Westerholt	Lower Saxony	Germany	Nacelle	Generator failure	-	Fire	Onshore
256	2017	January	3	Neu Wulmstorf , Hamburg	Lower Saxony	Germany	Structural	Structural failure	-	Collapse wind turbine	Onshore
257	2017	January	13	Bad Rappenau	Baden-Württemberg	Germany	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
258	2017	February	2	Melle	Lower Saxony	Germany	Structural	Structural failure	Collision	Stop operation	Onshore
259	2017	February	7	Aquilonia	Campania	Italy	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
260	2017	September	28	Windpark Zeewolde	Flevoland	Netherlands	Nacelle	Generator failure	-	Fire	Onshore
261	2017	September	29	Deerfield Wind Energy Project, Huron County	Michigan	USA	Blade	Blade failure	-	Blade break	Onshore
262	2017	October	9	Sigel Wind Park	Michigan	USA	Blade	Blade failure	-	Blade break	Onshore
263	2017	October	9	Ravne 1	Pag	Croatia	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
264	2017	December	19	Gols	Burgenland	Austria	Nacelle	Generator failure	Short circuit	Fire	Onshore
265	2017	December	28	Südharz	Saxony-Anhalt	Germany	Gearbox	Gearbox failure	-	Idle blades	Onshore
266	2017	January	2	Bocholt	North Rhine-Westphalia	Germany	Blade	Ice forming failure	Cold weather	Ice forming on blades	Onshore
267	2018	January	25	Chatham-Kent	Ontario	Canada	Structural	Blade failure	Blade Failure	Collapse wind turbine	Onshore
268	2018	February	2	Addison	Texas	USA	Blade	Blade failure	-	Blade fall down	Onshore
269	2018	January	2	Vendée	Bouin	France	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
270	2018	May	30	Ransonmoor wind farm, Cambridgeshire	England	UK	Nacelle	Generator failure	Storm	Fire	Onshore

271	2018	January	4	Volksdorf, Schaumburg	Lower Saxony	Germany	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
272	2018	January	4	Portela de Unhais	Pampilhosa da Serra	Portugal	Nacelle	Generator failure	-	Fire	Onshore
273	2018	January	10	Willmar	Minnesota	USA	Nacelle	Structural failure	Equipment failure	Stop operation	Onshore
274	2018	January	16	Crockbrack Hill, Inishowen	Donegal	Ireland	Blade	Lightning failure	Lightning	Blade damaged	Onshore
275	2018	January	23	Mount Wachusett Community College	Massachusetts	USA	Blade	Ice forming failure	Cold weather	Ice forming on blades	Onshore
276	2018	February	23	Bent Tree Wind Farm, Hartland	Minnesota	USA	Blade	Ice forming failure	Cold weather	Ice forming on blades	Onshore
277	2018	March	29	Trebover Farm, Llanychaer, Wales	Wales	UK	Gearbox	Gearbox failure	-	Stop operation	Onshore
278	2018	April	2	University of Maine, Presque Isle	Maine	USA	Nacelle	Generator failure	-	Fire	Onshore
279	2018	April	5	Hog Creek Windfarm, Hardin County	Ohio	USA	Blade	Blade failure	Storm	Blade break	Onshore
280	2018	April	25	Tule Wind Project	San Diego	USA	Cable	Structural failure	Faulty underground power cable	Stop operation	Onshore
281	2018	April	26	Alpha Ventus offshore wind farm	Off North Sea	Germany	Nacelle	Structural failure	-	Nacelle fall down	Offshore
282	2018	May	4	Bruce Power Visitors Centre, Tiverton	Ontario	Canada	Blade	Blade failure	Storm	Blade damaged	Onshore
283	2018	May	10	Dio-et-Valquieres Windfarm	Hérault	France	Blade	Blade failure	Storm	Blade fall down	Onshore
284	2018	May	21	Locust Ridge II Windfarm, Union Township	Pennsylvania	USA	Nacelle	Generator failure	-	Fire	Onshore
285	2018	July	12	Great Falls College MSU	Montana	USA	Structural	Structural failure	Expensive maintenance	Stop operation	Onshore
286	2018	July	19	Chitradurga	Karnataka	India	Blade	Blade failure	Storm	Blade fall down	Onshore
287	2018	August	3	Monts d'Ain park	Izenave	France	Nacelle	Generator failure	-	Fire	Onshore
288	2018	August	16	Haeckel Hill, Whitehorse	Yukon	Canada	Structural	Structural failure	Material fatigue	Stop operation	Onshore
289	2018	August	24	Awaji Island	Hyogo Prefecture	Japan	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
290	2018	September	3	Zearing	Iowa	USA	Blade	Blade failure	Storm	Blade damaged	Onshore
291	2018	September	20	St. Olaf, Northfield	Minnesota	USA	Blade	Blade failure	Storm	Blade damaged	Onshore
292	2018	October	12	Carnkie, Cornwall	England	UK	Blade	Blade failure	Storm	Blade fall down and broke	Onshore
293	2018	October	22	Maui	Hawaii	USA	Nacelle	Generator failure	Energy fluctuation	Stop operation	Onshore
294	2018	October	28	Furukshima	Fukushima Prefecture	Japan	Structural	Structural failure	Expensive maintenance	Removal of turbine	Offshore
295	2018	October	31	Nakhon Ratchasima and Chaiyaphum	Nakhon Ratchasima and Chaiyaphum	Thailand	Structural	Structural failure	-	Collapse wind turbine	Onshore
296	2018	November	14	Ravenshoe	Queensland	Australia	Generator	Generator failure	-	Fire	Onshore
297	2018	November	15	Ömossa Windfarm	Kristinestad	Finland	Blade	Blade failure	-	Stop operation	Onshore
298	2018	August	30	Hinterm Busch, Haren , Emsland	Lower Saxony	Germany	Nacelle	Generator failure	-	Fire	Onshore
299	2018	December	8	Big Turtle Windfarm, Huron	Michigan	USA	Blade	Blade failure	-	Blade fall down and broke	Onshore
300	2018	November	30	Vinningen Windfarm	Rhineland-Palatinate	Germany	Generator	Generator failure	-	Fire	Onshore
301	2018	March	12	Offshore, Kent	England	UK	Blade	Blade failure	Eroding blades	Stop operation	Offshore
302	2018	January	20	Bilster Berg, Pömbesen, Bad Driburg	North Rhine-Westphalia	Germany	Blade	Blade failure	Storm	Blade fall down and broke	Onshore
303	2018	April	26	Anholt offshore Windfarm	Kattegat	Denmark	Blade	Blade failure	Edge erosion	Stop operation	Offshore
304	2018	June	29	Confederation Beach Park, Hamilton	Ontario	Canada	Structural	Structural failure	Base problem	Collapse wind turbine	Onshore
305	2018	July	27	Lynemouth Windfarm, Ashington	England	UK	Nacelle	Generator failure	-	Fire	Onshore
306	2018	September	5	Sheldon Wind Project, Wyoming County	New York	USA	Generator	Generator failure	-	Explosion	Onshore
307	2018	December	10	Gau-Bickelheim Windfarm	Rhineland-Palatinate	Germany	Blade	Blade failure	-	Blade fall down and broke	Onshore
308	2018	August	12	Krackow	Mecklenburg-Vorpommern	Germany	Nacelle	Generator failure	-	Fire	Onshore
309	2018	May	11	Löcknitz, Bergholz	Mecklenburg-Vorpommern	Germany	Blade	Lightning failure	Lightning	Fire	Onshore
310	2018	January	18	Wildpoldsried, Allgäu	Bavaria	Germany	Blade	Lightning failure	Lightning	Blade fall down and broke	Onshore

311	2018	April	11	Bad Lausick, Frohburg	Saxony	Germany	Nacelle	Lightning failure	Lightning	Fire	Onshore
312	2018	May	23	Standenbühl , Breunigweiler	Rhineland-Palatinate	Germany	Blade	Lightning failure	Lightning	Fire	Onshore
313	2018	May	27	Steinweg, Ostermarsch	Lower Saxony	Germany	Trafo	Structural failure	-	Fire	Onshore
314	2018	June	10	Oberhavel, Altiüdersdorf	Brandenburg	Germany	Nacelle	Lightning failure	Lightning	Fire	Onshore
315	2018	October	11	Langenthal	Hesse	Germany	Gearbox	Gearbox failure	Oil Leak	Stop operation	Onshore
316	2018	June	26	Wrohm, Dithmarschen	Schleswig-Holstein	Germany	Nacelle	Generator failure	-	Fire	Onshore
317	2018	June	26	Trendelburg, Langenthal	Hesse	Germany	Nacelle	Generator failure	Technical fault	Fire	Onshore
318	2018	July	25	Highway 65	Iowa	USA	Blade	Blade failure	Storm	Blade bend	Onshore
319	2018	August	8	Block Island	Rhode Island	USA	Cable	Structural failure	Exposed cable	Stop operation	Offshore
320	2018	August	28	Wartenberg Windfarm	Hesse	Germany	Trafo	Structural failure	Storm	Transformer damaged	Onshore
321	2018	September	26	Wüstenbuch, Schlüsselfeld	Bavaria	Germany	Blade	Blade failure	Storm	Blade fall down and broke	Onshore
322	2018	October	25	Bockelwitz, Leisnig	Saxony	Germany	Gearbox	Gearbox failure	-	Idle blades	Onshore
323	2018	October	29	Hofa Windfarm, Al Mazar	Irbid	Jordan	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
324	2018	December	26	Freudenberg	North Rhine-Westphalia	Germany	Structural	Structural failure	-	Nacelle part fall down	Onshore
325	2018	April	30	Fond du Lac County	Wisconsin	USA	Gearbox	Gearbox failure	Oil Leak	Stop operation	Onshore
326	2019	May	31	Casa Mesa Wind Energy Center	New Mexico	USA	Structural	Structural failure	-	Collapse wind turbine	Onshore
327	2019	May	22	Chisholm View 2 Windfarm, Hunter	Oklahoma	USA	Structural	Structural failure	-	Collapse wind turbine	Onshore
328	2019	September	27	Butterwick Wind farm, Sedgfield	England	UK	Nacelle	Generator failure	-	Fire	Onshore
329	2019	July	22	Bickleton, Klickitat County	Washington	USA	Generator	Generator failure	-	Fire	Onshore
330	2019	March	16	Pubnico Point	Nova Scotia	Canada	Nacelle	Generator failure	-	Fire	Onshore
331	2019	September	17	Lal Lal Windfarm, Ballarat	Victoria	Australia	Blade	Lightning failure	Lightning	Blade break	Onshore
332	2019	January	4	Eastern Kings Wind Farm	Prince Edward Island	Canada	Blade	Blade failure	Storm	Blade fall down and broke	Onshore
333	2019	January	16	Südgeorgsfehne, Uplengen	Lower Saxony	Germany	Nacelle	Generator failure	-	Fire	Onshore
334	2019	January	30	Hatay	Yayladağı	Turkey	Nacelle	Generator failure	-	Fire	Onshore
335	2019	January	1	Agerfeldvej	Sørvad	Denmark	Nacelle	Generator failure	-	Fire	Onshore
336	2019	March	15	Nortorf, Steinburg	Schleswig-Holstein	Germany	Blade	Lightning failure	Lightning	Blade fall down and broke	Onshore
337	2019	February	4	Espinhaço de Cão	Aljezur	Portugal	Generator	Generator failure	-	Fire	Onshore
338	2019	April	22	Sumac Ridge Windfarm, Pontypool, Kawartha Lakes	Ontario	Canada	Blade	Blade failure	-	Blade bend	Onshore
339	2019	April	15	Brauel Windfarm, Wriedel	Lower Saxony	Germany	Blade	Blade failure	Storm	Blade fall down and broke	Onshore
340	2019	April	14	Paul's Hill windfarm, Speyside	Scotland	UK	Nacelle	Generator failure	-	Fire	Onshore
341	2019	March	22	Aberdeen Bay Windfarm (Offshore)	Offshore	UK	Structural	Lightning failure	Lightning	Stop operation	Offshore
342	2019	May	22	Garden peninsula	Michigan	USA	Blade	Blade failure	-	Blade break	Onshore
343	2019	June	17	Palm Springs	California	USA	Nacelle	Generator failure	-	Fire	Onshore
344	2019	July	5	Upstream Wind Energy Center, Neligh, Antelope County	Nebraska	USA	Structural	Structural failure	-	Collapse wind turbine	Onshore
345	2019	July	23	Ventos de São Clemente wind complex	Pernambuco	Brazil	Structural	Structural failure	-	Collapse wind turbine	Onshore
346	2019	August	16	Hornsea 1 Offshore Windfarm	England	UK	Power station	Structural failure	Technical fault	Stop operation	Offshore
347	2019	August	27	Mulberry canyon, Taylor County	Texas	USA	Nacelle	Generator failure	-	Fire	Onshore
348	2019	September	4	Town of Denmark, Lewis County	New York	USA	Blade	Lightning failure	Lightning	Blade damaged	Onshore
349	2019	September	30	Brauel Windfarm, Wriedel	Lower Saxony	Germany	Blade	Blade failure	Storm	Blade fall down and broke	Onshore
350	2019	October	1	Kittsee	Burgenland	Austria	Nacelle	Generator failure	-	Fire	Onshore

351	2019	October	12	Ocean Gate, Ocean County	New Jersey	USA	Blade	Blade failure	-	Blade fall down	Onshore
352	2019	October	29	Daluwa	Puttalam	Sri Lanka	Nacelle	Generator failure	-	Fire	Onshore
353	2019	October	31	Diamond Vista Windfarm, Marion County	Kansas	USA	Trafo	Structural failure	Transformer fault	Stop operation	Onshore
354	2019	October	30	Mojave, Kern County	California	USA	Nacelle	Generator failure	-	Fire	Onshore
355	2019	November	7	Rampion Offshore	England	UK	Trafo	Structural failure	Fault in an electrical distribution system	Stop operation	Offshore
356	2019	November	14	Seascale Primary School, Cumbria	England	UK	Structural	Structural failure	-	Parts of turbines fall down	Onshore
357	2019	November	16	Lackawanna	New York	USA	Structural	Structural failure	Equipment failure	Stop operation	Onshore
358	2019	December	9	Jorwert	Friesland	Netherlands	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
359	2019	June	8	Shinn Estate Vineyards, Mattituck	New York	USA	Structural	Generator failure	Electrical fault	Fire	Onshore
360	2019	March	4	Baumholder Windfarm, Hahnweiler	Rhineland-Palatinate	Germany	Blade	Blade failure	Storm	Blade fall down and broke	Onshore
361	2019	January	3	Limouzi nière	Loire-Atlantique	France	Nacelle	Generator failure	-	Fire	Onshore
362	2019	January	11	Riutunkari	Huiku	Finland	Blade	Ice forming failure	Cold weather	Ice forming on blades	Onshore
363	2019	January	18	Bosbüll, Nordfriesland	Schleswig-Holstein	Germany	Nacelle	Generator failure	-	Fire	Onshore
364	2019	January	21	Nordwald, Schoneberg, Soest	North Rhine-Westphalia	Germany	Blade	Blade failure	-	Blade fall down	Onshore
365	2019	February	1	Haraççı garden area, Aliağa	Izmir	Turkey	Blade	Blade failure	Storm	Blade fall down	Onshore
366	2019	February	8	Langenhard, Lahr	Baden-Württemberg	Germany	Nacelle	Generator failure	-	Fire	Onshore
367	2019	February	13	Syke, Jardinghausen	Lower Saxony	Germany	Generator	Generator failure	-	Fire	Onshore
368	2019	February	18	Buehlertann	Baden-Württemberg	Germany	Blade	Ice forming failure	Cold weather	Ice forming on blades	Onshore
369	2019	March	12	Alsdorf	North Rhine-Westphalia	Germany	Blade	Blade failure	Storm	Blade break and bend	Onshore
370	2019	March	17	Wittighausen Windfarm	Baden-Württemberg	Germany	Blade	Blade failure	Storm	Blade fall down and broke	Onshore
371	2019	July	27	Prinzhöfte Windfarm, Schulenberg	Lower Saxony	Germany	Blade	Lightning failure	Lightning	Blade break	Onshore
372	2019	September	19	Dubener Platte Windfarm	Brandenburg	Germany	Structural	Structural failure	-	Collapse wind turbine	Onshore
373	2019	November	5	Summerside	Prince Edward Island	Canada	Blade	Blade failure	Storm	Blade break	Onshore
374	2019	July	2	Kappandagudda, Gadag	Karnataka	India	Blade	Blade failure	Storm	Blade fall down	Onshore
375	2020	January	6	Phong Dien 1 Wind Farm	Tuy Phong District	Vietnam	Nacelle	Generator failure	-	Fire	Onshore
376	2020	January	9	Evia Wind Turbine	Evia	Greece	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
377	2020	January	18	Bodenwerder Wind Farm	Lower Saxony	Germany	Nacelle	Generator failure	-	Fire	Onshore
378	2020	January	21	Cohocton Wind Turbine	Ohio	USA	Blade	Blade failure	-	Blade fall down and broke	Onshore
379	2020	January	31	Wittstock Wind Turbine	Müritz	Germany	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
380	2020	February	11	Leisnig Wind Turbine	Leisnig	Germany	Nacelle	Generator failure	-	Fire	Onshore
381	2020	February	16	Emsdetten Wind Turbine	Emsdetten/Essen	Germany	Blade	Blade failure	Storm	Blade fall down and broke	Onshore
382	2020	February	15	Albhausen Wind Turbine	Albhausen	Germany	Nacelle	Generator failure	-	Fire	Onshore
383	2020	February	23	Taft and Portland Wind Farm	Oregon	USA	Nacelle	Generator failure	-	Fire	Onshore
384	2020	February	28	Stofferstorf Wind Farm	Stofferstorf	Germany	Blade	Blade failure	-	Blade fall down and broke	Onshore
385	2020	March	4	England	England	UK	Blade	Blade failure	-	Parts of turbines fall down	Onshore
386	2020	March	24	Parc de la Bouleste Wind Turbine	Flavin	France	Generator	Generator failure	-	Fire	Onshore
387	2020	April	20	B58 Wind Turbine	Haltern	Germany	Blade	Blade failure	Storm	Blade brake and bend	Onshore
388	2020	May	15	Minsca Wind Farm	Waterbeck	UK	Blade	Blade failure	-	Blade damaged	Onshore
389	2020	June	4	Altenberge Wind Turbine	Altenberge	Germany	Blade	Blade failure	-	Blades fall down	Onshore
390	2020	July	14	Nolan/Taylor County Wind Farm	Nolan/Taylor County	USA	Nacelle	Generator failure	-	Fire	Onshore

391	2020	August	9	Rein in Taufers Wind Turbine	Pustertal	Austria	Nacelle	Generator failure	-	Fire	Onshore
392	2020	August	22	Montaves Wind Farm	Tierras Altas	Spain	Nacelle	Lightning failure	Lightning	Fire	Onshore
393	2020	September	18	Adair County Wind Turbine	Kentucky	USA	Blade	Blade failure	-	Blade fall down	Onshore
394	2020	September	13	Fiefbergen Wind Farm	Fiefbergen	Germany	Nacelle	Generator failure	-	Fire	Onshore
395	2020	September	24	Oswaldtwistle Wind Farm	Oswaldtwistle	UK	Nacelle	Generator failure	-	Fire	Onshore
396	2020	September	18	Tönsen Wind Farm	Tönsen	Sweden	Blade	Blade failure	-	Blade damaged	Onshore
397	2020	October	6	Dundonnell Wind Farm	Victoria	Australia	Blade	Blade failure	-	Blade fall down	Onshore
398	2020	October	12	Schwanebeck Wind Farm	Harz	Germany	Blade	Blade failure	-	Blade fall down	Onshore
399	2020	October	26	89 of the Milligan 1 Wind Farm	Nebraska	USA	Blade	Blade failure	-	Blade break and bend	Onshore
400	2020	November	4	Saitec floating wind turbine	Bilbao	Spain	Structural	Structural failure	Storm	Wind turbine damaged	Offshore
401	2020	November	22	Skellefteå Wind Farm	Jörn	Sweden	Structural	Structural failure	-	Collapse wind turbine	Onshore
402	2020	November	26	Hundhammerfjellet Wind Farm	Nærøysund	Norway	Blade	Blade failure	-	Blade parts fall down	Onshore
403	2020	November	25	Hildesheim Wind Farm	Harsum	Germany	Blade	Blade failure	-	Blade fall down and broke	Onshore
404	2020	November	30	Jesup Wind Turbine	Georgia	USA	Nacelle	Generator failure	-	Fire	Onshore
405	2020	December	22	Cheyenne Wind Farm	Cheyenne	USA	Generator	Generator failure	-	Fire	Onshore
406	2021	January	14	New Town Collage Wind Turbine	New Town	UK	Structural	Structural failure	-	Collapse wind turbine	Onshore
407	2021	January	12	Brökeln Wind Turbine	Brökeln	Germany	Nacelle	Generator failure	-	Fire	Onshore
408	2021	January	21	Jeggeleben Wind Farm	Jeggeleben	Germany	Blade	Blade failure	-	Blades fall down	Onshore
409	2021	February	2	Hamilton Beach Strip Wind Turbine	Ontario	Canada	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
410	2021	February	15	Texas Wind Farm	Texas	USA	Structural	Temperature and Environmental failure	Cold weather	Stop operation	Onshore
411	2021	February	17	South Dakota Wind Farm	South Dakota	USA	Structural	Temperature and Environmental failure	Cold weather	Stop operation	Onshore
412	2021	February	17	Lake Lawtonka Wind Farm	Oklahoma	USA	Structural	Temperature and Environmental failure	Cold weather	Stop operation	Onshore
413	2021	March	12	Park Spring Wind Farm	Barnsley	UK	Blade	Blade failure	-	Blade fall down	Onshore
414	2021	March	11	Clachan Flats Wind Farm	Mid Argyll	UK	Generator	Generator failure	-	Fire	Onshore
415	2021	March	13	Locust Ridge Wind Farm	Schuylkill County	USA	Nacelle	Generator failure	-	Fire	Onshore
416	2021	March	17	Little Houghton Wind Farm	Barnsley	UK	Blade	Blade failure	-	Blade parts fall down	Onshore
417	2021	March	19	Park Spring Wind Farm	Grimethorpe	UK	Blade	Blade failure	-	Blade fall down	Onshore
418	2021	March	23	Gretna Wind Farm	Gretna	USA	Blade	Blade failure	Storm	Blade fall down	Onshore
419	2021	March	26	Ohio Northern University Number 3 Wind Turbine	Ohio	USA	Nacelle	Generator failure	-	Fire	Onshore
420	2021	April	24	Johnston County Wind Turbine	North Carolina	USA	Nacelle	Lightning failure	Lightning	Fire	Onshore
421	2021	May	6	Lindewitt Wind Turbine	Lindewitt	Germany	Nacelle	Generator failure	-	Fire	Onshore
422	2021	May	22	Horns Rev 1 Wind Farm	North Sea	Denmark	Nacelle	Generator failure	-	Fire	Offshore
423	2021	July	6	Grey County Road 8 Wind Turbine	Ontario	Canada	Blade	Blade failure	-	Blade fall down and broke	Onshore
424	2021	July	23	Nantucket High School Wind Turbine	Massachusetts	USA	Trafo	Lightning failure	Lightning	Stop operation	Onshore
425	2021	August	30	Helena Wind Farm	Oklahoma	USA	Blade	Blade failure	-	Blade damaged	Onshore
426	2021	August	28	Bow Lake Wind Farm	Ontario	Canada	Structural	Structural failure	-	Collapse wind turbine	Onshore
427	2021	September	16	Ocotillo Wind Turbine	California	USA	Structural	Structural failure	-	Collapse wind turbine	Onshore
428	2021	October	1	Haltern am See Wind Turbine	Haltern am See	Germany	Structural	Structural failure	-	Collapse wind turbine	Onshore
429	2021	October	2	Kent Hills Wind Turbine	New Brunswick	Canada	Structural	Structural failure	-	Collapse wind turbine	Onshore
430	2021	October	3	Haltern AV9 Wind Farm	Essen	Germany	Structural	Structural failure	-	Collapse wind turbine	Onshore

431	2021	October	6	Tararua Wind Farm	Palmerston North	New Zealand	Nacelle	Generator failure	-	Fire	Onshore
432	2021	October	21	Nattheim Wind Turbine	Heidenheim	Germany	Blade	Blade failure	Storm	Blade fall down and broke	Onshore
433	2021	October	30	Borssele 1 & 2 Offshore Wind Farm	Ørsted	Netherlands	Nacelle	Generator failure	-	Fire	Offshore
434	2021	October	28	Caney River Wind Farm	Elk County	USA	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
435	2021	October	31	Woolnorth Wind Farm	Tasmania	Australia	Nacelle	Generator failure	-	Fire	Onshore
436	2021	November	2	Wilhelmshaven Wind Turbine	Wilhelmshaven	Germany	Blade	Blade failure	-	Blade bend	Onshore
437	2021	November	1	Eberschütz Wind Turbine	Eberschütz	Germany	Blade	Blade failure	-	Blade fall down	Onshore
438	2021	November	12	Frøya Wind Farm	Trondheim Fjord	Norway	Blade	Blade failure	-	Blade fall down	Onshore
439	2021	December	18	Güstow Wind Turbine	Prenzlau	Germany	Nacelle	Generator failure	-	Fire	Onshore
440	2021	December	21	Frøya Wind Farm	Trondheim Fjord	Norway	Gearbox	Gearbox failure	Oil Leak	Stop operation	Onshore
441	2022	January	2	Eper Fuchte Wind Farm	Eper Fuchte	Germany	Blade	Blade failure	-	Blade fall down and broke	Onshore
442	2022	January	8	Kingfisher County Wind Farm	Oklahoma	USA	Nacelle	Generator failure	-	Fire	Onshore
443	2022	January	14	Nysted Offshore Wind Farm	Rødsand	Denmark	Structural	Structural failure	-	Collapse wind turbine	Offshore
444	2022	January	30	Hohenlochen Wind Farm	Oberwolfach	Germany	Blade	Blade failure	Cracks on the blade	Stop operation	Onshore
445	2022	February	3	Haarstrang-Nord Wind Turbine	Haarstrang	Germany	Blade	Blade failure	-	Blade fall down	Onshore
446	2022	February	6	Gänserndorf Wind Turbine	Gänserndorf	Austria	Blade	Blade failure	-	Blade fall down and broke	Onshore
447	2022	February	7	Wilstermarsch Wind Farm	Wilstermarsch	Germany	Blade	Blade failure	Storm	Blade fall down and broke	Onshore
448	2022	February	15	Pant Y Wal Wind Farm	Bridgend	UK	Structural	Structural failure	Storm	Collapse wind turbine	Onshore
449	2022	February	17	Nauener Platte Wind Farm	Brandenburg	Germany	Blade	Blade failure	Storm	Blade fall down and broke	Onshore
450	2022	February	17	Hesket Newmarket Wind Turbine	Cumbria	UK	Blade	Blade failure	Storm	Blades fall down	Onshore
451	2022	February	18	Belgian Offshore Wind Farms	Belgium	Belgium	Structural	Temperature and Environmental failure	Storm	Stop operation	Offshore
452	2022	March	4	Cheyenne Wind Farm	Wyoming	USA	Structural	Structural failure	-	Collapse wind turbine	Onshore
453	2022	March	1	Wilstermarsch Wind Farm	Steinburg	Germany	Blade	Blade failure	-	Blade break	Onshore
454	2022	March	25	North Texas Wind Farm	Texas	USA	Structural	Structural failure	Storm	Blade bend and collapse wind turbine	Onshore
455	2022	April	7	Montezuma Hills Wind Farm	California	USA	Nacelle	Generator failure	-	Fire	Onshore
456	2022	April	8	Wind Turbine North of Alta	Iowa	USA	Nacelle	Generator failure	-	Fire	Onshore
457	2022	April	8	Anholt Offshore Wind Farm	Ørsted	Denmark	Rotor	Blade failure	-	Blades fall down	Offshore
458	2022	May	4	Kincardine floating wind farm	Aberdeen	UK	Structural	Structural failure	Component replacement	Stop operation	Offshore

Appendix-B

Paper to be submitted to “Wind Energy”, a journal issued by Wiley Publishing Company

Analysis and assessment of onshore and offshore wind turbines failures

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Abstract

The rapidly increasing energy demand and the inevitable negative effects on the environment caused by energy production, have made renewable energy technologies increasingly important and preferred among the widely used energy sources in the last decades. Wind energy is one of the leading renewable energy technologies. Wind energy comes to mind when it comes to renewable energy, as it is a carbon free, environmentally friendly, competitive technology. A step forward in production of wind energy is offshore and onshore wind turbines, with their numerous advantages.

Today, the increasing energy needs in the world and new searches related to this make onshore and offshore wind turbine applications an increasingly widespread renewable energy source. However, with this spread, challenges arise during the operation phases or being associated with the strength of the wind turbines. Potential failures must be known in advance so that they can be dealt with strongly and effectively. Damages and failures have a negative effect on the continuation of the operation and cause material and moral impacts. The aim of this study is to assess and analyze the damages to wind turbines onshore and offshore in order to reduce the risk of potential failures, damages and collapse of wind turbines. It will be attempted to be aware of the potential challenges that these systems may face and to contribute to their long-term viability. According to the results of all these studies and analyzes, the database should represent the general failure rate in the industry.

Keywords: failures, collapse, risk, wind, wind turbine, wind turbine failure analysis, data analytics

1 INTRODUCTION

The research is analysis and assessment of damages to wind turbines, onshore and offshore with the objective to reduce the risk of wind turbine failures and collapse by learning from these failures. The aim of this study is to assess and analyze the damages to wind turbines onshore and offshore in order to reduce the risk of potential failures, damages and collapse of wind turbines. Thus, damages and failures that may occur in wind turbines will be identified, and the importance of strengthening wind turbines and certain maintenance requirements will be discussed. It will be attempted to be aware of the potential challenges that these systems may face and to contribute to their long-term viability.

Today, there are 6-MegaWatt wind turbines. In addition to the installed power, the blade diameters are also increasing. While it was around 20 meters in the 1980s, it reached 100 meters in the 2000s. As of the 1990s, the installation of offshore wind turbines has begun. The

increase in wind energy orientation in the 2000s, the decrease in productive places for onshore wind energy generation, and the high maintenance and repair costs of hard-to-reach places accelerated the installation of offshore wind turbines. Offshore wind farms can be found in Europe and in many parts of the world. In Figure 1 below, the blade diameters and power distributions of wind turbines are shown according to years.

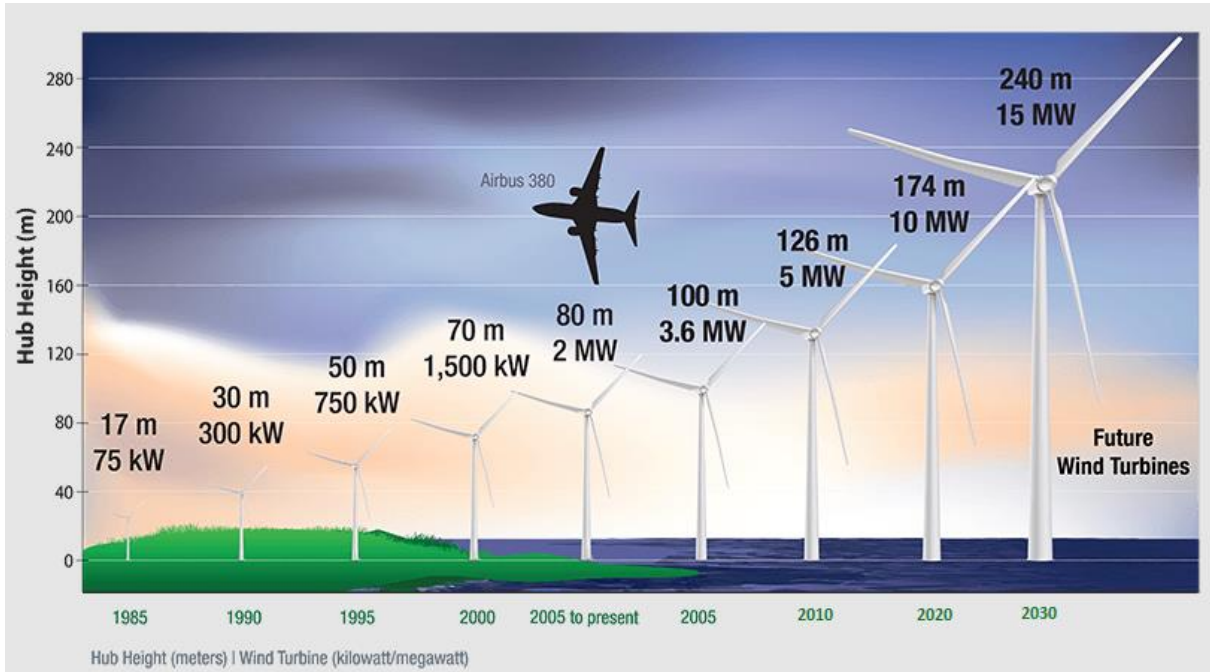


Figure 1 Blade diameters of wind turbines and distribution of power by years, source [Josh Bauer, NREL, 2020]

Global wind power has roughly quadrupled over the past 10 years, making it one of the most cost competitive and resilient energy sources worldwide, according to the 2021 Global wind report. While this is the case, with the increasing investments and energy demand, risk situations such as failures, collapses and fire during the operation of wind turbines have been observed widely.

A wind turbine must operate safely for operators working for maintenance, for people around, and for itself. All risks and hazards must be minimized in order for it to work in an orderly and efficient manner. It is possible to obtain a long-lasting and sustainable wind turbine life by minimizing these risks. Blade, generator, structural and gearbox come to the fore as the most common failure components of wind turbines. These failures cause extra maintenance costs and preventive approaches in physical designs. In this research, a total of eight failure types that occur during the operation of wind turbines and cover most of the failure types are mentioned.

1.1 Blade failure

Reliability is extremely important in wind turbine blades. The blades are responsible for using the mechanical energy of the wind and are exposed to the loads during operation. In addition, they may be exposed to abrasion or higher loads, due to environmental conditions such as wind, rain, snow, and storm etc. It can be said that the starting point of the failure in the blades

is the transport stage. While the wind turbine blade, which is out of production, is transported to the operation area, minor or major damage may occur in certain parts of the blade. These damages may increase with the assembly and may fail quickly with the loads it is exposed to during use. Another reason is the blade size. Making the blade larger to use more of the mechanical energy in the wind also causes rotor imbalances, corrosion and greater loads on the blade. Blade failures result in blade dropping, breakage, bending or wear.

1.2 Generator failure

Generators are the parts used to convert the energy obtained into electrical energy. There are many types of generators used. The most commonly used generator type is the double-fed asynchronous generator. There are wind turbines that have become unusable due to generator failures. Failures in generators can be divided into mechanical and electrical failures. Mechanical failures are mostly caused by misalignment or bearing failures. Electrical faults are caused by stator and rotor winding faults and slip ring faults.

1.3 Yaw system failure

Yaw system is the system used to position the blades according to the desired angle. In Yaw systems, shaft cracks, gear failures, bearing failures and damage to these parts are encountered. These damages occur in case of bad weather conditions and exposure to heavy loads. Failure in the yaw system can lead to larger failures, for example, damage to incorrectly positioned blades or excessive load on the blades.

1.4 Gearbox failure

The gearbox is a system consisting of gear wheels that bring the rotational speed of the low-speed shaft to a suitable level for electricity generation. In wind turbines, fixed and variable gear ratios can be used between the turbine rotor and the electric generator. The use of variable gear ratios can result in more stable and stagnant electricity and provide higher aerodynamic efficiency. In gearboxes that are under heavy operating conditions for a long time, shaft misalignment, bearing damage, gear damage, shaft damage, etc. failures occur.

1.5 Temperature and environmental failure

Wind turbines are installed in a variety of different geographical areas, from a hot and dry climate to a humid and cold climate. In addition, the installed wind turbine is exposed to different climatic conditions and seasonal changes throughout the year. These seasonal and climatic changes have an impact on wind turbines. For example, in the selection of the lubrication and grease used in the gearbox, it is important to choose it according to the region where the wind turbine will be installed. With the change of seasons, the wind turbine is subject to different conditions. The manufacturer must take into account the climatic conditions of the region where the wind turbine will be installed.

Different components are used to cool the engine section of a wind turbine in summer and to heat it in winter. These parts can be fans, blowers and heaters. In summer, blowers that circulate the outside air inside are used to cool the gearbox and generator located in the nacelle part. In winter, if the temperature inside the nacelle is not sufficient, the heaters give

warm air in order to keep the interior at the desired temperature. Nonetheless, if the wind turbine is shut down for a long time, the gearbox lubricate may decrease to ambient temperature and cause damage. Temperature change is not only important for lubrication. At the same time, bad weather conditions can affect the maintenance work, resulting in longer maintenance time and downtime. Another effect is on anemometers. The anemometer measures the wind speed and maintains turbine control. Extremely cold weather, freezing rain may stop the anemometer from working and the wind speed may be zero, in which case the control orders given will be wrong, resulting in time, cash and damage. For offshore and coastal installations, the effect of sea salt on various components must be taken into consideration, whereas the onshore wind farms are immune from these effects.

1.6 Lightning

Lightning is the discharge of millions of volts of static electricity between the clouds and the ground in a very short time with intense light, thunder and a great destructive power. As the size of the wind turbines increases and the blade length increases, the blades become much more open to lightning and attract lightning just like a lightning rod. The impact of this destructive power on any metal or non-metal part on the wind turbine can cause irreversible damage to the wind turbine. Especially the damage it causes on the blades can prevent the wind turbine from working. Blade damage due to lightning strike is shown in Figure 2 below.

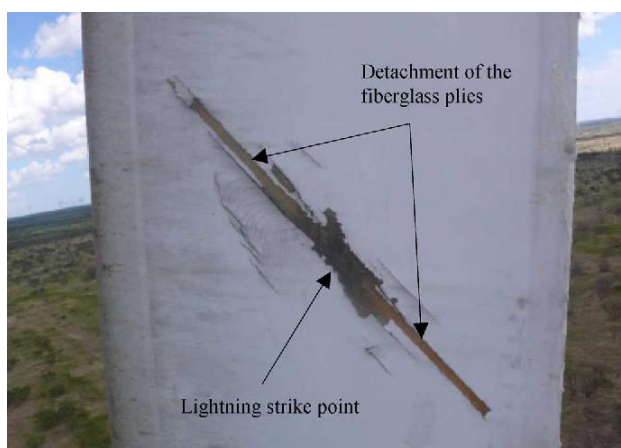


Figure 2 Damage from lightning to a turbine blade, source [A. Garolera et al., 2016]

1.7 Ice forming failure

Ice formation can be observed on the blades of wind turbines that are freezing cold and operating at temperatures close to the freezing point. The temperature of the air, which is not at the freezing point, but passing through the blade edge at a temperature close to it, may reach the freezing point. Different amounts of ice may be formed due to rain or humidity in the air. The ice layer formed on the blade edges changes the blade profile and causes the drag and lift coefficients to change. The power capture capacity of the blade decreases, causing less energy to be obtained. Depending on the weight of the ice in the area, it may even disrupt the balance of the blades. At the same time, in much freezing rain and cold, the entire airfoil can freeze, resulting in high losses. Another issue is the falling of ice pieces from a height. It can damage the surrounding structures, living things or settlements.

1.8 Structural failure

Another type of failure is structural failure. These failures are results such as collapse, fracture, or blade fracture. There are two main causes, extreme winds and the ground where the wind turbine is located.

Extreme winds can be very dangerous to the structural integrity of wind turbines. Especially in regions where natural disasters such as typhoons and hurricanes occur, damage to wind turbines is inevitable in some cases, and blade fracture and simple failures are considered acceptable. However, this is not exactly the case. When the wind speed is more than 25 m/s wind speed, the operation mode of the turbine is changed to "standstill" or "idling" state. In these cases, the blades return to the feather position and the turbine is free to yaw. This allows the nacelle to turn in the direction of the wind. In this case, it is ensured that both the blades and the tower carry the minimum wind loads. However, in case of any power loss, mechanical failure, electrical imbalance or instability (likely to be seen in extreme typhoons and hurricanes), the operating mode is "fault parked" or "emergency stop". In these operating states, the blades return to the feather position, but the yaw system is locked. As a result, the turbine has to maintain the wind coming from any direction without changing its position. In such cases, exposure to high forces as well as weakness in the ground cause wind turbines to collapse or get damaged easily. Due to the design, reductions in shell wall thickness and bending stiffness may appear in certain parts of the wind turbine.

2 METHOD

The method used for this research was determined as a qualitative method. For this research, it is aimed to analyze specific faults by evaluating the data available from the internet, literature, or various sources, and to reach a result by categorizing the faults and damages of wind turbines in the light of the data obtained. It is desired to list and explain the data identified. At the same time, possible comparison studies will be carried out; tables to be created, etc., Thus, a quantitative research method will be used in order to obtain certainty, based on numerical and scientific data. Thus, it is desired to achieve the best results within the available time.

Malfunctions, risks and faults that occur in wind turbines are collected and their causes are stated. Case data were collected by specifying the previous failures, hazards and risks and their causes.

It should also be noted that in some of the data that resulted in the fire, as listed in the dataset, the cause of the fire was not specified as the reason was not stated by the data sources or the authorities. However, these cases cover some fire data, not all fire data as stated. For example, statements such as "the wind turbine engine caught fire, the nacelle caught fire even though there was no storm, the engine cover started to burn even though there was no lightning or storm, and the reason is unknown" were found in the source. In these cases, if there is no lightning or storm, the failure type is specified as generator failure in this study. The date of completion of the failures investigations was May 4, 2022. Additionally, although the sample identified is very large and suitable for careful assessment, it should be noted that there may be other failures that are not identified and recorded.

2.1 Data collection and data review

The dataset analyzed in this study is a compilation of 458 news reports from 2010 to 2022. The data source was created using the results obtained from the Google search engine using the search terms "wind turbine failures", "wind turbine accidents", "wind turbine collapse", etc., and the results of many articles and literature studies reviewed throughout the study. In many of the resulting news articles, irrelevant, repetitive, and unverifiable news were eliminated. Only news reports that provided a certain level of detail were included, and a most reliable data was created. All the data obtained are listed in detail in dataset.

This analysis is based on publicly failures and risks news. Without full access and detail to all wind turbine failures and accidents, it is impossible to say that the data used in this study or similar studies are representative of all wind turbines. Because it will not be possible to convince all wind turbine manufacturers to share all their data on accidents, let alone convince one manufacturer. The data in this study is reliable as the data base was created with extreme precision and meticulousness regarding data collection and examination, but it should not be forgotten that there are different types of failures that are not recorded.

Most of the sources of the data obtained are in English. The last time non-English news sources were checked using Google Translate in May 2022, and complete data analysis was conducted again. In terms of analysis quality, data quality, and study reliability, it has been validated more than once, with special emphasis on the translation of technical terms in addition to high translation quality.

All of these data, obtained from 2010 to 2022 about failures, risks, damages, and dangerous situations were related to the operation of offshore and onshore wind turbines. Therefore, failure and risk factors during construction or transportation are not included in the data. Much effort was required in a short time to expand the framework and collect potential, reliable and large amounts of data.

Details such as location, date, type of failure, cause of failure, type of wind turbine and more features have been carefully and painstakingly manually generated by reading each news reports in detail and understanding the content and researching online the information to complement any missing information. Data sources have been recorded in order to ensure originality and scientific reproducibility.

2.2 Data attributes

The attributes in the structured dataset are the following:

- Turbine No : Turbine number defined for each failure
- Year, month, day : Year, month, and day of failure reporting
- Wind turbine location: The specific location of the turbine and name
- Location : State, province, county in which the failure occurred
- Country : Country where the failure occurred
- Failure location : Section showing which part of the wind turbine fails
- Failure type : Section showing the type of fault

- Failure cause : Section that explains the reason for the failure
- Failure effect : Section showing damage and result of the wind turbine failure
- Type : Offshore or onshore wind turbine classification

3 RESULTS

Data analytics refers to the analysis of data collected in order to extract patterns, discover the desired information, and create knowledge in line with the determined purpose. These terms are presented in the light of visualization and summary of statistical information. Data analysis is done according to the data collected in the project, the structure of the data, the audience receiving the analysis, and the experience of the analyst.

In this research, statistical information has been prepared in the light of the data obtained, and during the operation of offshore and onshore wind turbines, the failure and risk situations were determined, and the data obtained were analyzed.

This section summarizes the data collected and generated during the research, such as failure rates, country distributions, risk factors, with table and graphic analyzes.

The first analysis in this research was the analysis of the collected data showing the rate distribution of the failure types of the datasets. The Figure 3 chart below shows the failure rates.

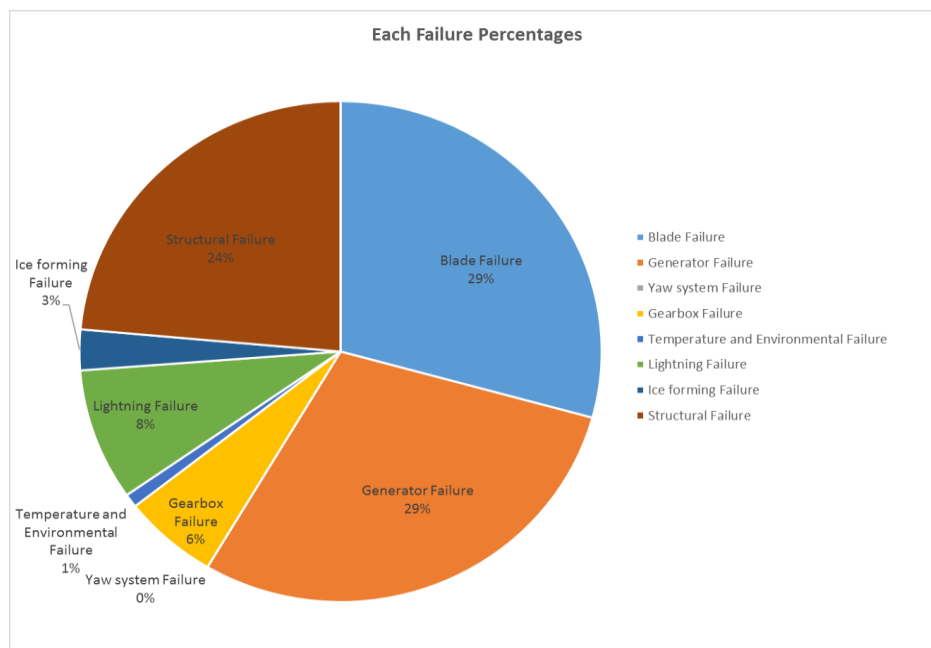


Figure 3 Graph showing failure percentages

The first analysis focused on the distribution of failure rates as shown in the above figure. As can be seen from the graph, blade and generator failures cover offshore and onshore wind turbines failures and risks with a 29% percentile each. Structural failures follow with 24%. There are lightning failures with 8%, gearbox failures with 6%, ice forming in turbines 3% and faults caused by temperature and environmental effects of 1%. Yaw system failures were not found in the collected data, this detail is evaluated as a comment in the next chapter. Table 1 failure rates are shown below for easier assessment of the graphic results.

Table 1 Failure percentages

Failure Type	Failure Percentage (%)
Blade Failure	29
Generator Failure	29
Structural Failure	24
Lightning Failure	8
Gearbox Failure	6
Ice forming Failure	3
Temperature and Environmental Failure	1

The percentage shares of the causes of blade failures, which have a high rate of overall failure, are shown Figure 4 below.

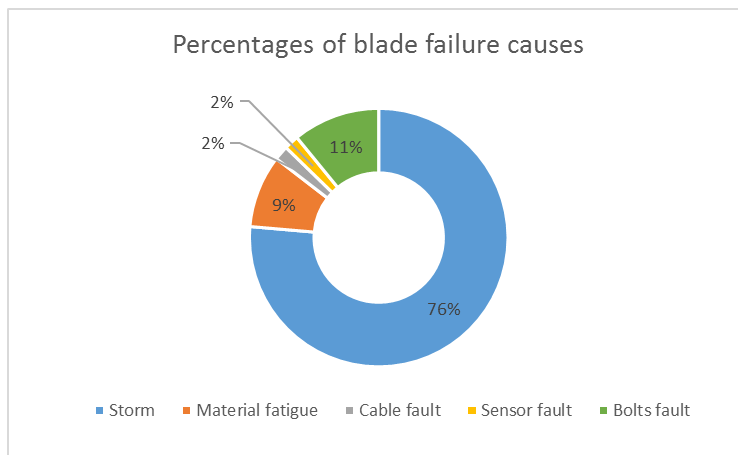


Figure 4 Percentages of blade failure causes

Considering the known causes of blade failures, which account for 29% of the overall failure rate, it is seen that 76% are due to storm, 11% are bolt and fastener faults, 9% are due to material fatigue, and 2% are cable and sensor faults. As a result of these failures and risks, results such as blade break, falling, damage to the blade, bending of the blade were encountered.

The percentage shares of the causes of generator failures are shown Figure 5 below.

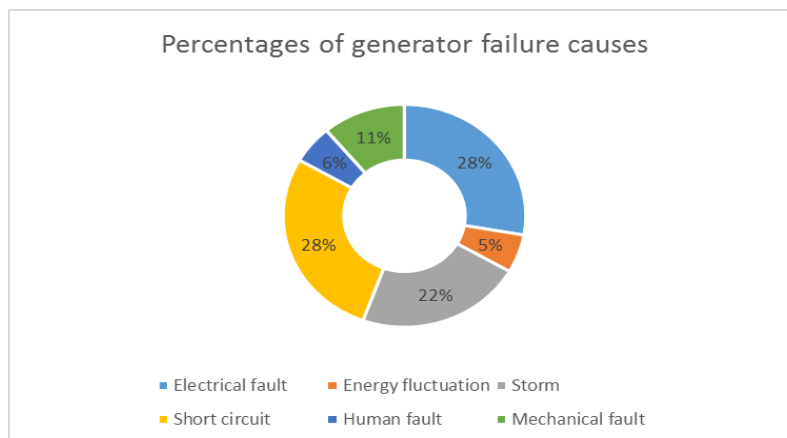


Figure 5 Percentages of generator failure causes

When the known causes of the generator failure data obtained are examined, the percentage of failure causes is as seen in figure 5.3. Short circuit and electrical faults are seen to contribute with 28%. Electrical faults include faults made in the electrical panel, voltage conditioning fault, converter fault, for more detailed information, see Appendix-A. It is seen that the failure rate in the generator due to storms is 22%, mechanical faults represent 11%, human faults are 6% and energy fluctuations are 5%. The vast majority of generator failures result in fire.

The failure cause percentages of structural failures with overall failure percentage of 24% are shown in Figure 6 as follows.

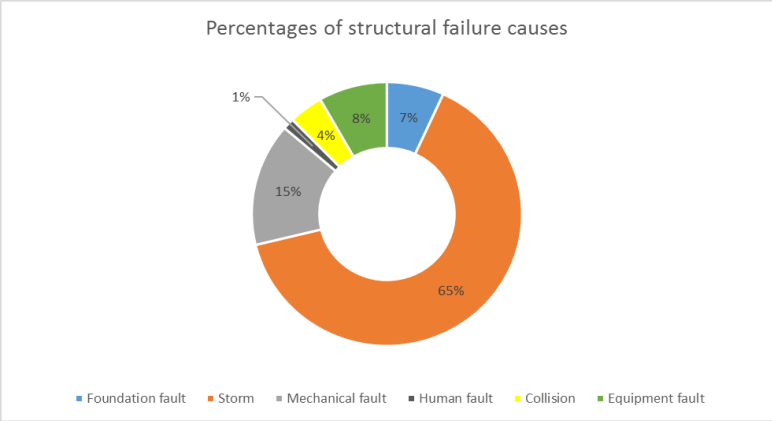


Figure 6 Percentages of structural failure causes

When the percentiles of the known causes of structural failures are examined, wind turbines were damaged due to storm with 63% in the first place, mechanical failures such as misalignments and stabilization faults are 15%, high maintenance costs, faults such as missing mechanical parts are equipment failures 8%. 4% is collision and 1% is human fault. More detailed information can be seen in Appendix-A. The vast majority of structural failures result in the collapse of wind turbines.

In Figure 7, percentiles of the causes of gearbox failures, which constitute 6% of general failures, are shown. There was no need to show the causes of ice form failure, lightning, and temperature and environmental failures that make up the remainder of the faults.

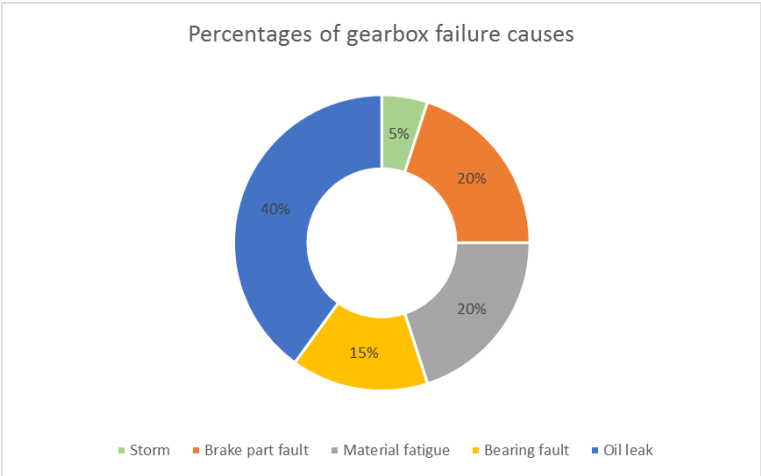


Figure 7 Percentages of gearbox failure causes

The main problem of gearbox failure causes is oil leakage with 40%. It was seen that the braking system and material fatigue represents 20%, the faults in the bearing 15%, and the failure and risk situations as a result of the storm with 5%.

Another analysis focused on the distribution of failures by country, as shown in Figure 8. The countries USA, Germany, UK and Canada constitute the majority of the failures in the dataset. Because the research is conducted and reported in English and the search terms are in English, it is likely that there will be a large number of English-speaking countries represented in the full dataset. However, it was not possible during the study period to extend the search to other languages.

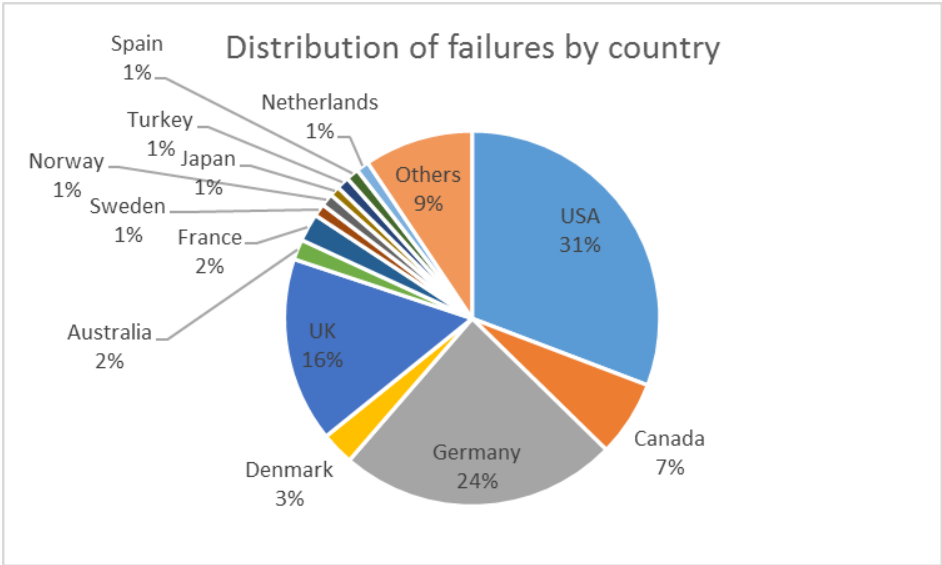


Figure 8 Distribution of failures by country

Considering the distribution of faults by country, USA is in the first place with 31%, in the second place by Germany with 24%, in the third place by the UK with 16%, in the fourth place by Canada with 7%, and in the fifth place by Denmark with 3%. More detailed information can be found in the dataset.

According to the collected and analyzed data, the distribution ratio of the failure types according to the countries is given in Figure 9.

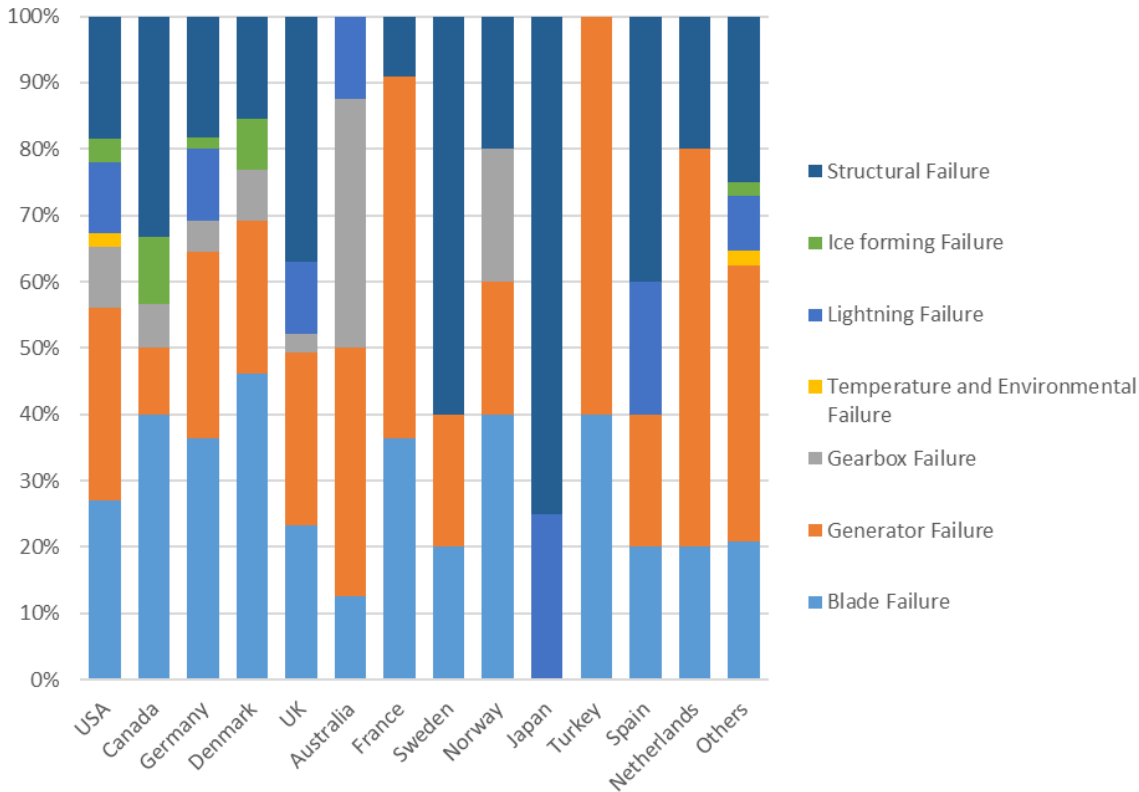


Figure 9 Failure types of rates by country

In Table 2, the distributions by country are examined in detail. Blade failures, generator and structural failures seem to be leading as a result of examining the distributions in countries with high number of data, such as USA, Germany and the United Kingdom.

Table 2 Percentages of failure types by countries

Countries (Total Cases)	Blade Failure	Generator Failure	Gearbox Failure	Temperature and Environmental Failure	Lightning Failure	Ice forming Failure	Structural Failure
USA (141)	27%	29%	9%	2%	11%	4%	18%
Canada (30)	40%	10%	7%	0%	0%	10%	33%
Germany (110)	36%	28%	5%	0%	11%	2%	18%
Denmark (13)	46%	23%	8%	0%	0%	8%	15%
UK (73)	23%	26%	3%	0%	11%	0%	37%
Australia (8)	13%	38%	38%	0%	13%	0%	0%
France (11)	36%	55%	0%	0%	0%	0%	9%
Sweden (5)	20%	20%	0%	0%	0%	0%	60%
Norway (5)	40%	20%	20%	0%	0%	0%	20%
Japan (4)	0%	0%	0%	0%	25%	0%	75%
Turkey (5)	40%	60%	0%	0%	0%	0%	0%
Spain (5)	20%	20%	0%	0%	20%	0%	40%
Netherlands (5)	20%	60%	0%	0%	0%	0%	20%
Others (43)	21%	42%	0%	2%	8%	2%	25%

Another analysis is the failure rates of wind turbine types. There are 29 offshore wind turbines and 429 onshore wind turbines in the dataset with covers 458 cases, this detail is evaluated

as a comment in the next chapter. Failure rates of offshore and onshore wind turbines are shown in Figure 10.

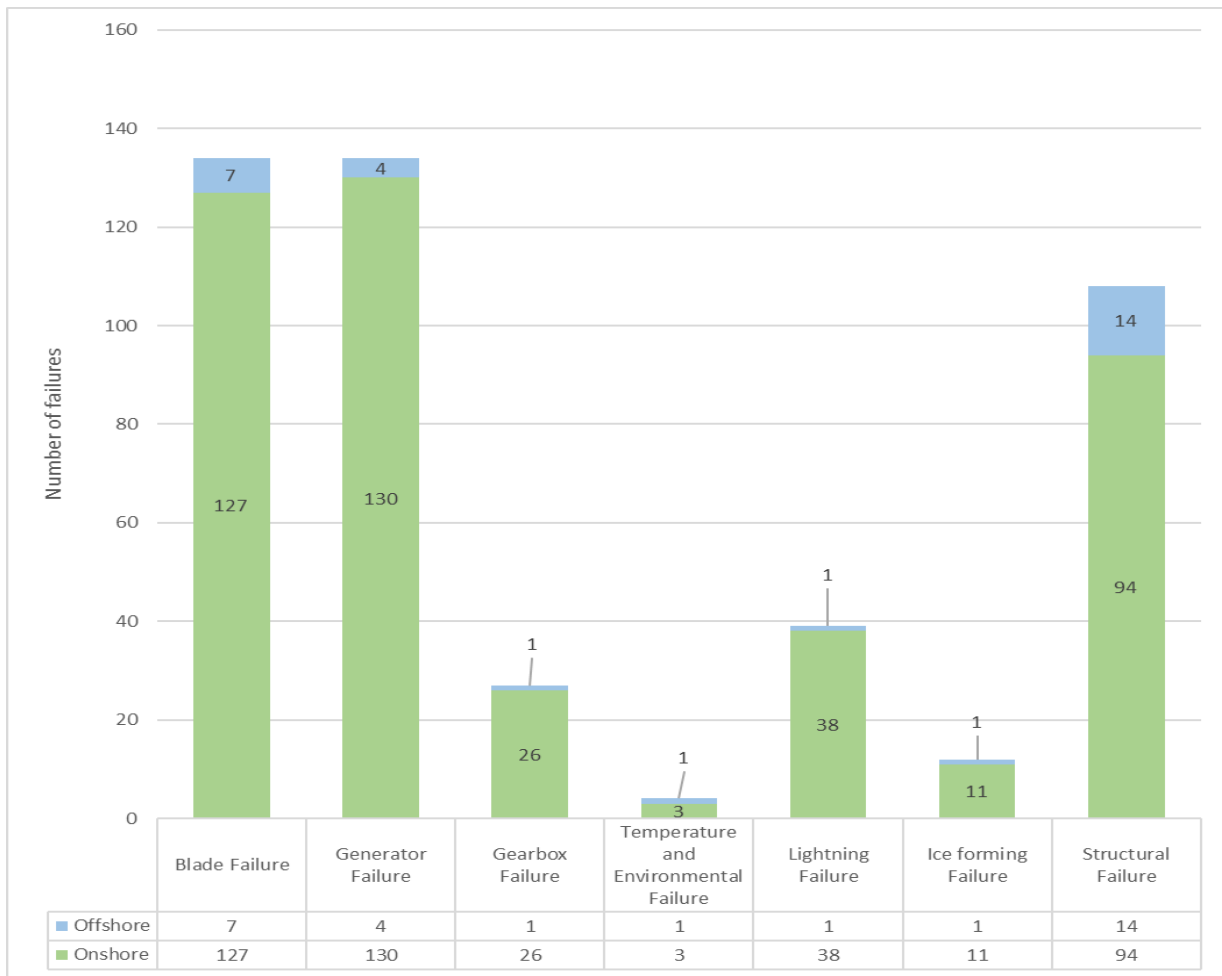


Figure 10 Failure rates of offshore and onshore wind turbines

Types of failures of offshore wind turbines are followed by firstly structural failures with 14 cases, blade failures with 7 cases, and generator failures with 4 cases. In other failure types, there is 1 case each.

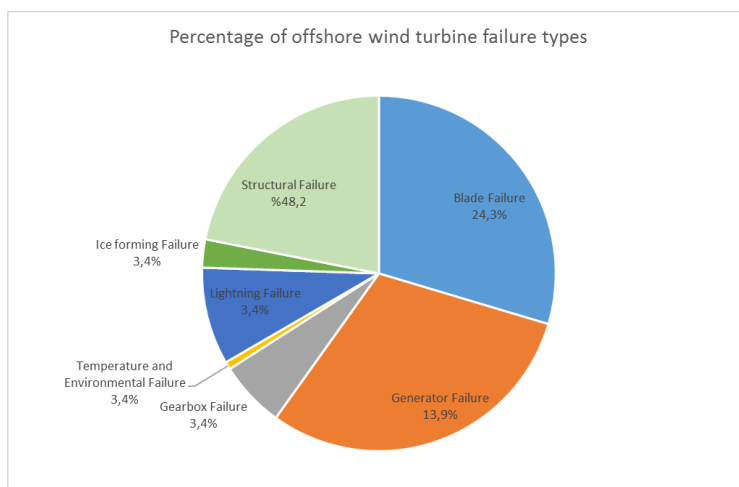


Figure 11 Percentage of offshore wind turbine failure types

The percentage of offshore wind turbine failure types is shown in Figure 11. Structural failures take the biggest share with 48.2%, followed by blade failures with 24.3% and generator failures with 13.9%. The remaining faults represent 3.4% each.

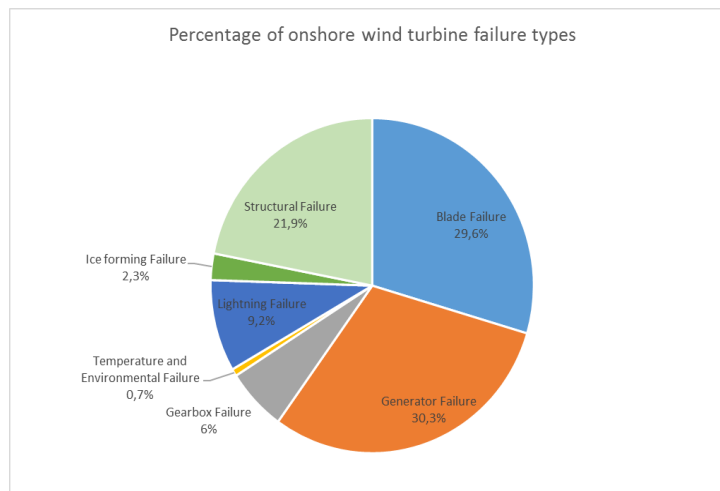


Figure 12 Percentage of onshore wind turbine failure types

The percentage of onshore wind turbine failure types is shown in Figure 12. Generator failures ranked first with 30.3%, followed by blade failures with 29.6%, structural failures with 21.9%, lightning with 9.2%, gearbox failures with 6%, ice forming failure with 2.3% and finally temperature and environmental failures are included with 0.7%.

In the light of the data obtained, the causes and consequences of the failure types are shown in Table 3 Failures represent various risks and damages. These summary statistics, based on the recent decade of failures, can be used in many ways, including where to focus on reducing failures and in the calculation of rates for risks.

Table 3 Causes and consequences of failure types

Failure Type	Failure Cause	Failure Effect
Blade Failure	<ul style="list-style-type: none"> • Storm • Material fatigue • Cable fault • Sensor fault • Bolt fault 	<ul style="list-style-type: none"> • Fall down • Bend • Crack • Break • Stop operation
Generator Failure	<ul style="list-style-type: none"> • Electrical fault • Storm • Energy fluctuation • Short circuit • Human fault • Mechanical fault 	<ul style="list-style-type: none"> • Fire • Noisy operation • Stop operation • Oil leak • Explosion
Gearbox Failure	<ul style="list-style-type: none"> • Storm • Brake part fault • Material fault • Bearing fault • Oil leak 	<ul style="list-style-type: none"> • Idle blades with high rotation speed • Stop operation • Fire • Blade and gearbox fall down • Gearbox break

Temperature and Environmental Failure	<ul style="list-style-type: none"> • Cold weather • Storm • Sudden weather changes 	<ul style="list-style-type: none"> • Stop operation • Oil leak • Expansion
Lightning Failure	-	<ul style="list-style-type: none"> • Fire • Stop operation • Crack on blades • Damage to turbine
Ice forming Failure	<ul style="list-style-type: none"> • Minus temperature 	<ul style="list-style-type: none"> • Ice forming on blades
Structural Failure	<ul style="list-style-type: none"> • Foundation fault • Storm • Mechanical fault • Human fault • Collision • Equipment fault 	<ul style="list-style-type: none"> • Collapse • Stop operation • Parts fall down • Damage to turbine • Tower bend • Unstable • Remove to turbine • Fire

4 DISCUSSION

Our dataset aimed to create sustainability for the operation of wind turbines by focusing on the failure and risk situations of offshore and onshore wind turbines. In this section, our explanations for each type of fault and discussion on the best mitigating measures that can be taken based on the analysis results are presented below.

The vast majority of blade failures are caused by storms. In addition, results such as falling, bending, and cracking of blades as a result of material fatigue, wiring and assembly faults, and sensor faults were observed. It should, however, be noted that data about the age of failed blades is not known and aero-elastic considerations have recently become much more important during the design phase of modern wind turbines to avoid blade failures. Aerodynamic and structural modeling should be integrated according to the location of the offshore and onshore wind turbines, and climatic conditions should be among the main factors to be considered in wind turbine design. A delicate balance must be found between durability, aerodynamic properties and noise. Especially in today's wind turbines with large rotor diameters, this issue is of vital importance in order to solve the interaction of fluid and structure and to minimize excessive loads. In addition, the selection of aero-elastic materials should be made under these conditions, and structural health monitoring by using online feedback sensors should be implemented in wind turbine blades that are quite long. In order to avoid these failures and associated risks, regular and routine maintenance work should be carried out, and the time between maintenance should be decreased if necessary.

The main causes of generator failures are electrical faults which include short circuits and energy fluctuation, storms, and mechanical failures. The majority of generator failures result in fire, causing the entire turbine to be out of service. Since it is difficult to intervene in a wind turbine that has started to burn, the fire is expected to burn out. This type of fire not only damages the turbine, but it also damages the environment. Therefore, electric stability analysis of all turbines or wind turbines in the wind farm should be done in order to minimize and overcome generator failures. Thus, energy fluctuations, current differences, and electrical faults that wind turbines are exposed to can be detected. Spectral analysis method can be

used to detect winding faults, which are frequently encountered in generator failures, in this method the fault sidebands of a signal in the frequency dimension are looked at. In this way, failures can be detected and tracked. A dynamic state space model can be created to detect short-circuit faults in the stator windings. More information on these methods can be found in the literature. In addition, there are methods that use generator output power to detect and prevent mechanical faults in the generator, such as axial misalignment. Vibration and generator current analysis can be performed for bearing failures. This situation should be prevented by simultaneous current monitoring and time-frequency monitoring.

The majority of structural failures are caused by storms. In addition, mechanical faults such as assembly and misalignment and foundation faults are among the causes. As a result of these faults, the wind turbine collapses, turbine parts fall, the turbine tower bends or becomes unstable. In order to prevent structural failures, aerodynamic and structural models should be developed, just like for blade failures. The response of the wind turbine to excessive loads should be determined beforehand. This involves collection of wind-data at site to ensure the turbines are designed to withstand the actual wind velocities and the wind turbulence at the site with a low probability of exceedance (normally the design is to withstand the wind conditions having an annual probability of exceedance of 2×10^{-2}). During the wind turbine construction phase, the tower foundation should be made stable and solid. The most suitable wind turbine should be designed in accordance with climatic and environmental conditions, that is, according to the location. With the monitoring of the latest model sensors providing online feedback, the wind turbine should be kept under constant control and routine maintenance should be carried out and the frequency of maintenance periods should be increased if necessary. At the same time, maintenance activities should be considered in order to prevent assembly faults. Assembly faults can be detected by vibration analysis.

The main causes of gearbox failures are oil leakage, braking mechanism faults, and material fatigue. For these reasons, results such as from idle wind turbine blades rotating at high speed and then abruptly stopping the operation, have been encountered. Gearbox diagnostics are difficult. Vibration analysis is performed for fault detection in the gearbox communication chain, but due to the working principle of the gearbox, fault detection with vibration analysis may not always be successful. Therefore, it has been seen that a common amplitude and frequency demodulation analysis method based on the energy separation algorithm has been proposed in the literature. This method can be used to detect wear and damage in the gearbox. In order to detect gearbox failures, apart from routine maintenance, performing these analyses at regular intervals by experts can prevent oil leakage, healthy functioning of the braking system, and material fatigue.

Regarding temperature and environmental failures and ice formation failures, the region where the wind turbines are located is very important. Especially if the seasonal differences in the region where the wind turbines are located are high, it is possible for the wind turbine to be affected by these seasonal differences. It is seen that temperature difference damages turbine parts and the lubrication oil. In order to prevent this situation, it is important to choose the materials and the lubrication suitable for the climatic conditions of the region where the wind turbine is located. The wind turbines operating in the offshore are affected by salt water

and salty sea-spray, and all parts are negatively affected. Regular and frequent maintenance is required to prevent this situation. In addition, decrease in the air temperature to minus or close to minus causes ice formation on the blades. In order to prevent this situation, regular maintenance should be done, and operational activities should be stopped, especially in certain seasonal conditions. On the other hand, in dusty regions a turbine eventually gets dirty. A cleaning of the blades and tower, although relatively expensive, may prolong the useful life as well as the efficiency of operation of a turbine. As a matter of fact, the inside of a turbine nacelle, hub, and tower must always be kept clean from oil spills, grease, and other materials used by a turbine or for maintenance works. It is the responsibility of an operator to make sure that after maintenance work, everything is back to normal, and no pieces of tools or extra stuff are left behind.

Fire and associated damage occur as a result of lightning strikes to wind turbines. There are two different suggestions for mitigating effects of lightning. The first is to protect from lightning, the second is to reduce the effect of lightning. Firstly, a strong grounding system should be established to protect against lightning. It is possible for wind turbines to attract lightning due to their size. For such cases, lightning rods should be used, and the high energy voltage obtained should be removed from the system by grounding. Thus, energy fluctuations, current changes, etc. faults are avoided. Maintenance work should be increased, especially after stormy weather. The second method is to use coordinated surge protection units for power supply systems to prevent lightning damage. These lightning surge arrester systems are effective in the coordinated protection of wind turbine components and in reducing the consequences of sudden voltage differences.

Yaw system failures were not found in the data set. In the obtained data and news sources, the cause of the failure was not specifically stated as yaw system failures. Among the main reasons for this is the indication of such failures as structural failures, technical failures or failures in the engine part. Although this type of failure is rare compared to other types of failures, and the fact that the owners of the companies did not specify the reasons for the failures made it difficult to find a yaw system failure.

5 CONCLUSION

As can be seen from the data analysis, the number of offshore wind turbine failures are less than the number of onshore wind turbine failures. Apart from the fact that there are fewer offshore wind turbines and that these turbines represent a newer technology, factors such as the high installation and maintenance costs, the absence of an infrastructure that every country can establish, and the inaccessibility of the place where they will be located explain this situation. In addition, in this study, it is desired to draw attention again to generator failures. As can be seen from the dataset, generator failures are common, and most generator failures result in fire. A blade can be obtained at a certain, and perhaps high cost as a result of a blade failure, but there is no another choice to wait for the entire turbine to be dismantled by a generator failure resulting in a fire. It is very common to wait for the fire to burn out on its own by taking the surroundings under control.

While obtaining the data, many cases were evaluated, and the appropriate ones were included in this research. While collecting the data, the research period is limited, every case does not overlap with the research, the background reasons for the failures are not specified, the transportation and construction phases (other than the operation) are not included because failures during these phases are not related to the operation of the wind turbines or the subject of this research. Furthermore, processing the data is difficult and time consuming. There are such limitations when collecting data, but the database includes many failures, and all cases have been obtained as a result of serious investigation. According to the results of all this research and analysis, the database should represent the general failure rate in the industry.

This research revealed recurring themes and patterns. This research, which provides new insights, has created clear and unambiguous statements as the results of the analysis. This research and dataset can be used by wind energy industry stakeholders, governments, academic universities, and communities to make data-driven plans and decisions. Different stakeholders can create information flow and innovations by presenting different views and ideas. In addition, when analyzing these data, results such as downtime, cost, total operational hours or age of defective wind turbines were not evaluated. There is a need, and it is necessary to record all datasets and failures in an international database so that it will be a source that can be used by all mentioned stakeholders and future work.

Although governments, academic universities, communities and non-governmental organizations, and all other stakeholders, have their own reasons for adopting green energy, they should focus more on the issue of wind turbine failures. This research can support different stakeholders by facilitating discussions and interactions, giving ideas on this issue. It can be the inspiration to create a large database and additional insights for future works. Similar analysis can shed light on offshore and onshore wind power. Preventive actions can be adopted to reduce the occurrence and negative consequences of these failures. The research can be a reference for researches such as which measures can be taken in which region, and which measures can be taken in which country. In our increasingly digitalized age, it may be possible to avoid such risks and failures by using much more digital and robotic monitoring systems for the future.

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