FACULTY OF SCIENCE AND TECHNOLOGY

MASTER'S THESIS

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Author: **Syed Ali Bilal Naqvi**	
Supervisor at UiS: **Charlotte Obhrai** External supervisor(s): **Jawad Raza (Moreld APPLY)**	
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Abstract

Since the demand for renewable energy sources on a global scale has increased substantially over the past few years, a great number of businesses have made investments in this industry and are doing their utmost to make additional developments and discoveries in the field of wind energy. Wind farms, both onshore and offshore, are considered to be key contributors to the production of sustainable energy because they offer significant benefits, including a reduction in the negative effects on the environment and the production of harmful gases.

The purpose of this thesis was to analyse and explore the lifecycle activities of a wind farm, in order to determine the failure modes, failure effects, and failure consequences of the critical components, as well as the strategies that can be used to counteract these failures. As many wind farms are reaching their end of life, so this thesis also focused on the techniques and strategies that can be done before dismantling, The thesis also includes a reliability analysis, failure mode effect and criticality analysis of generator and gearbox of wind turbine, and also lifecycle cost analysis of an offshore wind farm. These studies improved our knowledge of offshore windfarm operations, maintenance strategies and give a brief information about cost reduction techniques. Several steps from maintenance strategies based on NORSOK Z-008 and ISO-14224, as well as knowledge gained from research papers and interviews with engineers in moreld, were implemented to achieve the goals of this thesis.

Acknowledgements

This thesis was successfully completed with the help and guidance of my industrial supervisor Doctor Jawad Raza and my University supervisor Charlotte Obhrai. I want to thank both for their inputs, guidance, assistance, and countless support throughout this journey.

I'd also like to thank the entire team of Moreld APPLY's Lifecycle Management Department for guiding me, answering my questions, and boosting my confidence throughout this journey. A special thanks to Maintenance Engineer Syed Taha, who passed on his knowledge and experience in maintenance to me.

I would like to dedicate this thesis to my father Syed Ali Zamin Naqvi who left this world on 8 March 2023, just as I began working on this thesis, he was the one who used to provide me all the moral support and courage, Thank you father for all the prayers and support.

I want to express my gratitude to my family, especially my mom and brother, who have been tremendous sources of inspiration and encouragement throughout my life. Finally, I'd like to thank my best friend Sameen Mukhtar, who has been there for me through thick and thin.

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List of Abbreviations

GHG	Green House Gases
LCOE	Levelized Cost of Energy
AE	Acoustic Emissions
UT	Ultrasonic Testing
FMECA	Failure Mode effect and criticality analysis
TLP	Tension Leg platform
RPN	Risk Priority Number
AUVs	Autonomous Underwater Vehicle
GW	Gigawatts
LCCA	Life-cycle cost analysis
CBM	Condition based monitoring
T2S	Tow to Shore
FOW	Floating offshore wind turbine

CHAPTER 1: Introduction

This chapter presents the overview of the thesis, it provides introduction to the research objectives, the scope of work, structure of thesis and the methodology employed for this thesis.

1.1 Background and Context

The global demand for renewable energy sources has increased significantly in last few years, many companies have invested in this sector and are trying their best for more advancements and innovations in the field of wind energy. Onshore and Offshore wind farms are considered as key contributors to sustainable energy production, offering significant benefits such as reducing the environmental impacts and production of harmful gases. Managing and supervising wind farms throughout their lifecycle is a challenge for companies as efficient operations and maintenance ensure their optimal performance, reliability, and efficiency.

Norway has seen significant growth in wind energy sector due to sustainability and pollution free production. Norway first wind farm was installed in 2002 producing only 40 MW of electricity. According to reports issued in 2021 Norway produced almost 7 % of its electricity from 53 wind farms, and this capacity is increasing every year with new projects both in offshore and onshore [1].

Wind turbines have a life span of almost 25 years, so operation and maintenance are very critical aspects for wind turbines. The generator, blades and gear box are very critical components of the wind turbine and have high maintenance costs and labor requirements among all the components of wind turbines.

1.2 Research Objectives

Operations, maintenance, and decommissioning are very crucial stages of lifecycle management, this thesis aims to explore and analyse the activities related to lifecycle of wind farms, focusing on finding the failure modes and failure effects and reliability of critical components, the following are some objectives that were considered in this thesis

- Outline business impact, logistic issues and economical constraints, and uncertainties.

- Review the failures that arise during operations and find strategies to counter these failures with the help of FMECA.
- Categorize challenges and align these with risks and regulatory requirements and do a lifecycle cost analysis study.
- Enlist the future trends and identify new digitalization opportunities for operations and maintenance. Develop framework for efficient decommissioning of wind turbines and analyze supply chain management.

1.3 Methodology

To achieve the above-mentioned research objectives, a comprehensive methodology was used. This thesis involves combination of literature review, data analysis, and expert interviews. The literature review of different research papers, journals and books were done to get the detail insight about the existing knowledge, theories, and strategies related to wind farms. NORSOK Z-008 and ISO 14224 were studied and used to develop the technical hierarchy, functional breakdown, system context diagrams, an effort was made to develop failure mode effect and criticality analysis (FMECA) of the gearbox and generator of the offshore wind turbine, interviews with industry professionals and literature review were handy while doing this analysis.

1.4 Scope of thesis

The scope of this thesis encompasses the lifecycle management of wind farms, with more focus towards operations, maintenance and decommissioning of offshore wind farms and the challenges, maintenance strategies, and technologies linked with it. This thesis also includes reliability analysis, failure mode effect and criticality analysis and lifecycle cost analysis of the offshore wind farm. These analysis further helped in understanding operations and maintenance strategies and cost optimization of offshore windfarms.

1.5 Structure of thesis

Chapter 1: This chapter presents the holistic view of the thesis, it provides introduction to the research objectives, the scope of work, structure of thesis and the methodology employed for this thesis.

Chapter 2: This chapter provides a brief introduction about onshore and offshore wind turbines, their current capacity, future projects and different types of foundations and the reasons behind the move from onshore to offshore.

Chapter 3: The chapter focuses on the critical failures encountered in wind turbines, the maintenance strategies used to fix these failures, this chapter also give a brief information about new technologies and strategies in operations and maintenance of wind turbines.

Chapter 4: This chapter is all about end-of-life management of wind turbines including various concepts like extension of life, recycling, repurposing, and decommissioning. It also explores the challenges that are related to efficient decommissioning starting from vessels accessibility to regulations and licensing.

Chapter 5: This chapter contains all the analysis and system diagrams which were done to achieve the goals of the thesis, presenting the results of every step.

Chapter 6: This chapter contains summary of the thesis and concludes the research work done in order to achieve the goals of thesis.

CHAPTER 2: Literature Review

This chapter provides a brief introduction about onshore and offshore wind turbines, their current capacity, greenhouse gas emissions, future projects and different types of foundations and the reasons behind the move from onshore to offshore. This chapter also discusses about the considerations that should be considered before site selection.

2.1 Onshore Wind Turbines

Onshore wind turbines use wind power to generate electricity and are huge, tower-like structures with rotating blades. Onshore wind turbines are installed mostly in open plains, hilltops, and near coastlines, where wind speeds are high and more consistent. According to the Global Wind Energy Council, by the end of 2021, the system had added 72.5 GW of new wind capacity, bringing onshore wind capacity to 780 GW, this was a significant increase from the 5 GW installed capacity in 1995. From the following figure it can be seen that despite of the challenges posed by COVID-19, there was rapid increase in the onshore wind capacity, China played a leading role and added 30.45 GW into system, followed by USA and Brazil [2].

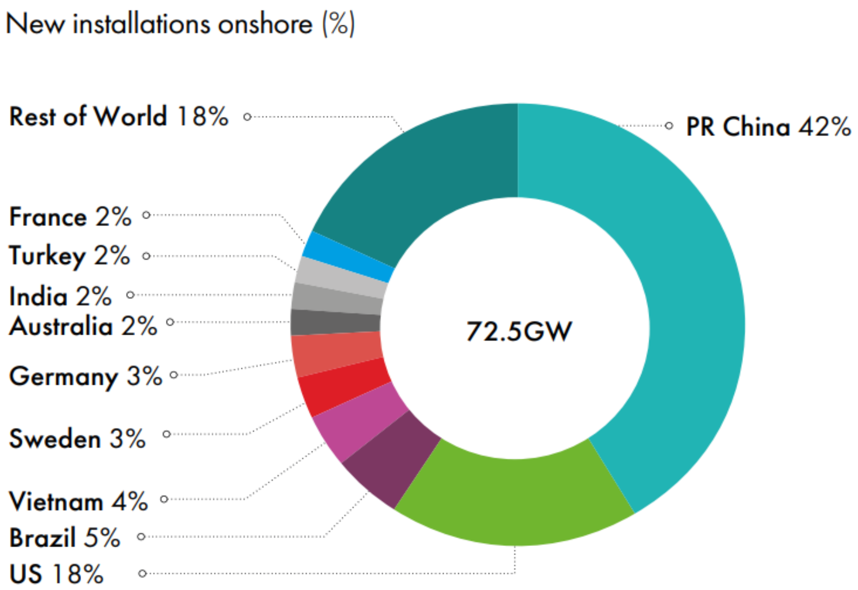

FIGURE 1. NEW INSTALLATIONS ONSHORE [2].

By the end of 2021, total onshore wind capacity was approximately 780.3 GW, and China, US and India were major onshore wind markets.

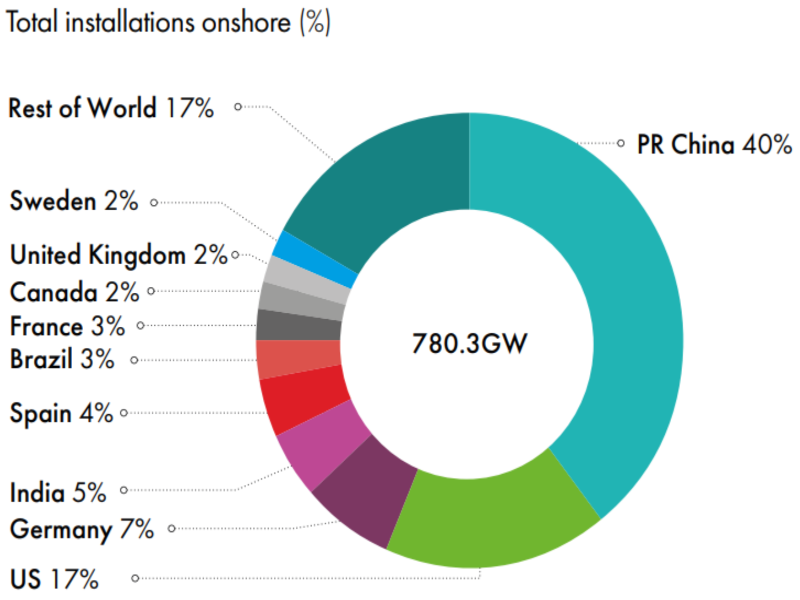

FIGURE 2. PERCENTAGE OF TOTAL INSTALLATIONS ONSHORE [2].

2.1.2 Onshore Wind Turbines Foundations

The design and construction of an onshore wind turbine foundation depends on the following factors: turbine size, soil conditions and geotechnical conditions. The foundations must be designed to support the weight of the turbine and its components and withstand wind and earthquake loads and prevent soil erosion around the foundation [3].

As wind turbine capacity and tower height increases, more robust foundations are needed to support the systems. The design process should consider financial factors and target to improve reliability. For onshore wind turbines, gravity base or spread foundations are often preferred due to their simplicity. These foundations consist of a cylindrical pedestal which is mounted on a large reinforced concrete base and have a circular or octagonal shape. The central pedestal has a radius of 8.5 m to 10.5 m and is connected to the tower. The foundation width typically ranges from 15 m to 20 m, with the centre being 2 m to 3 m thick and tapering to 1.0 m or less at the edges [4].

2.1.3 Advantages of Onshore Wind

There are several benefits of onshore wind farms, some of them are listed below

Cost effective: Onshore wind turbines are less expensive than the offshore ones, installation and maintenance costs for onshore wind turbines are much lower than those of offshore turbines, making them a more cost-effective way to generate electricity.

Fast installation: Onshore wind turbines can be installed in months; installation methods are simple and can be performed very quickly when comparing with offshore wind turbines.

Easy access to maintenance: Onshore wind turbines maintenance cost and maintenance time is less when compared to offshore turbines, as they are located on land and do not require specialised equipment's and weather windows.

Reduced environmental impacts: Onshore wind turbines construction, installation, operations, and maintenance create less emissions and do not impact the marine life [5-6].

2.2 Offshore Wind Turbines

Offshore wind turbines are huge structures installed in water bodies; oceans or large lakes, use to generate electricity from wind energy. These turbines are larger than their land-based counterparts, with blades having length up to 100 meters or more and are designed to withstand harsh marine environments. The use of offshore wind turbines has surged rapidly in recent years as all countries are trying to increase their renewable energy capacity and reduce carbon emissions [7]. According to the Report of Global Wind Energy Council published in 2022 almost 21.1 GW of electricity from offshore wind was added to the system, this number was very encouraging for the offshore wind industry and was a record itself. From this 21.1 GW of electricity almost 80 percent was added by China,11 percent by United Kingdom, followed by Vietnam and other countries [2].

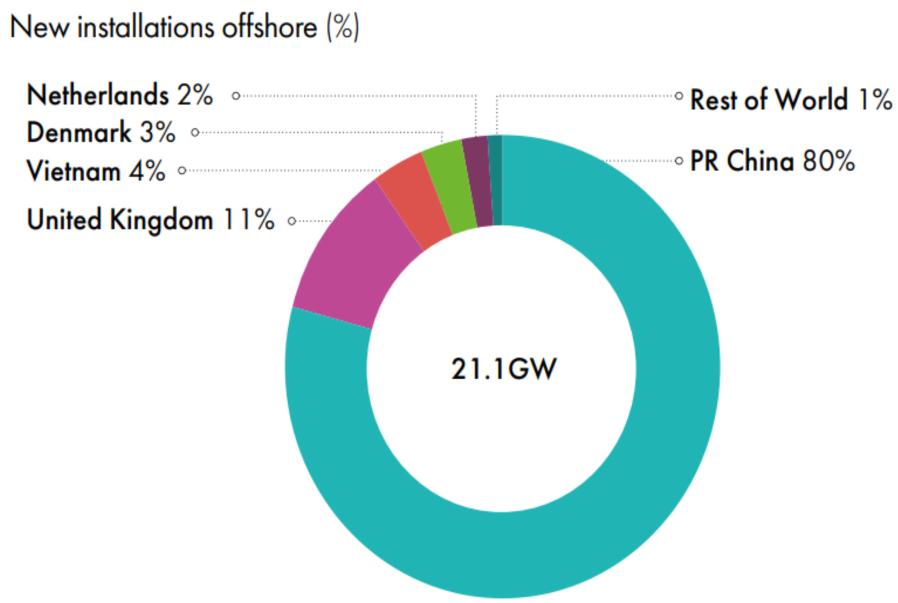

FIGURE 3. NEW INSTALLATIONS OFFSHORE [2].

According to the reports, 57.2GW electricity in world was produced from offshore wind turbines in 2021 and major contributing countries were China and United Kingdom.

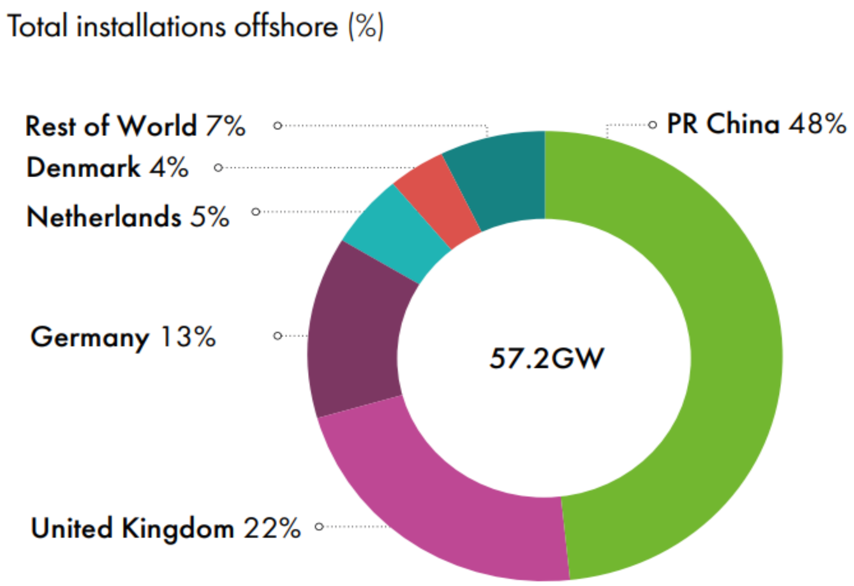

FIGURE 4. PERCENTAGE OF TOTAL INSTALLATIONS OFFSHORE [2].

2.2.1 Reasons to go Offshore

There were several reasons to move from onshore wind farms to offshore wind farms, some of them are discussed below

- **More consistent wind**: High average wind speeds are observed offshore due to reduced friction that's why offshore wind turbines generate more energy compared to onshore turbines. These homogenous conditions are due to the absence of natural and man-made obstacles, such as hills, buildings, and trees, which can cause wind turbulence.
- **Less acceptance issues**: Offshore wind turbines are located far from the shore, so they are less visible, less noise pollution and have less impact on the surrounding environment compared to onshore turbines.
- **Huge turbine sizes**: Offshore turbines are huge structures and much larger than the onshore turbines, with rotor diameters reaching up to 220 meters, large size allows them to capture more wind energy and generate more electricity, whereas onshore turbine sizes have come to a limit due to transportation issues.
- **Matter of space:** Offshore wind farms have more potential for expansion and can be easily expanded because there is usually more available space in the ocean as compared to land.

2.3 Offshore wind turbines foundations

The choice of foundation for offshore wind turbines mostly depends on depth of water, distance to shore, seabed features, wave loads, wind loads, economical costs, and available construction technologies [8]. Offshore wind turbines can be bottom fixed or floating depending upon the water depth, distance to shore and some other critical factors, we will discuss both types in detail here.

2.3.1 Bottom fixed turbines

These turbines are generally used in water depths up to 50-70 meters and are suitable when we have relatively stable seabed conditions. These turbines are more cost-effective and easier to install than floating wind turbines. However, they are not suitable for deeper waters or areas with more challenging seabed conditions. Different types of bottom fixed turbines are discussed further [9].

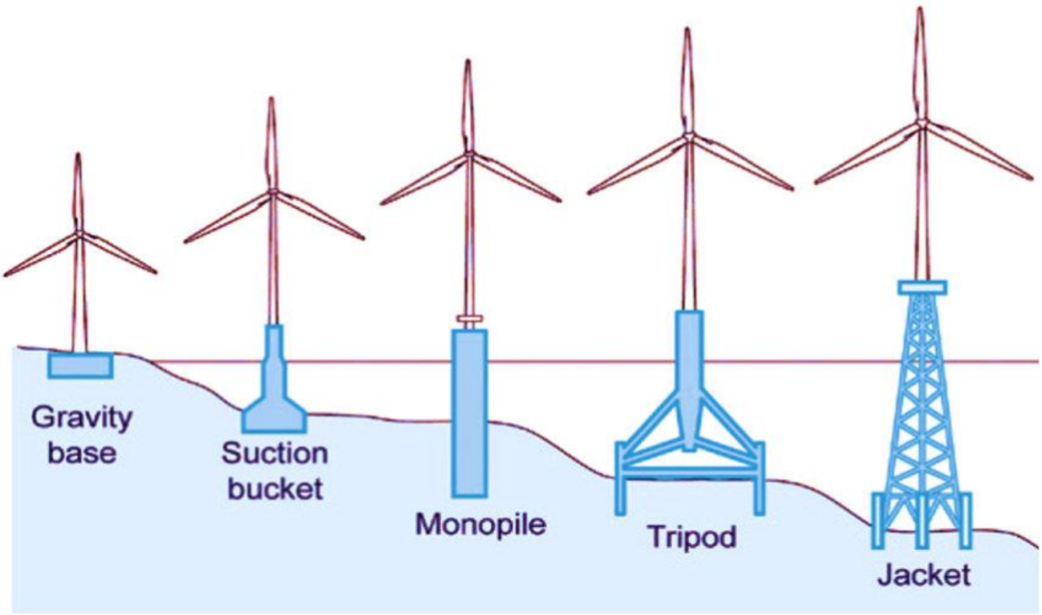

FIGURE 5. TYPES OF BOTTOM FIXED TURBINES IN OFFSHORE INDUSTRY [9].

2.3.1.1 Gravity Base

The Gravity base structure also called as GBS is made up of a transition piece, a turbine tower, and a central concrete or steel shaft filled with sand, rocks, and iron ores. When operating in water deeper than 20 meters, the Gravity base structure is optimal [12].

2.3.1.2 Suction Bucket

Suction buckets are like upside-down buckets, which can be brought down into the seabed to anchor the offshore structures. When the water is pumped out of the bucket, the pressure inside the bucket skirt drops, creating negative pressure that works in tandem with the foundation's weight to push it deeper into the seafloor [10].

2.3.1.3 Monopile

Monopile foundations are the most common bottom fixed foundations for offshore wind, they are suitable for sites having water depth from 0-40m, they consist of large cylindrical steel pipes with a diameter of several meters [11] and their installation requires hydraulic hammering of monopiles into the seabed [12].

2.3.1.4 Jacket Structure

The piles used in jacket structures have four legs and are made up of cross braces that are connected to one another. Pile sleeves are used to drive the foundation's base piles into the seabed to the required depth of water. When the water depth at the site is between 25 and 50 meters, jacket structures form good supports [12].

2.3.1.5 Tripod Structure

The tripod structure is light-weight three-legged steel jacket structure; below the steel column in the centre of the structure there is a steel frame which is used to transmit the load forces from the tower to the three steel piles, at all leg position piles are fixed in order to hook the tripod structure to the seabed [12]. Usually, to install this type of foundation system two to three working days are required with specialized equipment’s [13].

2.3.2 Floating turbines

Floating wind turbines are mounted over a floating platform which is anchored to the seafloor. As the offshore industry developed, and we go further in deep water, bottom fixed turbines were uneconomical and there was need of floating turbines which can go easily in deep water and capture the strong winds of the oceans, the platform of floating wind turbines is connected to the seabed with the help of mooring lines, these mooring lines make sure that wind and wave loads don’t move the turbines. There are various types of floating wind turbines [14].

- Tension Leg platform (TLP)
- Semi-Submersible
- Spar

This thesis provides basic information about three types further.

FIGURE 6. TYPES OF FLOATING TURBINES IN OFFSHORE INDUSTRY [14].

2.3.2.1 Spar Foundation

The spar foundation is basically a cylindrical structure which hangs below the wind turbine tower and floats vertically in deep water. To lower its centre of gravity, ballast is added to the bottom of the cylinder. The platform is anchored, but the lines are slack to enable it to move with the water and prevent damage [14].

There are several advantages of this foundation listed in the article [15].

- Simple Design
- Low cost
- Motions induced by waves are limited

Figure 7 is a schematic diagram of spar type foundation and helps in understanding the concept in more detail [15].

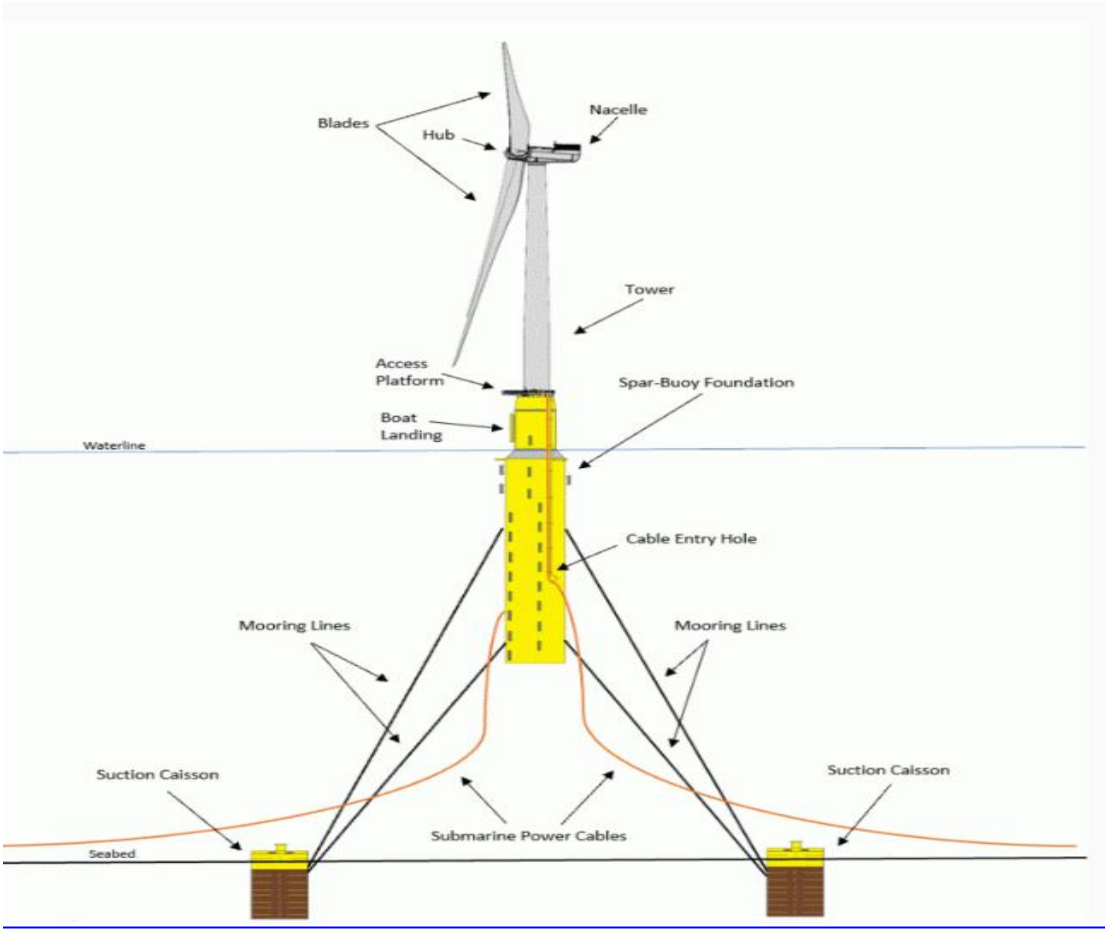

FIGURE 7. SPAR TYPE FOUNDATION [15].

2.3.2.2 Semi-Submersible Foundation

These types of foundations are designed as stabilizing floaters in the wind industry which operates in deep waters [16]. Integrated pontoons with number of columns having beams and braces are key features of semi-submersible foundation, by ballasting the structure the required draft is obtained depending upon the load on the wind turbine. Catenary mooring lines are used to connect the semi sub with the seabed, this design is unique and almost have the advantages of both the spar and barge buoys.

Pros of semi-submersible foundation are given below

- Can be constructed onshore
- Less mooring cost
- Turbines can be installed onshore and then transported towards the site.

Complex and difficult fabrication, high material cost and poor hydrodynamic stability are some disadvantages of this foundation [15].

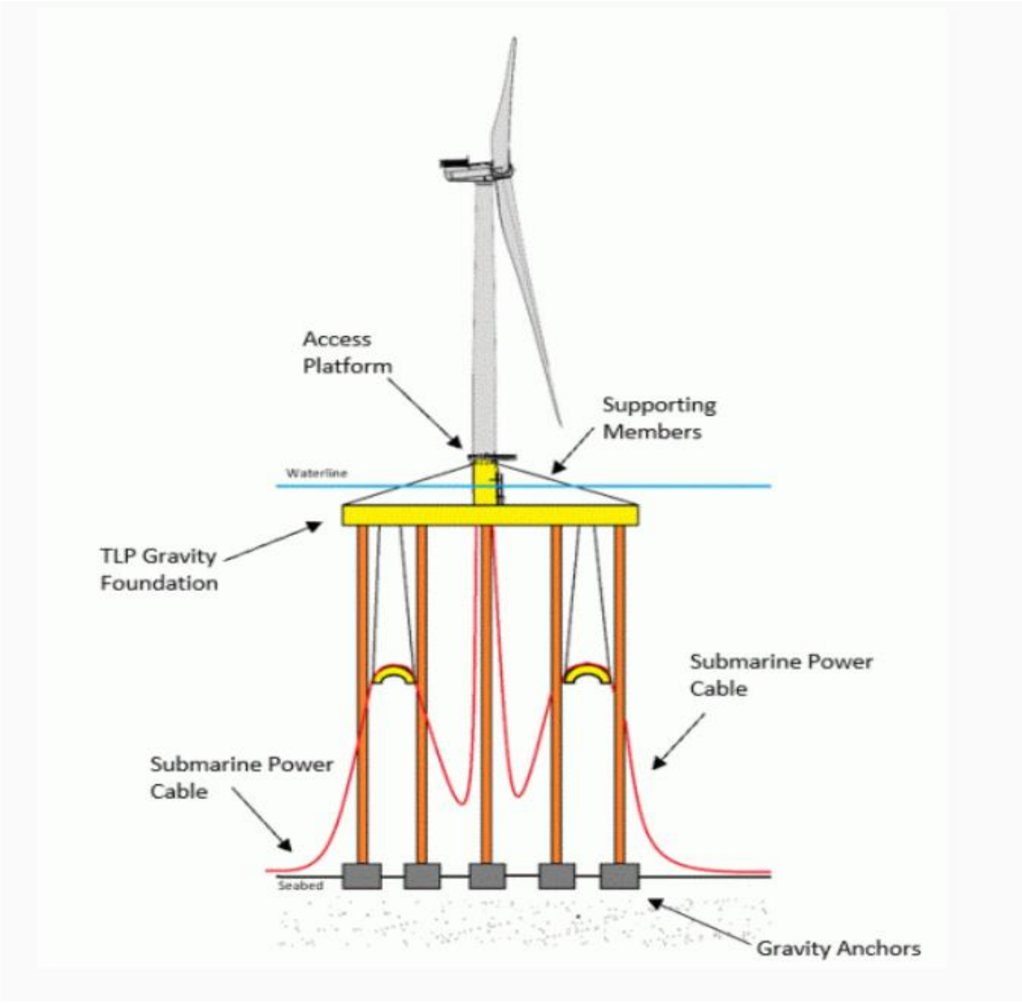

FIGURE 8. SEMISUBMERSIBLE TYPE FOUNDATION [15].

2.3.2.3 TLP Foundation

Tension Leg Platforms (TLPs) have smaller, lighter platforms which are supported by taut vertical lines that connects to the seafloor below. This design allows the platform to move with the water while maintaining its stability [14].

Some advantages of TLP are listed below

- Light weight
- Used in deep waters (50-60m)
- Can be assembled onshore

While high cost of mooring lines and difficulty to maintain stability during Installation and transport are some cons of this foundation [15].

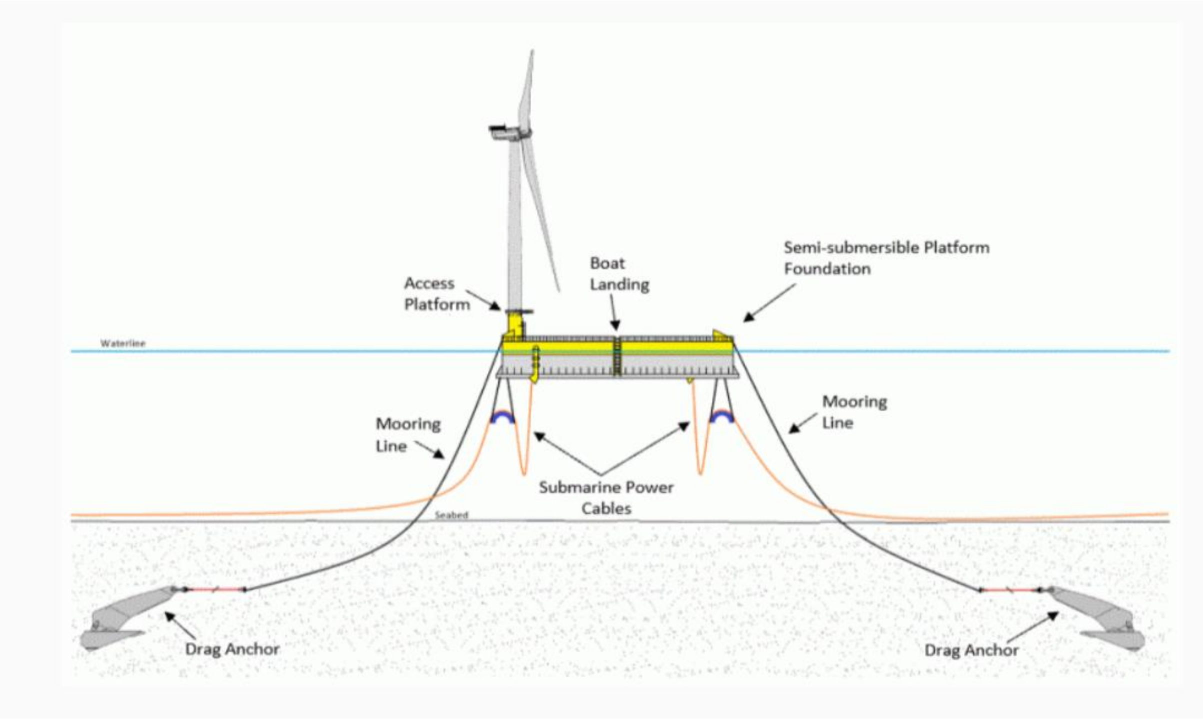

FIGURE 9. TLP TYPE FOUNDATION [15].

2.4 Considerations for site selection

Selecting a site for a wind turbine involves number of considerations, such as wind resources, sea depth, environmental impacts, distance from coastline, and regulatory requirements. Usually, a team of professionals including engineers and environmental consultants work together and do the analysis of the possible sites.

2.4.1 Wind Resources

Wind velocity is very important parameters for calculating power production and is studied in detail when the analysis of possible site is undergoing. Wind velocity is calculated with the help of anemometer, they are connected to wind turbines, and are used to control the starting and shutting of wind turbines depending upon the wind speed [17].

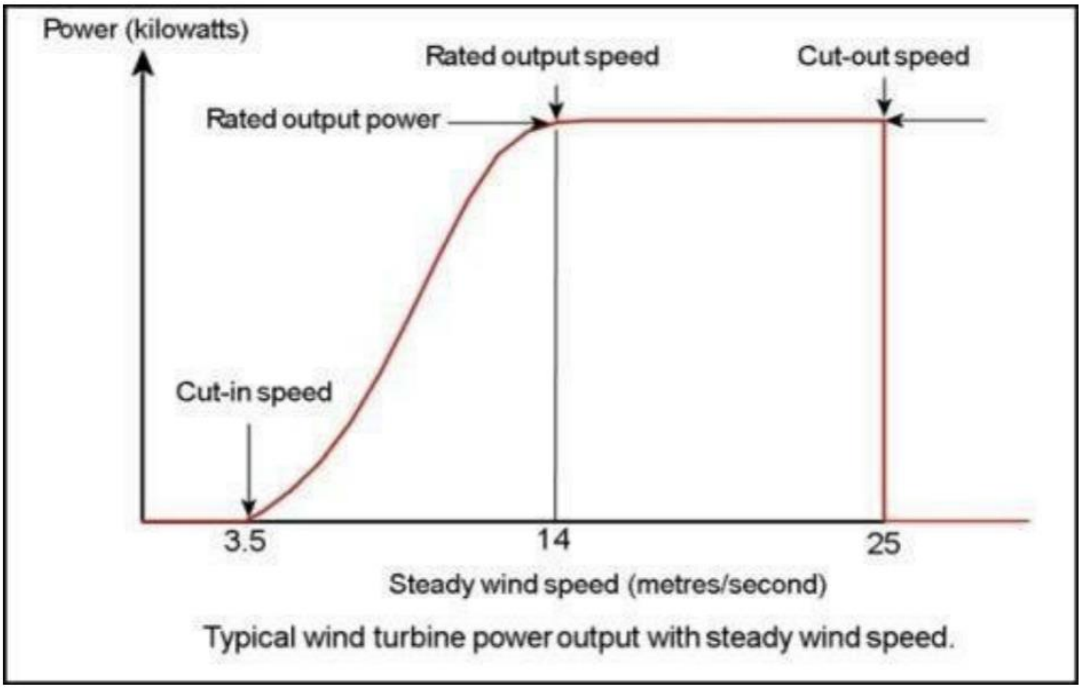

FIGURE 10. WIND TURBINE POWER OUTPUT CURVE WITH STEADY SPEED OF WIND [18].

From this graph it can be seen that when the speed is below 3.5 m/s there is no power production from the wind turbine, as soon as the wind speed reaches 3.5 m/s turbine blades start rotating and generator will start producing electricity, this speed at which production of electricity is started is called as cut in speed. Rated speed is the value at which power production from the wind turbine is maximum and when the speed of wind increases beyond 25 m/s, anemometer sends signal to controller to shut down the turbine to prevent any damage. The blades come to feather position allowing the wind to flow through them, and brakes are applied at the rotor hub. Turbine will restart, when the wind speed will return to a significantly lower speed, known as cut in speed [19].

2.4.2 Depth of sea

For offshore farms, sea depth is also very important parameter and should be considered before the selection of possible site, if sea depth is below 50 metres, then the foundations for the possible site will be fixed bottom, however if the depth is more than 50m than floating foundations will be used, the prices of these concepts vary hugely and have great impact on the economic feasibility of the site [17].

2.4.3 Distance from coastline and existing substations

Engineers assess both these distances, as they have significant impacts on the feasibility of the site, for O&M activities of the wind farm, distance from coastline should be minimum as it helps in easy transportation of crew members and parts of machinery that are needed to be replaced or repaired, and when analysing the cost of cables, it is recommended to have least distance from existing substations [17].

2.4.4 Environmental Factors

Onshore wind farms are considered to be dangerous and serious threat for birds and bats, in the similar way offshore farms affect the marine life in the region, and proper survey of the site should be done so fishing might not get affected, sound and visual impact are the two major concerns shown by community which are associated with operating onshore wind turbines and these should be properly addressed while making an decision about the possible site for the wind farm [20].

2.5 GHG Emissions

There is a misconception among common people; wind turbines have no greenhouse gas emissions, this statement can be true if we analyse only operational face of wind turbines but if we analyse whole lifecycle of wind turbines, we will find that they do emit GHG'S and effect the ozone layer. Onshore wind turbines foundations are usually made by concrete and reinforced steel whereas offshore foundations are made up of steel; extraction of materials, manufacturing, and transportation of materials to the site; all contributes to greenhouse gas emissions. Installation process of onshore and offshore is very different from each other, so does the amount of GHG emissions; onshore installations are usually done by excavator, forklifts, and cranes whereas for offshore installations we require special equipment's like tugboats, cranes, and hydraulic hammers etc [103].

The table below shows the amount of fuel consumed per hour during the installation process by the equipment's and provide a brief idea about GHG emissions.

Onshore		Offshore Shallow-Water		Offshore Deep-Water	
Equipment	**Fuel Consumption (L)**	**Equipment**	**Fuel Consumption (L)**	**Equipment**	**Fuel Consumption (L)**
Generator	418	Pull tunga boat	591	Crane	620.1
Crane	620.1	Workboat	148.5	Forklift	64.0
Truck Mixer	69.7	Crane	620.1	Tugboat	628
Truck Gravel	74.7	Self-propelled jack-up barge	21,330	Auxiliary boats	297
Forklift	64.0	Hydraulic Hammer	44.3		
Excavation digger	44.1				

TABLE 1. AMOUNT OF FUEL CONSUMPTION PER HOUR BY EQUIPMENT'S

From the following figures it can be noted that GHG emissions are reduced by increasing wind turbines size, but the ozone layer depletion rate increases with the increase in size, ozone layer depletion rate is a concern for engineers and scientists as this is direct source of UV rays and cause severe diseases in humans. These results are taken from [103], where 3 wind farms are analysed.

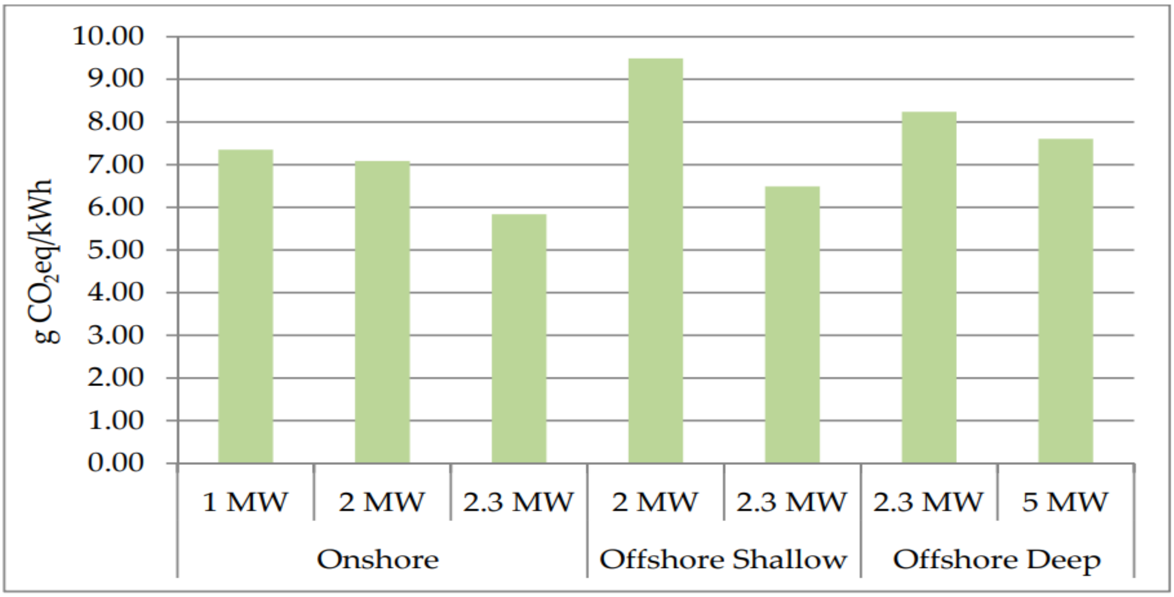

FIGURE 11. COMPARISON OF GLOBAL WARMING POTENTIAL [103].

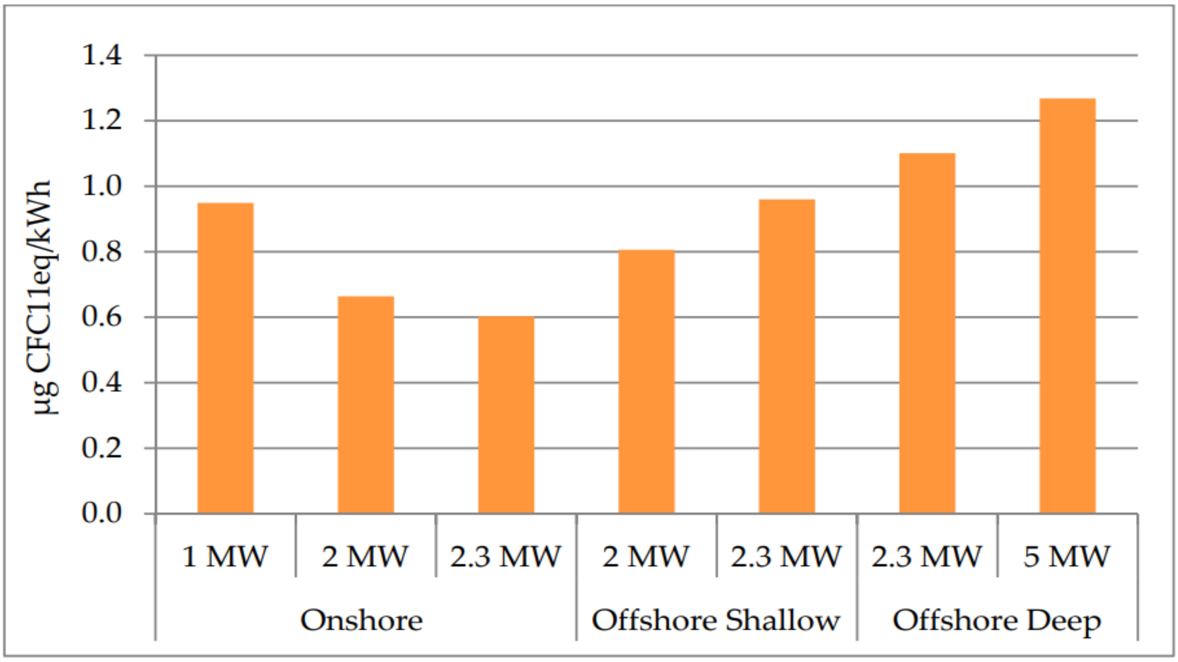

FIGURE 12. COMPARISON OF OZONE LAYER DEPLETION [103].

CHAPTER 3: Exploring O&M and Logistics Challenges

This chapter focuses on the critical failures encountered in wind turbines, the maintenance strategies used to fix these failures, this chapter also give a brief information about new technologies and strategies in O&M of wind turbines.

3.1 Operations and Maintenance

Wind turbines are huge structures with number of different components, operation and maintenance terms are often used together, but both are planned separately, operational activities basically focus on achieving maximum power from the wind, while maintenance activities aim to minimize risk of component failure of wind turbines. Some major components that fail during operations in wind turbines are blades, gearbox, and generator.

3.2 Gear box failure

The wind turbine's gear box is a crucial part of the machine and is used to convert low speed and high torque of main shaft to high speed and low torque for the generator, Different turbines use different configurations of gearbox, but still most wind turbines today in operation have constant gear ratios between the generator and rotor of the turbine, although wind turbines having variable gear ratio allows discrete changes to the speed of rotor and help in achieving high efficiency. Gearboxes have sun and planetary gears with parallel gears to get high values of transmission ratios, however prolonged running of wind turbines in harsh conditions can result in shaft imbalance, bearing damage, oil leakages and high temperatures, and hence can result in the failure of gearbox. Gearbox has highest failure rate among all components, longest downtime, and highest economical loss; according to statistical failure data of components gearbox failure contributes almost 18 percent to the maintenance cost of the wind turbine [26,27].

3.3 Failure of Blades

One of the most common causes of wind turbine breakdown is a malfunctioning blade, wind turbine blades are usually made of fiberglass or carbon fibre depending upon the operating conditions, these blades are subjected to severe mechanical and environmental stresses during their operations; ice, rain, moisture, sand, and erosion affect these blades badly, transportation, thunderbolts and bird collisions also impact the working of blades and causes failure of blades. [21-24]. A survey was conducted by wind turbine service men in order to detect links between failure mechanism of blades and age of the wind turbine, figure 13 illustrates the results obtained from this research [105].

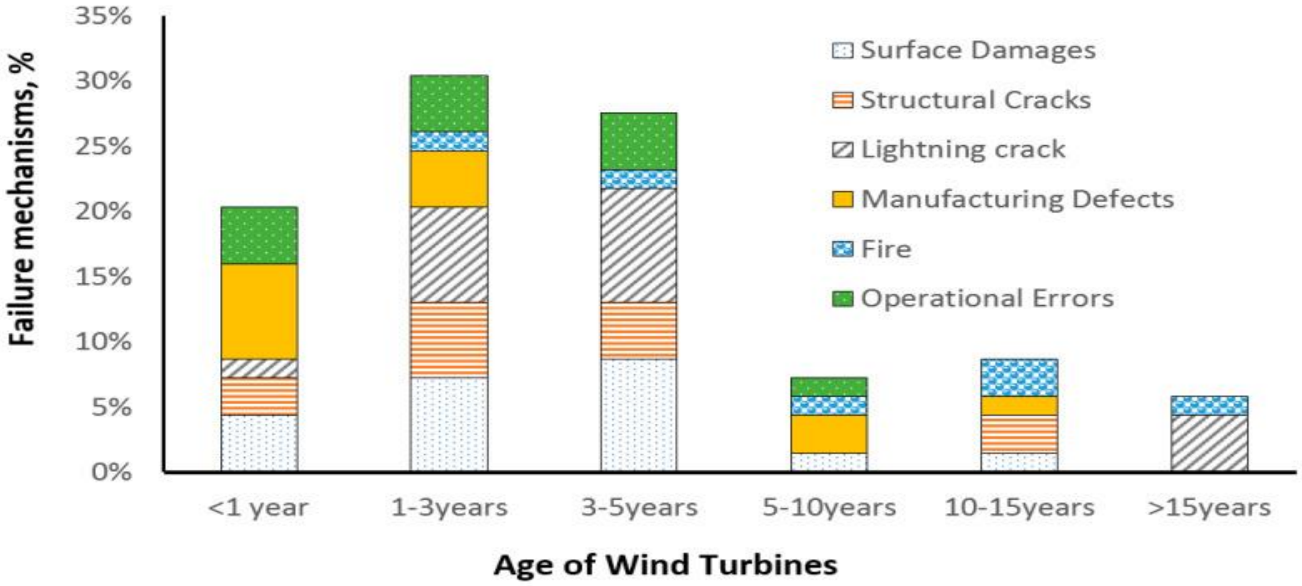

FIGURE 13. FAILURE MECHANISM OF BLADES AND AGE OF TURBINE [105].

3.4 Generator failure

Generators in wind turbines are used to convert the mechanical energy of the incoming wind into electrical energy. AC generators are preferred for wind turbines as DC generators have high initial and maintenance cost. Number of failures can arise in generators during operations due to overloading, electrical faults, and lack of lubrication to the mechanical components, these failures can be electrical failures, bearing failures, slip ring failures, overheating, abnormal noises, and damage to the insulation's failure [106].

3.5 Maintenance Strategies for Wind Turbines

Maintenance is very costly process both for onshore and offshore wind turbines and it is required to keep the smooth working of all the components, increase the availability of the equipment, ensure safety of workers; so different strategies are used to maintain these components. Two main strategies that are used for maintenance of wind turbines are preventive and corrective maintenance strategies. Scheduled maintenance and condition-based maintenance are two subsets of preventive maintenance.

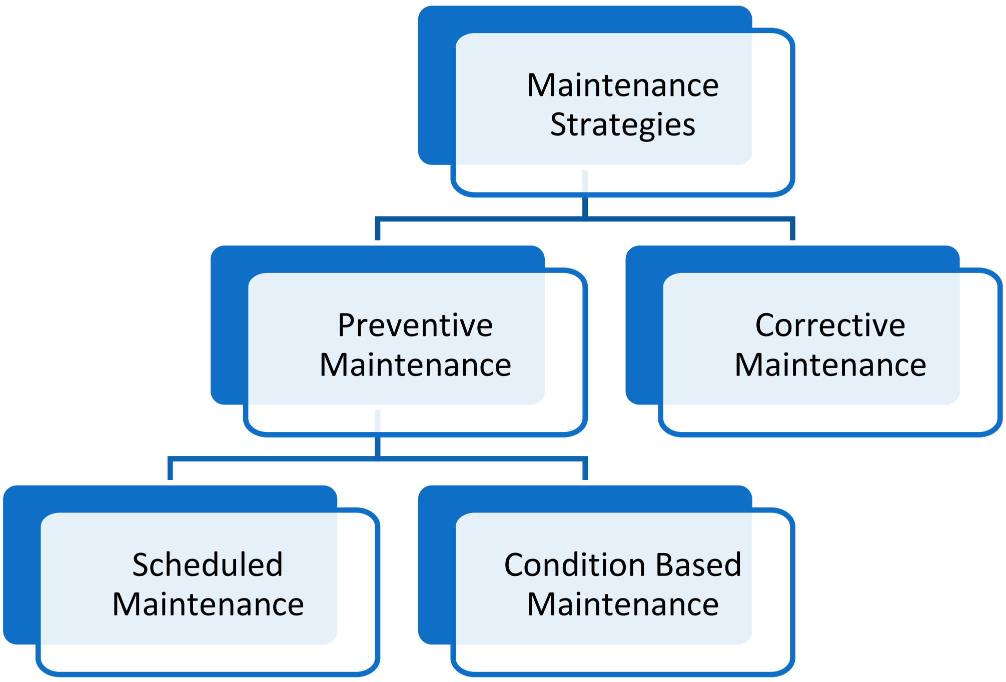

FIGURE 14. MAINTENANCE STRATEGIES FOR WIND TURBINES

3.5.1 Corrective Maintenance

This maintenance strategy is also called as run to failure, this maintenance concept is carried out when any fault is recognized and intended to put an item into a state in which it can carry out the desired task [28]. This strategy is used after the failure of a component, to bring the component back in working state and it is usually more useful for those assets whose failure has very low consequences i.e., no safety risks and has minimal effect on production [29].This maintenance strategy is usually implemented for non-critical components or when the maintenance cost is higher than the cost of changing the equipment after the failure.

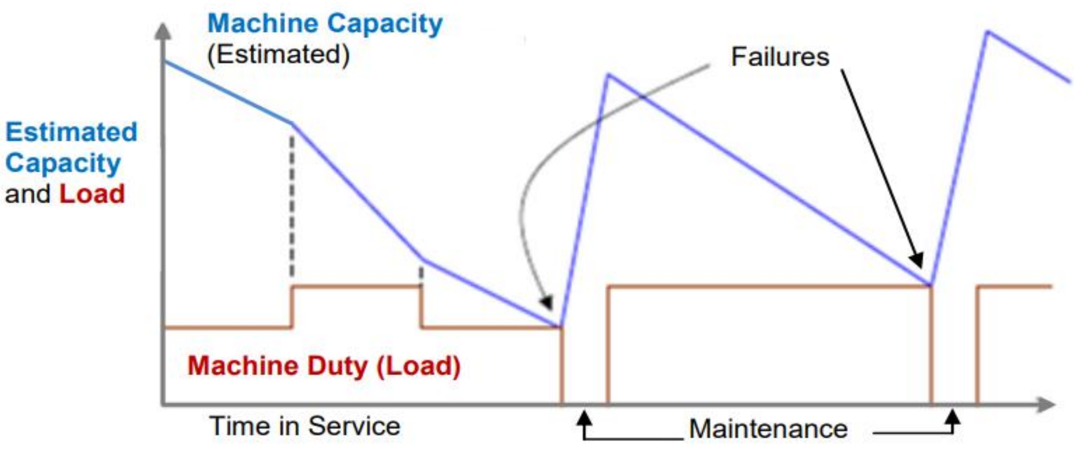

FIGURE 15. CORRECTIVE MAINTENANCE [33].

3.5.2 Preventive Maintenance

Preventive maintenance is defined as [28]: as "the maintenance plan which is performed to delay the onset of failure or the deterioration of an item's functionality by performing routine checks at regular intervals or in accordance with established criteria". The PM strategy is performed at regular intervals to delay failures or to head off failures from occurring. There are two different types of preventive maintenance techniques; the scheduled maintenance and the condition-based maintenance, differentiating factor between these two types is the way of deciding when to perform the preventive maintenance [30].

3.5.2.1 Condition Based Maintenance

This maintenance strategy is carried out when the physical condition of the equipment is to be analyzed [31]. This maintenance strategy is based on performance analysis and utilizes real-time data which is measured by sensors to detect failure symptoms [32]. From the following figure it can be seen that constant monitoring is being done of the desired component and when there is some difference in the desired values sensors detect the failure and send the signals to operators, that maintenance is required. Further in this chapter some condition monitoring techniques that are in use for maintenance of wind turbines are discussed.

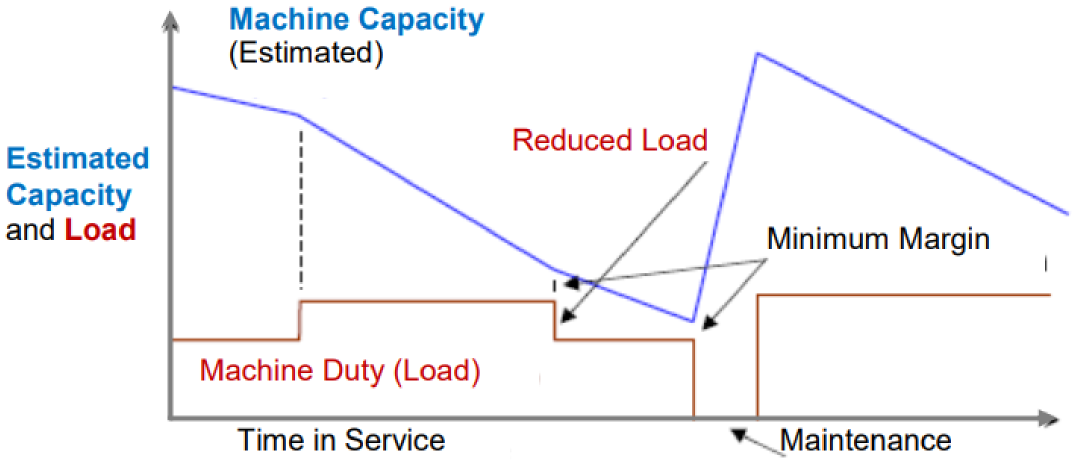

FIGURE 16. CONDITION BASED MAINTENANCE [33].

3.5.2.1.1 Vibration Analysis

In order to keep an eye on the condition of moving parts in wind turbines, vibration analysis is a common practice. Position transducers are used for low frequencies, velocity sensors are used for medium frequencies, accelerometers are used for high frequencies, and spectral emitted energy sensors are used for very high frequencies in this method [34].

Vibration analysis is suitable for monitoring various wind turbine components, including gearboxes, bearings, and blades. The sensor configuration in a nacelle, which houses many of the wind turbine components, is illustrated in reference [35]. Moreover, some other vibration and acoustic methods are used for condition monitoring of rolling bearings, as reviewed by Tandon and Nakra [36]. These methods include vibration and sound measurement in time and frequency domains, the shock pulse method, and the acoustic emission technique [38].

3.5.2.1.2 Acoustic Emissions

In order to detect the instantaneous release of strain energy and the generation of elastic waves when a metal structure is modified, acoustic emissions (AE) analysis has recently become a popular method. In wind turbines, AE technique is used to detect the propagation of cracks earlier than vibration analysis technique, The use of AE is increasing significantly for both condition monitoring of rotating wind turbine components as well as blades [38-41].

AE parameters for detecting faults in radially loaded ball bearings experiencing different speeds have been measured and interpreted in [42]. While vibration monitoring uses sensors to detect movement in a component, acoustic monitoring uses sensors to record sound directly by adhering them to a surface with a flexible glue that has low attenuation. Blades of wind turbines can be monitored for damage using AE sensors in a similar fashion to how bearings and gearboxes are monitored, as discussed in [43].

3.5.2.1.3 Ultrasonic testing

The Ultrasonic testing (UT) methods are commonly used in the wind energy industry for inspections of wind turbine towers and blades. This method assesses both visible and hidden flaws in wind turbine construction. [44-46]. It is a reliable method for determining the material properties of the major turbine components because ultrasonic waves propagate widely and permit estimation of the type and location of detected defects. In [47], a method using UT to visualize the internal structure of wind turbine blades is described.

3.6 Future Innovations in operation and maintenance

There are several potential innovations in operations and maintenance of wind turbines, many people believe that the future will be of floating wind turbines, and it is estimated that by 2040 70 GW of electricity will be produced by these FOW [48]. Tow to shore strategy is a new maintenance strategy and many engineers are willing to use this strategy soon for the maintenance of FOW. Now jack up vessels are used for removing major components of bottom fixed turbines, but these vessels are limited to 60m water depth [49] so major components replacement for FOW will be done either by on site methods; floating-to-floating transfer, floating cranes, and self-hoisting equipment or off-site methods such as T2S [50]. Many companies are planning to automize some maintenance activities for example using drones and robots for inspecting the condition of wind turbine blades, this will reduce the cost, save time, and reduce the downtimes and increase efficiency [51]. Due to high wind speeds and contact with different elements wind turbines blade erode and annual production reduces, drones have the ability to capture pictures of different elements and components which can be analysed by computers and help in detecting failure earlier. Figure 17 is visual representation of drones inspecting wind turbines blade and sending signals to the operator after detecting faults [51].

FIGURE 17. INSPECTION OF WIND FARM BY ROBOTICS [51].

Similarly, AUV and ROV'S are used for inspection of subsea structures and cables.

Digital twin technology is going to revolutionize the operations and maintenance of wind turbines, it will help in maximizing the production, reducing the downtimes and will optimize the wind turbine performance. This technology basically creates a digital copy or "twin" of the physical asset, and it allows real-time remote monitoring, digital twin; one of most promising technology of the wind industry allows the operator to control the functions and ensure better safety standards during operations and maintenance activities [53].

FIGURE 18. OVERVIEW OF DIGITAL WIND FARM [52].

3.7 Logistics and Supply chain

Logistics and supply chain management of the parts of the wind turbines are major concerns that should be prioritized, particularly in the offshore wind industry, different models have been proposed to evaluate the offshore logistics and results show that logistics depends upon factors like, distance to shore, weather conditions and sea depth etc. Improving LCOE is the objective of every owner and improved logistics can help the owners in achieving this goal. Poulsen and Hasager [54] proposed a complete definition for the offshore wind logistics: "*Parts, modules, components, people and tools are safely stored and moved, weather permitting, onshore, as well as offshore by air/ocean/land using various transportation assets and transport equipment*". During construction phase which is almost about 1 year the logistic operations are much more significant than during the maintenance phase. The construction phase starts from preassembly, transportation of turbines from port to the site, installation, offshore commissioning and ends after trial quality check. Installation vessels usually called as jack up vessels are used for transportation and installation of wind turbines; these vessels are of special kind and have foldable legs which can go down into the seabed providing a stable platform for the operations [55]. Support vessels like crew transfer vessels (CTV) and accommodation vessels are also used during construction phase and helps in transferring the crew to the site location.

The North Sea region has favourable conditions for offshore wind due to high wind speed; but this high wind speed and wave height creates a lot of problems during the installation process and only give 120 days in a year for this process [56,57]. As the wind turbines are growing their structures are becoming more fragile and prone to damage, so installation processes can be performed to a certain wind speed span which delays the project timelines and results in enormous unanticipated expenditures [58]. Logistics decisions are very crucial and have huge impacts on profitability [59]. Managing logistics is one of the major challenges faced by offshore industry and for each project different support tools are used for examination of supply chain methods. Installation depends on weather conditions and hence is considered as bottleneck for the supply chain, when the installation process is disturbed and manufactured parts are on time it creates stock backups in the supply chain.

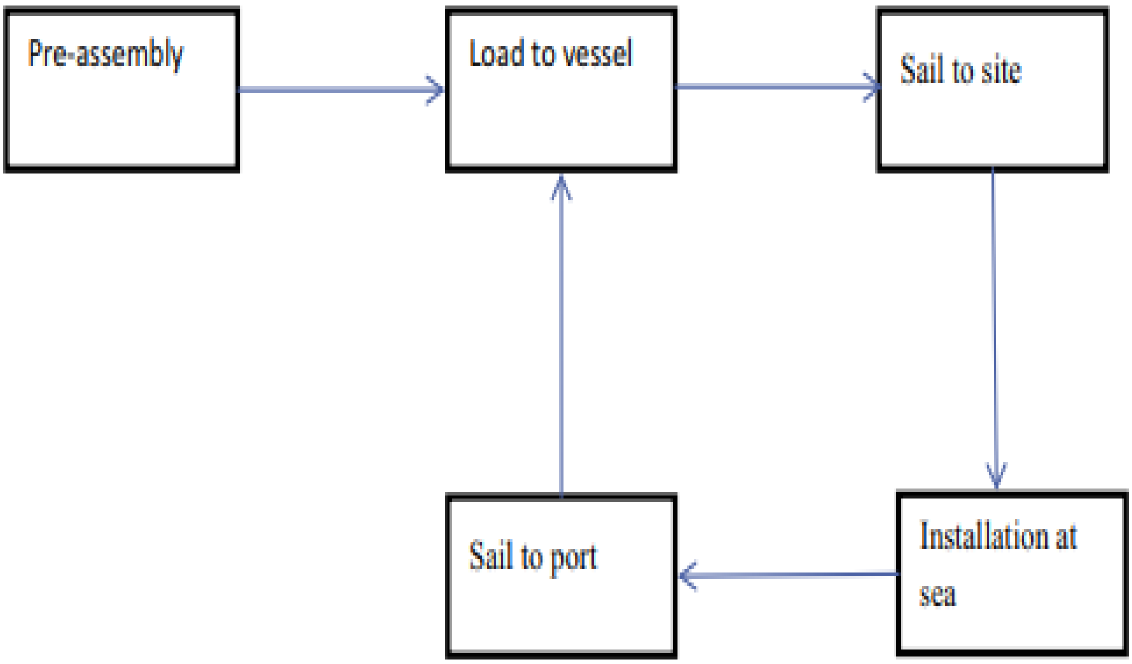

FIGURE 19. OVERVIEW OF OFFSHORE WIND INSTALLATION PROCESSES [60].

Figure 19 explains the installation process, multiple turbines are pre-assembled to prevent any delay and when the weather is favourable these turbines are loaded on vessels and sail towards the site, where jack up vessels perform the installation process. There are 2 main logistics strategies that are performed during offshore installation

- All in one strategy
- Feeder system strategy

In all-in-one strategy, the installation vessel serves as a dual-purpose vessel; it not only instal components but also transports the components. The vessel is first fully loaded with the components at the base port and then take them directly to the installation site. Once there, all the components are installed part by part by the same vessel without any unloading processes. After completing the installation process, the vessel goes back to port to pick up the next set of components. On the other hand, in feeder strategy the installation unit stays at the site and is being continuously supplied with components by smaller feeder vessels or barges, these feeder vessels bring the required components from one or more base ports to the installation unit [60].

CHAPTER 4: End of Life Cycle

This chapter is all about end-of-life management of wind turbines including various concepts like extension of life, recycling, repurposing, and decommissioning. It also explores the challenges that are related to efficient decommissioning starting from vessels accessibility to regulations and licensing.

The first offshore wind farm was constructed in 1991, and since then this industry has undergone significant growth, resulting in a total installed capacity of 19 GW in Europe [61]. While the initial challenges primarily were related to planning and construction [62], new concerns popped up regarding the ageing of the wind turbine fleet [63], which are like those encountered by onshore wind farms. However, the consequences of end-of-life decisions for offshore wind turbines are even more critical due to the unique environmental difficulties and constraints associated with offshore operations.

Wind turbines end-of-life has recently become a major area of interest for many companies, approximately 30% of Europe's total installed wind turbines will be over 15 years old by 2020 [63]. As the typical service life of wind turbines is 20 years, it is crucial to carefully prepare for various potential end-of-life scenarios [64].

The end of life of wind turbines can be very crucial and challenging, it is one of the hot topics in the industry due to the aging of assets. End-of-life strategies are considered and given great importance in the early design phase of any wind farm project. Failure to take this into account can result in severe consequences, including unexpected costs as noted in [65].

There are several technological and economic factors that operators keep in mind while planning the end of life of aging wind farms, sometimes it is feasible economically and technologically to perform direct decommissioning, and sometimes decommissioning is delayed by some intermediate processes, operators decide the best course of action for their farms and took the decision either to extend the lifetime, do repowering process or just go for decommissioning [66]. In this chapter intermediate processes and decommissioning process are discussed in detail.

4.1 Extension of Life

Life time extension assessment is usually carried out in the last years of operating permit, experts from different departments sit together and discuss the analytical and technical results, technical results come after doing onsite inspections and analytical results come after comparing the electricity generation data of the turbine with other turbines [67], a status report is generated which helps in determining a precise financial estimate of the expenses that will have to be bare to replace the critical parts and do repairs. The information collected from these reports is very critical in decision making for wind farm operators as it provides an insight about the opportunities and efforts that will be required in continuing the operations [68].

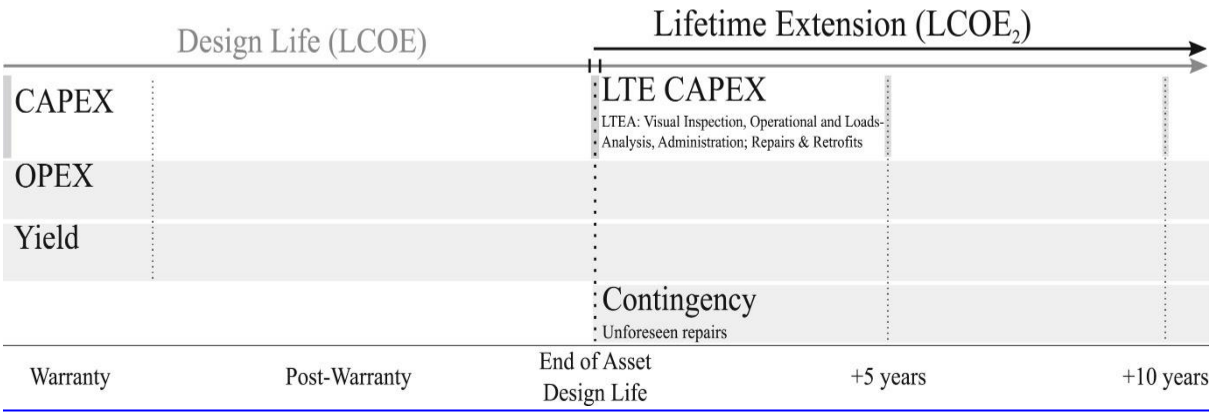

FIGURE 20. OVERVIEW OF LIFETIME EXTENSION METHODOLOGY [69].

4.2 Repowering

Repowering of wind turbines involves the process of utilizing the same location while replacing the worn out and obsolete wind turbine components and turbines with new and better ones, thereby elevating the wind farm's potential for producing electricity, The goal is to enhance the power output of the wind turbine and try to extend its lifespan [70].

There are two main strategies which are used in industry for repowering i.e., partial repowering and full repowering. Partial repowering involves substitution of small components of the wind turbine such as rotor, gearbox, and generators etc [71], whereas full repowering is process in which old turbines are decommissioned and removed from the site and replaced by new turbines of bigger capacity at the same site [71-72].

The reliability and power output of wind turbines are both improved by repowering them. Access to substations, grid connections, and significant cost savings due to existing licenses, agreements, and historical data are some other advantages of repowering wind turbines [73].

Repowering of wind turbines also involves several challenges; increased risk of failure of tower and foundations when reused. Furthermore, there might be some regulatory hurdles and challenges related to interconnection agreements and leases [72], Despite of all these challenges, repowering of wind turbines is getting popularity as it is considered as cost-effective way to increase the energy output and lifespan of wind turbines.

4.3 Decommissioning

Decommissioning is basically set of actions which are performed to restore a site into its original condition, decommissioning usually takes place when the project life is completed and is considered as last phase of the project, in this thesis our focus is towards decommissioning of offshore wind turbines, and challenges faced during the process. The primary parts that should be detached during decommissioning process of wind turbines are, underwater cables, wind turbine foundations, transition pieces and offshore substations [74]. The figure 21 depicts the number of wind farms which are going to be decommissioned in Europe from 2016 to 2038, and this number will increase significantly from 2028 to 2038, whereas figure 22 shows the number of turbines reaching 20 years in Europe.

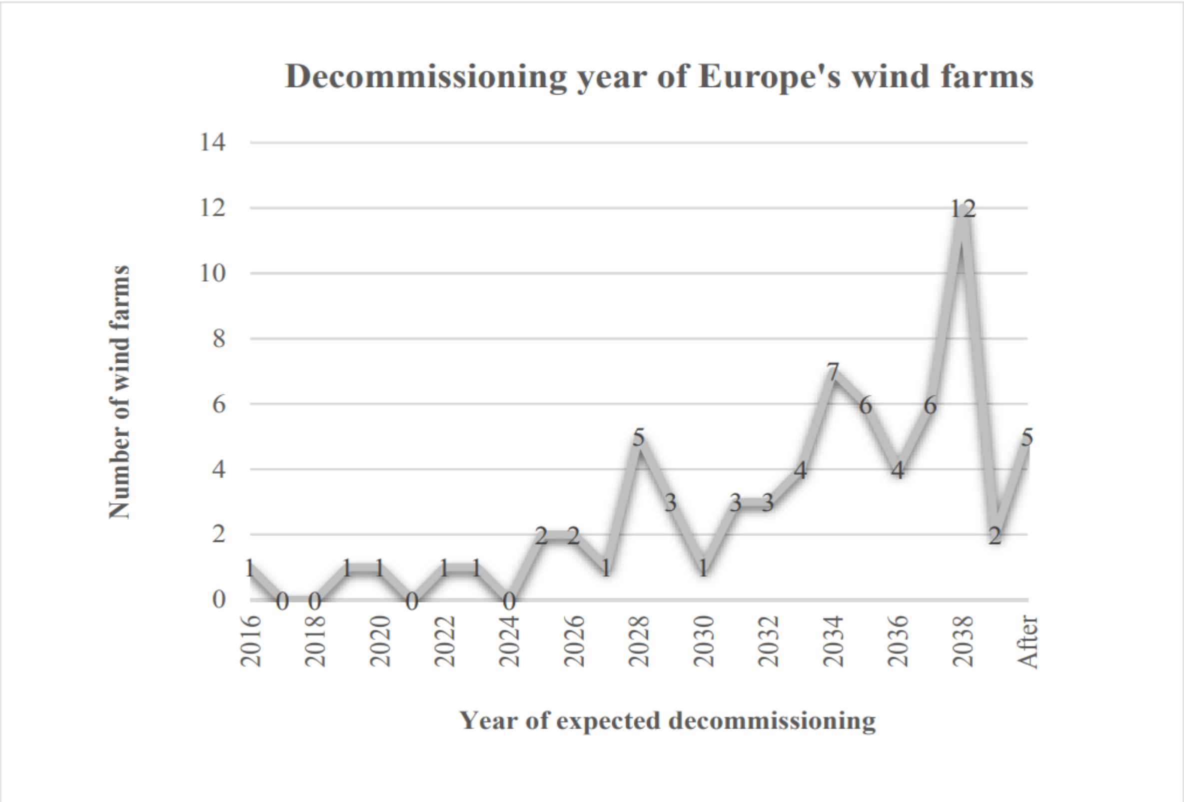

FIGURE 21. DECOMMISSIONING OF EXISTING OFFSHORE WIND FARMS AND EXPECTED YEARS [65].

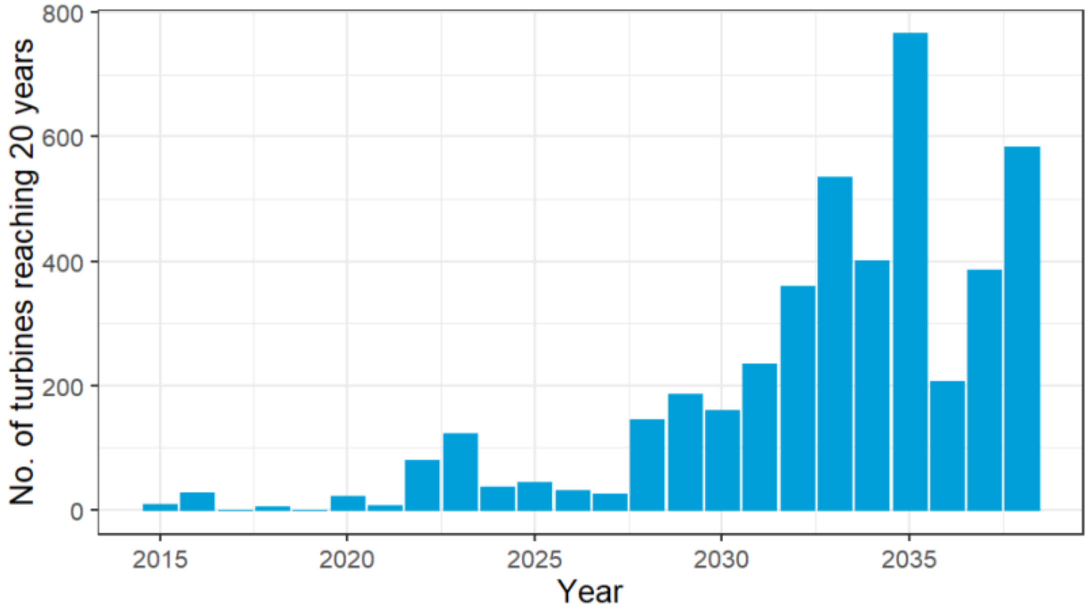

FIGURE 22. OVERVIEW OF WIND TURBINES IN EUROPE REACHING 20 YEARS [76].

There are some important parameters which must be kept in mind before decommissioning, some of them are given below.

1. The type of foundation
2. Depth of water
3. Wind speed
4. Wave Heights
5. Distance between shore and site
6. Availability of vessels and other lifting machinery

The main parameter is transportation of the complete structure onshore and then disassembling, this helps in reducing the costs of the process and reduces the risks that could be faced due to extreme weather conditions offshore [75].

4.4 Challenges in Decommissioning

During Decommissioning of wind turbines operators face a lot of challenges, and these challenges need to be given great importance before the process starts, according to paper [64] some important challenges that are faced by operators are listed below.

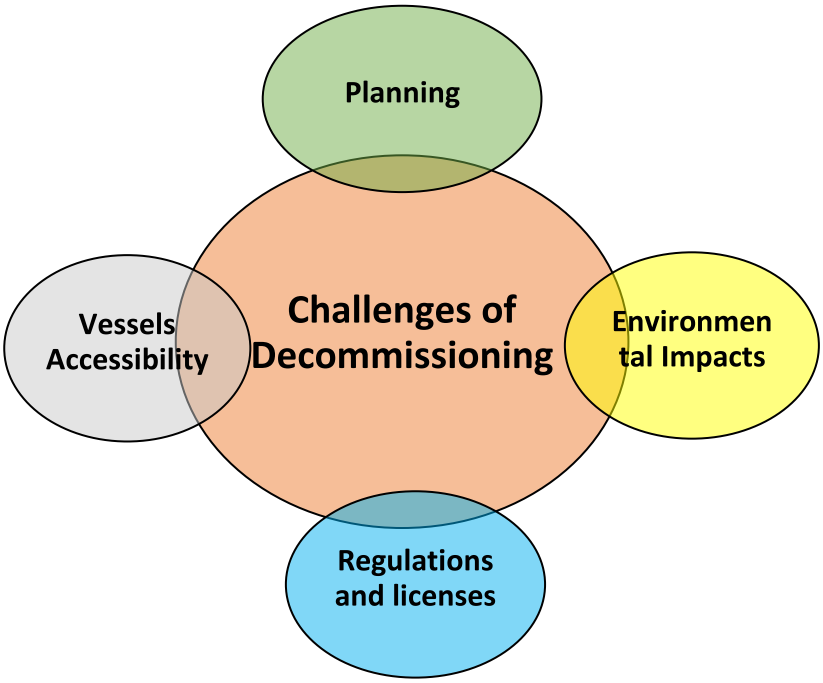

FIGURE 23. CHALLENGES OF DECOMMISSIONING [64].

4.4.1 Regulations and Licensing Issues

Decommissioning of wind turbines is very new for the industry, and so far only 5-6 wind farms have been decommissioned in Europe, and the whole process is not completely regulated and lacks data for the recommended practices, so far in the industry polluter pay principle is applied, which states wind farm owner will be responsible for any damage to the environment and he will make sure he returns the site in the original state after decommissioning [64-65].

4.4.2 Environmental and Ecological Effects

During installation of wind turbines, marine life is impacted badly; after installation with the passage of time the habitat is colonised again. During decommissioning there will be disruption again in the seabed and all the marine life living in that area will be disturbed. During dismantling high intensity noise is produced by vessels which affect the mammals and birds, the amount of disturbance also depends upon the type of foundations, monopile and gravity base foundations will have more impacts on the seabed (as they require concrete ballasts) than the floating ones. It is better to avoid decommissioning during breeding times else it will affect marine life badly [77-78].

4.4.3 Planning Procedure

Planning phase is very critical for decommissioning as it is strongly interlinked with the cost, planning is based on certain factors like the type of foundation, depth of water, weather conditions, distance between shore and site and total dismantling cost. Planning is done almost 9-10 years in advance; before actual decommissioning starts, so there is a chance of substantial changes, moreover due to absence of real time data and less experience; planning and cost estimates are highly effected [64], engineers are trying their best to solve this issue and have proposed an optimization model for decommissioning in [79] this optimization model will help in reducing the costs and scheduling the tasks in proper order.

4.4.4 Vessels Accessibility

Even though there are many vessels that can be hired for decommissioning [80], their accessibility can be limited because of the huge demands for new offshore installations in the coming years [82], operations and maintenance activities in ongoing projects, and decommissioning of oil and gas facilities that occur because of industry synergies. To prevent this possible impediment, it is necessary to secure contractual agreements well in advance. The vessels accessibility is influenced not only by expensive daily rates but also by significant factors of unpredictability, such as weather, equipment utilized, and market fluctuations. As a result, it is advisable to adopt a plan that minimizes the offshore lifting and operational duration to mitigate costs and potential hazards [81].

4.5 Cost Analysis for Decommissioning

Estimated cost for decommissioning any wind farm is almost 2-3% of the total capital cost and somewhat between 60-70% of the installation cost, operators need to keep in mind that end of life is also going to consume a lot of money and they should save during the middle of operational period, this cost can increased further if decommissioning has to be performed before the planned time [83].

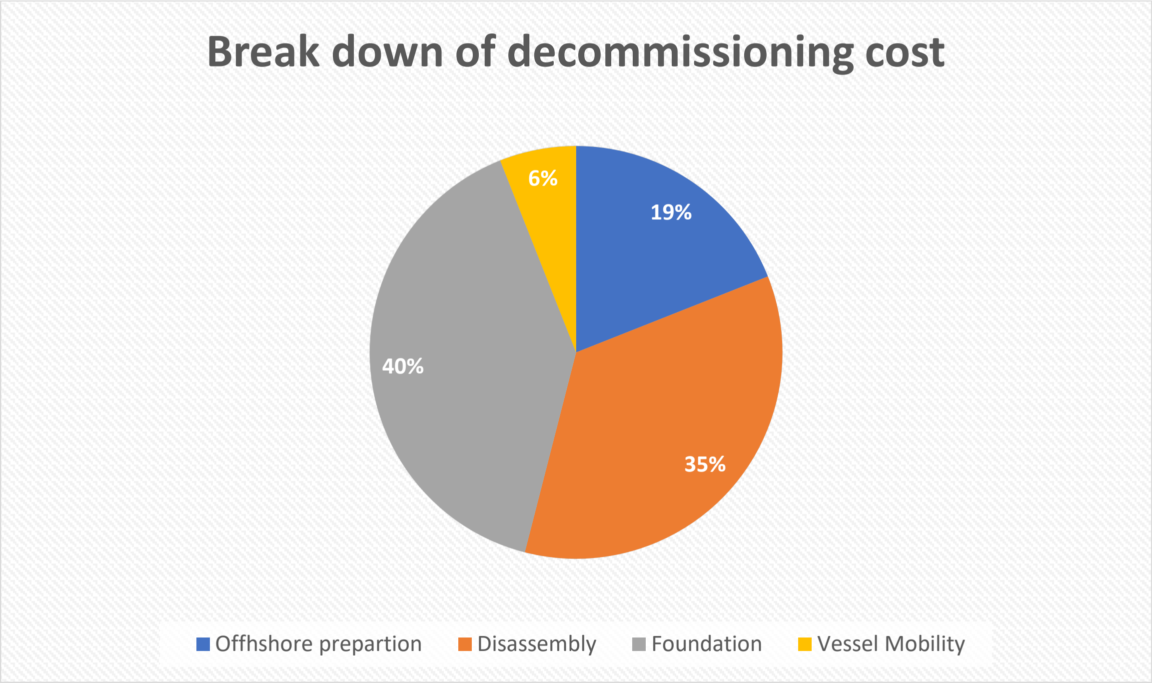

FIGURE 24. BREAKDOWN OF DECOMMISSIONING COST [83].

From the above figure, it can be observed that foundation removal process is very expensive process, as the foundations are heavy and require heavy machinery and complex techniques for removal, this breakdown is only subjected to fixed bottom turbines as work for decommissioning of floating is under considerations, disassembly cost is also very high due to time taking activities [65].

4.6 Recycling of Wind turbines

Wind turbines consist of 3 main parts: foundation, nacelle and three blades. Foundation is usually made from concrete or steel; the nacelle has steel and copper composition, and blades usually are made from composite materials. Concrete and composite material are considered hazardous for the environment. Wind turbines blades are made up of glass fibre reinforced fibres and polymer matrix [87]. Recycling of wind turbine blades is new topic in the industry, after reaching end of life stage, there are 3 options to deal with the blade’s material, either to landfill the material, which is least preferred or do incineration which is very common these days but have some defects like ash production, the third option is to do recycling [84]. Before the recycling process blades need to be intersected roughly, several techniques are used for disintegration of blades into smaller parts like jaw cutter technique, shredding and crushing [85], products after mechanical disintegration can be used for strengthening other products, making insulation products like pellets and panels. Smaller parts can be further processed by using different techniques like pyrolysis, solvolysis, decomposition of materials and then be used for the desired purpose as shown in the figure [86].

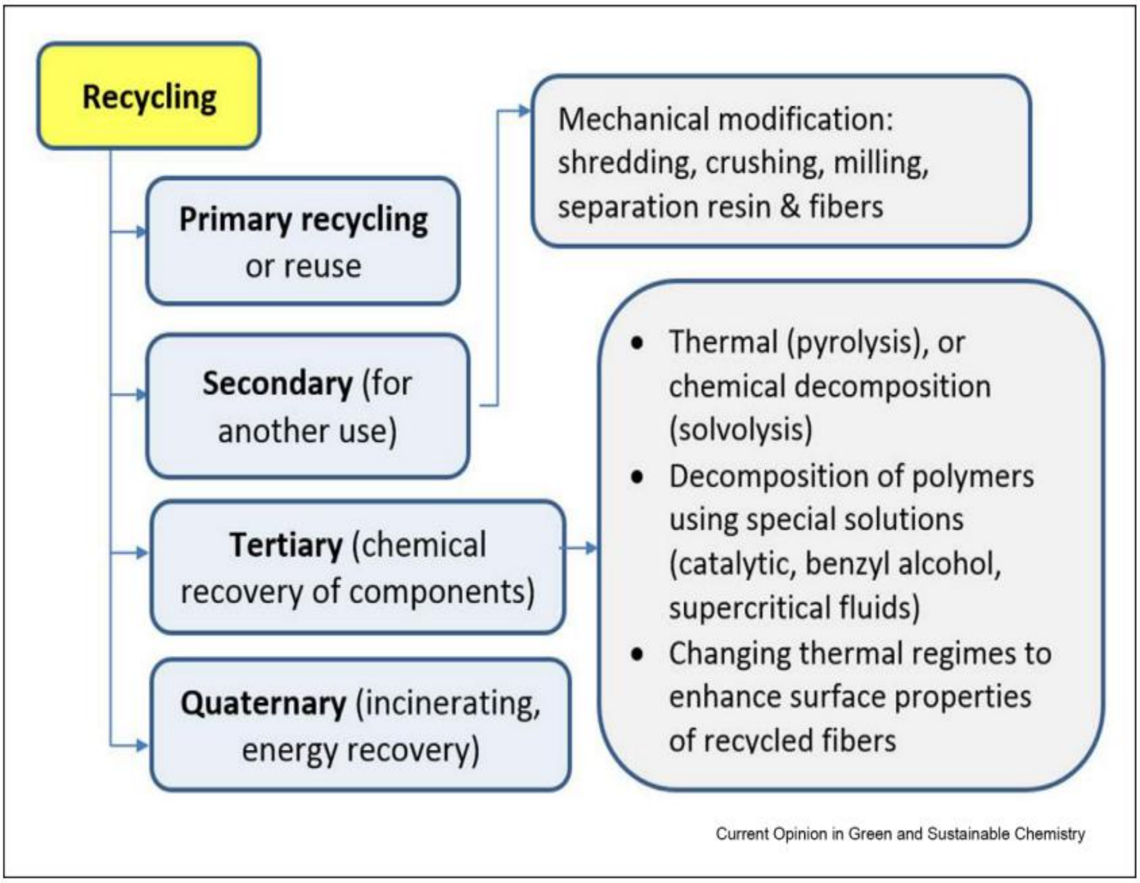

FIGURE 26. OVERVIEW OF POSSIBILITIES OF RECYCLING [86].

Chapter 5: Analysis and Results

This chapter focuses on system contexts diagrams, N square diagrams and Failure mode effects and criticality analysis of critical wind turbine components and highlights on lifecycle costing and calculations related to reliability of wind turbine components. The main target of this analysis is to identify those components of offshore wind turbine which have high failure rates, identify their failure modes, failure causes and consequences and give them a suitable risk priority number.

5.1 Technical Hierarchy

There are many ways in which offshore wind turbines can be divided into, With the knowledge gained from ISO 14224 standards and by research paper [88], a technical hierarchy has been developed, which categorizes wind turbine into equipment and component level. Figure 27 shows the whole hierarchy of the wind turbine under consideration. This thesis will only focus on main equipment's and components which are more important.

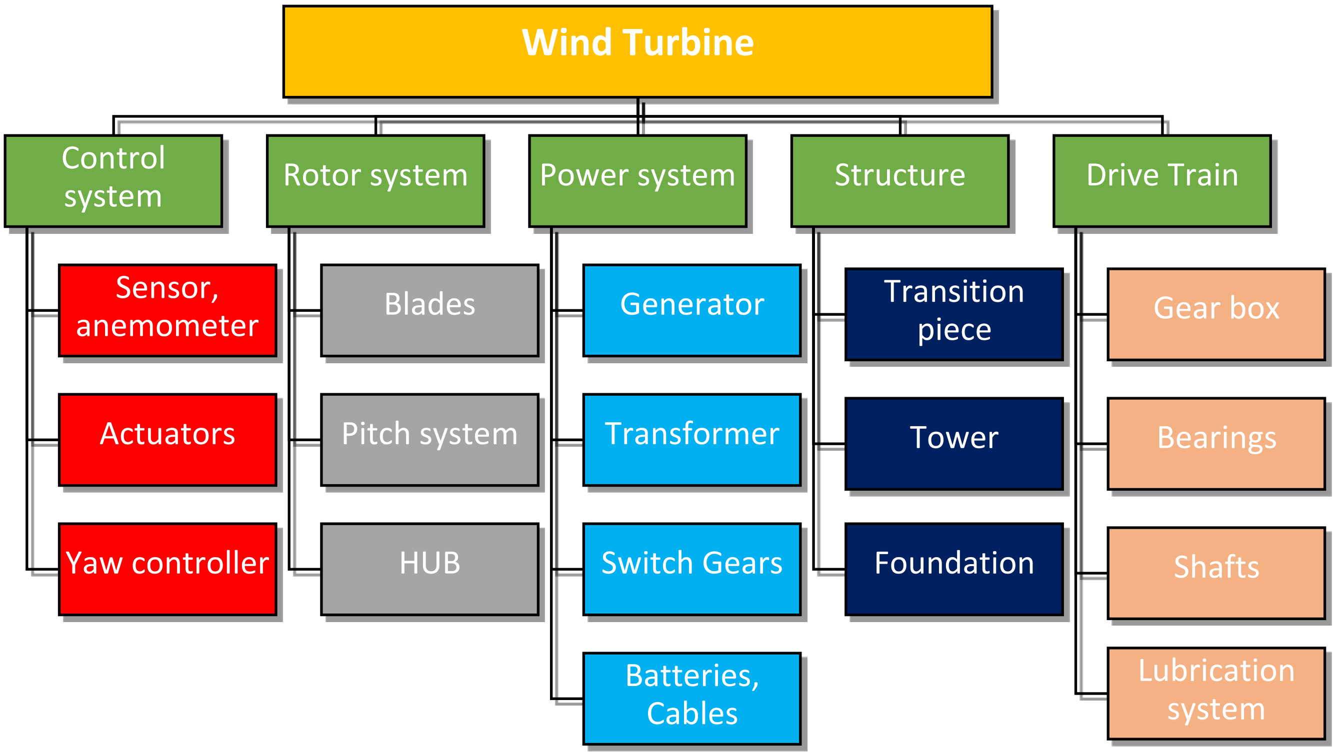

FIGURE 27. TECHNICAL HIERARCHY OF WIND TURBINE

- The control system makes sure that wind turbines operate safely and optimally without any disturbance in power generation. It consists of different actuators, sensors and algorithms, yaw controller makes sure that wind turbines rotor is aligned to the incoming wind and captures maximum energy from the wind.
- The rotor system converts the kinetic energy of wind into mechanical one and transmit it to the drive train with the help of shafts.
- The drive train increases the rotational speed of the low-speed shaft with the help of gear box and transfer the energy to generator.
- The components of power system are responsible for converting mechanical energy into electricity and then stepping up or down the voltage accordingly [88].

5.2 Functional Breakdown

Functional break down is an important process and is usually performed before starting the Failure mode effects and criticality analysis. In this process system boundary is defined and a block diagram is created to show the important functions of the system under consideration, it helps in understanding the system more clearly and shows the connections between different equipment's and components of the system. In figure 28 the main function of each component is stated, starting with rotor whose main function is to provide torque to the shaft, gearbox main function is to increase the rotational speed of the shaft and generator converts the mechanical energy into electricity, transformer increases the voltage and export cables transport the electricity to the substation. Brakes are connected to the rotor to control the speed of rotor, they are used for stopping the rotor during an emergency condition when there is some serious fault as well as regulating the rotor's rotational velocity, when the wind speed is very high. Yaw motors usually are electrical motors and are used to rotate the nacelle and rotor assembly and align it to the direction of incoming wind.

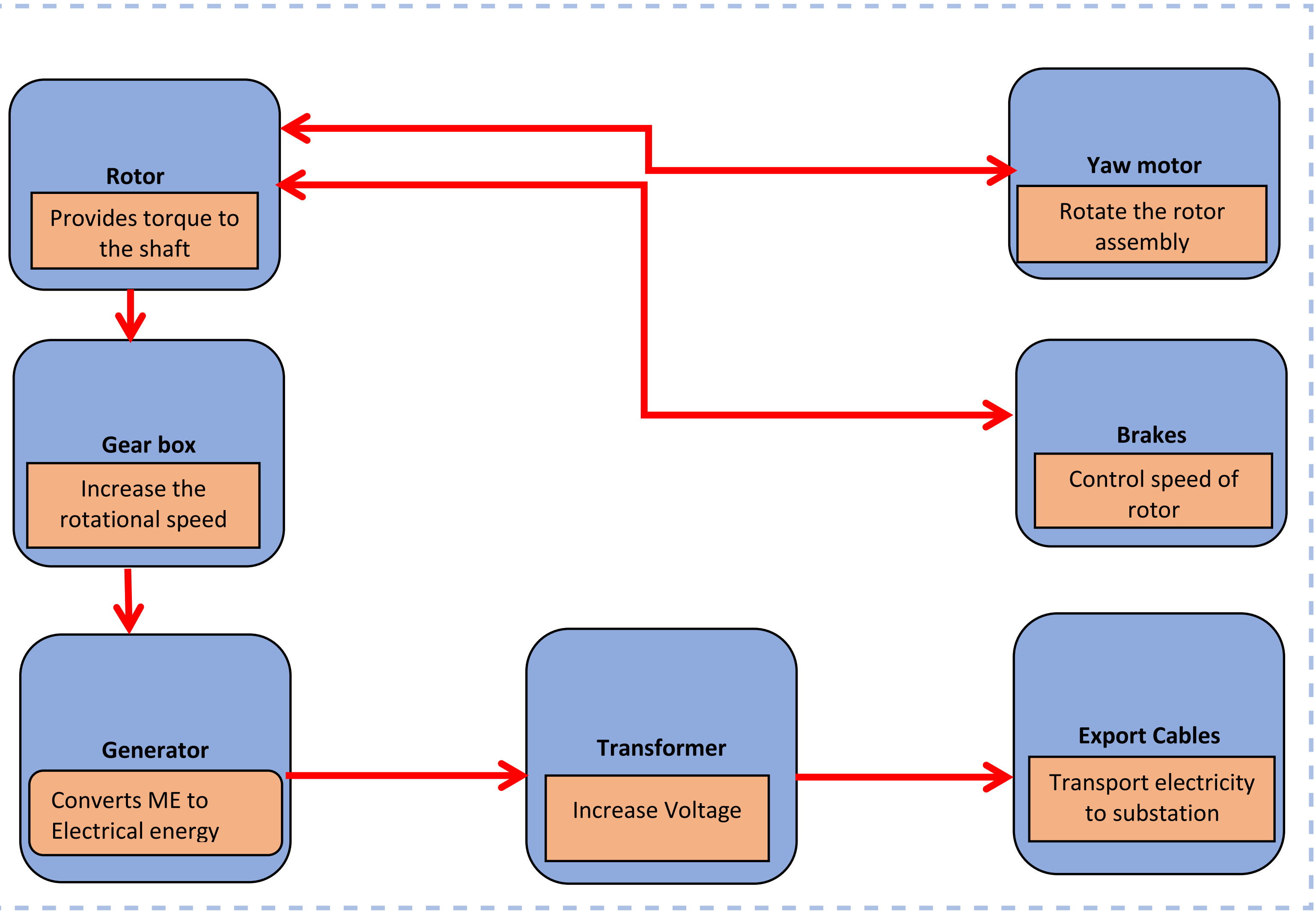

FIGURE 28. FUNCTIONAL BREAKDOWN OF WIND TURBINE.

After reading different research papers, meetings with industrial supervisors in Moreld, It was decided to further divide the system (wind turbine) into component level i.e. Gearbox and Generator, they are very critical part of the wind turbine and their failure rate is also high ,Several research papers provided data about their failure rates and helped in the analysis, The following section will entail a comprehensive analysis of the gearbox system of the wind turbine, where it will be examined as an independent system. This analysis will be followed by a subsequent analysis of the generator.

5.3 System Context Diagram

A system context diagram is basically a visual representation which defines the boundary of the system and shows the external entities it interacts with [89]. It usually consists of the system in the centre, represented as a box, surrounded by its external entities, which are represented in different shapes. Arrows are used to show the flow of information or interaction between the system and its external entities [90].

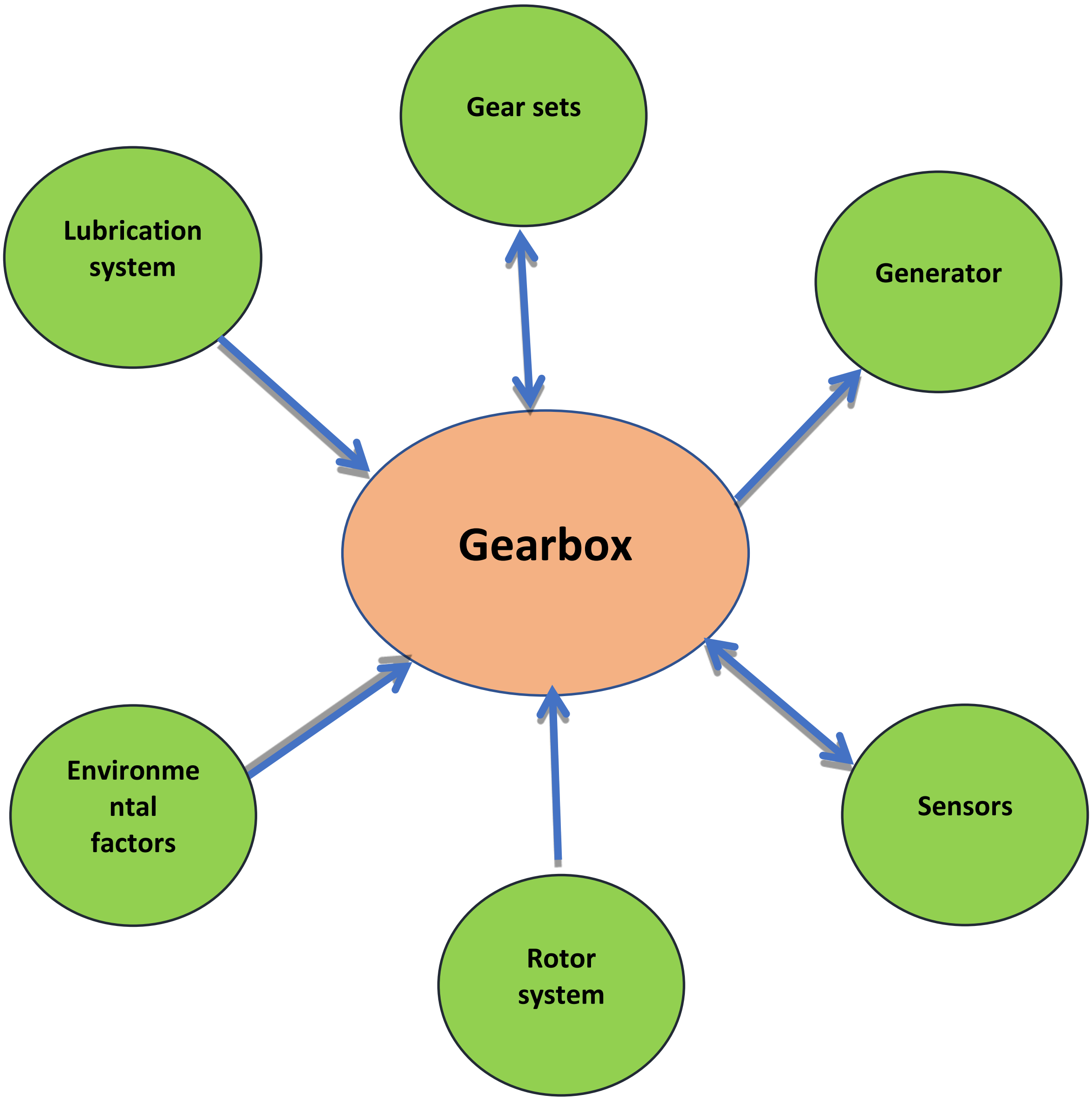

FIGURE 29. SYSTEM CONTEXT DIAGRAM OF GEAR BOX OF WIND TURBINE UNDER CONSIDERATION

The figure 29 shows the connections of gear box of wind turbine with external entities, it provides a brief overview of the components of wind turbine with which the gearbox interacts during the operations. Similarly figure 30 depicts the generator as the system and shows the inputs from/to external entities. Single-sided arrows pointing in the direction of the system indicate that the system is receiving some input from the external component, while those pointing outward indicates that the system is sending some output to that component.

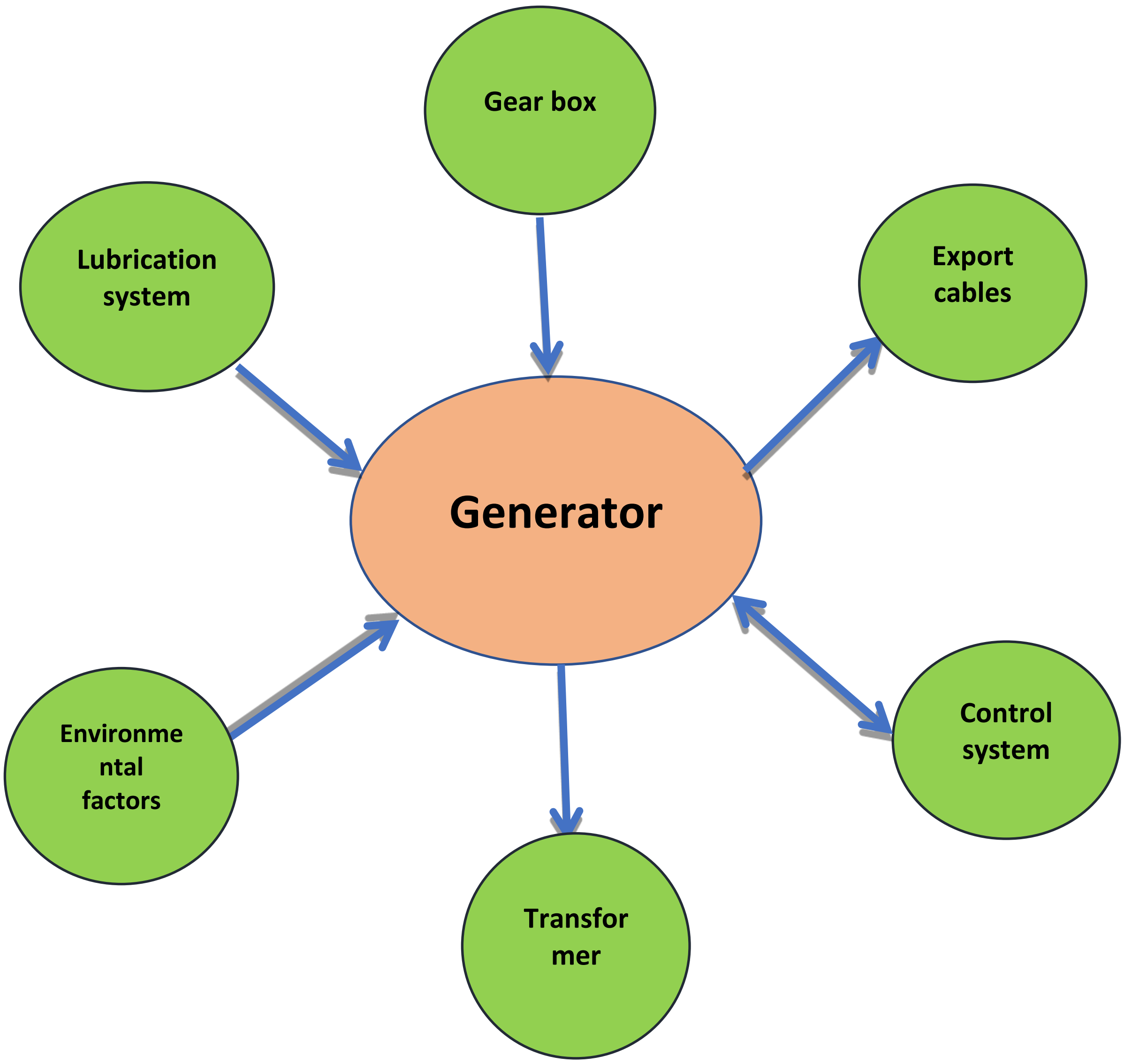

FIGURE 30. SYSTEM CONTEXT DIAGRAM OF GENERATOR OF WIND TURBINE UNDER CONSIDERATION

5.4 N^2 Analysis

N^2 Analysis is a tool which uses N*N matrix to find the interconnections between elements of a system [91]. The elements of a system, present in the diagonal, can be either software, hardware elements, functions or any kind of component belonging to the system under consideration. These matrices are called as diagrams, charts, and maps, interactions between the system's components, read clockwise, are the off-diagonal items [92]. The table 1 presents N^2 analysis of the internal components of the gearbox of the wind turbine and display the physical processes and physical connections which takes place between these internal components and show how they interact with each other.

N square diagram for Internal Components of Gearbox			
Low speed shaft	Gears Rotational energy	Bearings Gear teeth's Torque	-------------
couplings	**High speed shaft**	Bearings Gear teeth's	-------------
Mounted bearings	Mounted bearings High rotational speed	**Gears**	-------------
Lubrication Oil	Lubrication Oil	Lubrication Oil Oil pumps	**Lubrication system**

TABLE 2. N SQUARE ANALYSIS OF GEARBOX INTERNAL COMPONENTS.

Similarly, table 2 demonstrates the physical connections and processes between the internal components of the generator of the wind turbine.

N square diagram for Internal Components of Generator			
Generator Stator	Electromagnetic force	Alternating Current	-------------
synchronization Alternating current	**Generator Rotor**	Bearings Gear teeth's	-------------
-------------	-------------	**Rectifier**	Output terminals, busbars
Stator Windings	-------------	Electrical Cables	**Terminal Box**

TABLE 3. N SQUARE ANALYSIS OF GENERATOR INTERNAL COMPONENTS.

5.5 Failure Mode Effect and Criticality Analysis

The FMEA is a systematic method for determining potential points of failure and the consequences those failures could have, also helps in identifying failure modes, failure causes, and the effects of the failure on the system performance [94]. FMECA is extension of the FMEA in which risks associated with failure modes are also ranked by the help of RPN.

RPN is risk priority number and is calculated by multiplying the frequency of Occurrence (O) to Severity of the failure (S) to detectability index (D)

$$RPN = O * S * D$$

FMECA analysis is very crucial and helps in design phase starting from concept phase to development phase, The main goal of FMECA is to identify the critical failures in early design phase and find ways to eliminate or reduce these failures, this analysis is very important for reliability, maintainability, and maintenance task analysis [93].

Rating	Occurrence	Meaning	Possible failure rate
1	remote	Failure in unlikely.	≤1/1,500,000
2	low	Relatively few failures.	1/150,000
3	-	-	1/15,000
4	moderate	Occasional failures.	1/2,000
5	-	-	1/400
6	-	-	1/80
7	high	Repeated failures.	1/20
8	-	-	1/8
9	very high	Failure is almost inevitable.	1/3
10	-	-	≥1/2

TABLE 4. FMECA RATINGS FOR OCCURRENCE OF FAILURE [104].

Rating	Effect	Severity of Effect
10	Hazardous without warning	System failure resulting in hazardous effects almost certain.
9	Hazardous with warning	System failure resulting in hazardous effects highly probable.
8	Very high	System inoperable but safe.
7	High	System performance severely affected.
6	Moderate	System operable and safe but performance degraded.
5	Low	Reduced performance with gradual performance degradation.
4	Very Low	Minor effect on system performance.
3	Minor	Slight effect on system performance. Non-vital faults will be noticed most of the time.
2	Very Minor	Negligible effect on system performance.
1	None	No effect.

TABLE 5. FMECA RATINGS FOR SEVERITY OF FAILURE [104].

Rank	Detection	Criteria
1	nearly certain	With a very high probability a failure will be detected in a very early initial stage.
2	very high	With a high probability a failure will be detected in a very early initial stage.
3	high	With a high probability a failure will be detected in an early initial stage.
4	moderate high	With a high probability a failure will be detected after initial stage.
5	moderate	With a moderate probability a failure will be detected while existing a short while before getting critical.
6	low	A failure will be detected while existing a while just before getting critical.
7	very low	A failure will be detected while existing for a long while just before getting critical.
8	little	A failure will be hardly detected in a very late stage.
9	uncertain	The detection of a failure before becoming critical is uncertain.
10	nearly uncertain	The detection of a failure nearly is not possible

TABLE 6. FMECA RATINGS FOR DETECTION OF FAILURE [103].

Before starting the given system's FMECA, table 4 to table 6 should be fully comprehended and analysed as they help in calculating RPN.

The table 7 is failure mode effect and criticality analysis of the gear box of the wind turbine, which was under consideration, the data included in this FMECA is based on knowledge gained from different research papers and interviewing some senior engineers of the company, however for every turbine these factors will vary depending upon the operating conditions, and environmental effects. With the help of tables 4,5,6 RPN values are also being calculated for different failure modes which are more crucial and have high failure rates.

	Function	Safety consequences	Business consequences	Environment consequences	Failure mode	Failure cause	Failure effect	Occurrence	Severity	Detection	RPN
Gearbox FMECA	**Power Transmission/ Torque conversion**	H	H	M	**Gear Tooth wear**	**Improper gear ratio, misalignment**	**Tooth breakage, pitting**	**6**	**7**	**4**	**168**
		H	H	M	**Bearing Failure**	**Fatigue, less oiling**	**Reduced efficiency**	**7**	**7**	**3**	**147**
		M	H	M	**Lubrication problems**	**Degraded oil, particle contamination**	**Increase wear, overheating effects**	**4**	**6**	**5**	**120**

TABLE 7. FMECA OF GEAR BOX OF WIND TURBINE

Similarly, table 8 is FMECA of the generator of the wind turbine under consideration, failure modes having high failure rates like electrical failure, bearing failure and slip ring failures are analysed here, In the next column the causes of these failure modes are listed, and then the next column contain failure effects, these effects can either be local or global. With the help of these 2 FMECA, information about failure causes is obtained and this information is fruitful in reducing the failure rates of the given system, it helps maintenance engineer in deciding which maintenance strategy to be used for the given system.

	Function	Safety consequences	Business consequences	Environment consequences	Failure mode	Failure cause	Failure effect	Occurrence	Severity	Detection	RPN
Generator FMECA	Converts mechanical energy to electrical energy	H	H	H	Electrical failure	Corrosion, Overheating, poor components	Generator shutdown, safety hazards	5	8	4	160
		H	H	M	Bearing Failure	Fatigue, less oiling	Increased noise and vibration	7	7	3	147
		H	H	M	Slip Ring issue	Poor lubrication, particles contamination, wear	Damaged components reduced efficiency Overheating,	6	6	3	108

TABLE 8. FMECA OF GENERATOR OF WIND TURBINE

5.6 Reliability Calculations

There are certain assumptions that are made before calculating reliability of the gear box and generator of the wind turbine. Failure rate data was gathered from (SCADA) databases, some old operations and maintenance reports, and was then supplemented with information from references [96-99].

An assumption of constant failure rates was implemented in reliability calculations of gearbox and generator, of the given system because they are still in their useful lifetime.

The Weibull reliability function is given by [88].

$$R(t) = \exp[-(t/\eta)\ \hat{}\ \beta$$

shape parameter = β

β=1 for constant failure rates

scale parameter = η

$$\eta = (1 / \lambda)\ \hat{}\ (1 / \beta)$$

λ = failure rate per year

t= desired time at which reliability is to be calculate

The failure rate of gearbox and generator of two turbines with same power ratings, one offshore and one onshore is listed [99].

$\lambda_{\text{Gearbox offshore}} = 0.179$

$\lambda_{\text{Generator offshore}} = 0.150$

$\lambda_{\text{Gearbox onshore}} = 0.134$

$\lambda_{\text{Generator onshore}} = 0.110$

“Reliability is the likelihood that a component (or an entire system) will carry out its function for a predetermined amount of time” [100]. Therefore, reliability is a clear standard for determining whether something is working or not [100]. From the results it can be observed that onshore gearbox and generator are more reliable than their offshore counterparts.

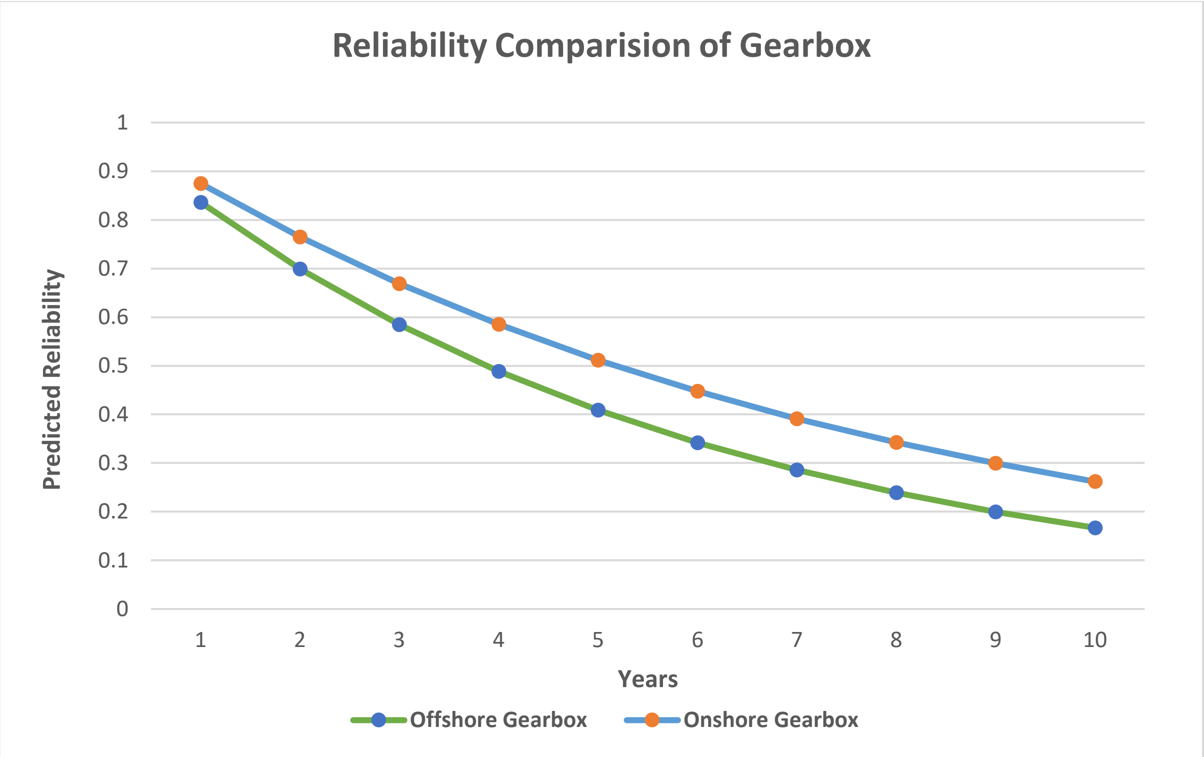

FIGURE 30. RELIABILITY COMPARISON OF GEARBOX (ONSHORE AND OFFSHORE).

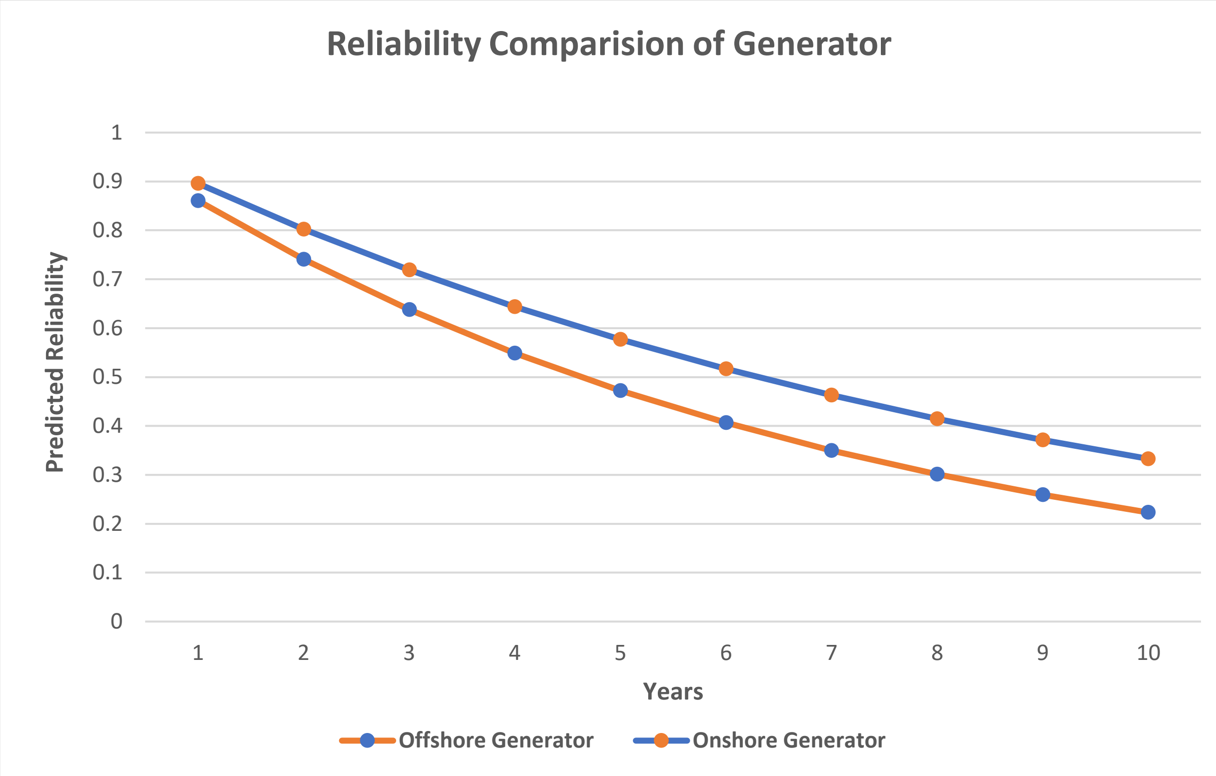

FIGURE 31. RELIABILITY COMPARISON OF GENERATOR (ONSHORE AND OFFSHORE).

5.7 Lifecycle Cost Analysis

Life-cycle cost analysis (LCCA) is a method done to evaluate the project economically, this analysis encompasses all costs that arise from development, installation, operation, maintenance, and disposal of a project as these are considered to play potentially important role in decision making [101].

The LCCA methodology used for this thesis is only limited to the economic analysis of a 450 MW floating windfarm having turbines of 15 MW and 100 m water depth at site. It is assumed that wind farm will operate for almost 21 years with different maintenance strategies and operations being performed, this article [102], provided the estimates of the cost for this wind farm and helped in the analysis. Furthermore, there were some assumptions made after discussions with the supervisor for the division of cost for each year.

Table 9 below shows the lifecycle costing and benefits of the wind farm, which is under consideration, with a column of costs of different lifecycle phases, and how these phases, if done efficiently, can have an impact on reduction of costs. Last column illustrates the importance of SHEQ during each phase and how it can be implemented in that phase.

LIFE CYCLE COSTING AND BENEFITS			
Economical			**Environmental**
Lifecycle Phase	**Cost (Euros)**	**Cost or Losses Saving (Benefits)**	**SHEQ**
Design	68 M	Reduce logistics costs, avoid delays, rework	Ensure industry standards, minimize noise and vibrations
Installation	170M	Reduce labour hours, major accidents	Check quality of components and installation process
Operations	231M	Improve the reliability, reduce downtimes	Implement quality control measures, keep documentations and records
Maintenance	400M	Increase lifetime	Implement CBM and advance sensors and strategies
Decommissioning	68M	Reduce maintenance costs due to ageing.	Ensure Waste management, recycling, and disposal

TABLE 9. LIFECYCLE COSTING ANALYSIS OF WIND FARM

Figure 32 Illustrates the annual cost which is related with different stages of wind farms lifecycle.

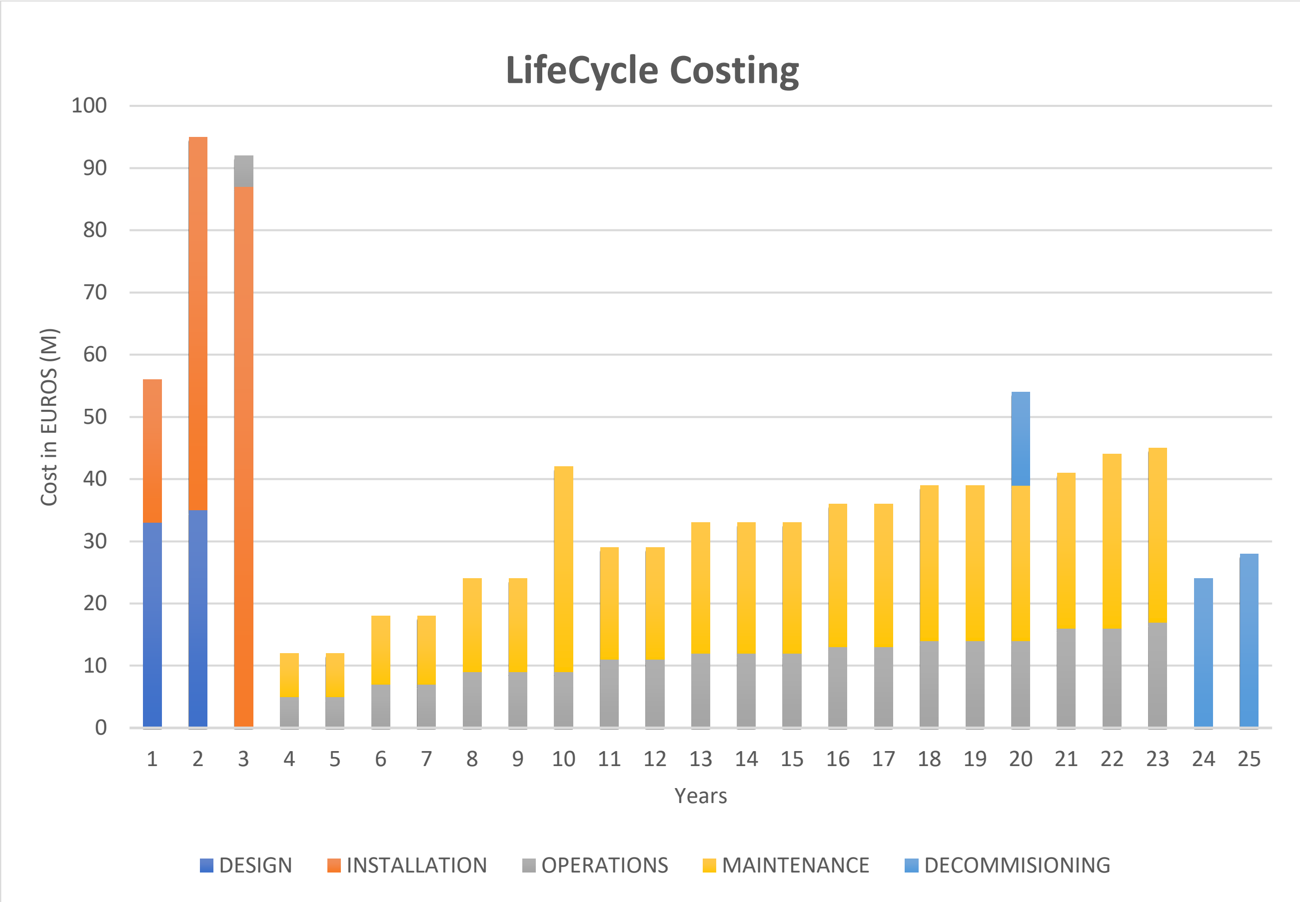

FIGURE 32. LIFECYCLE COSTING OF WIND FARM UNDER CONSIDERATION.

Chapter 6: Conclusion

This thesis analysed different factors relating to Lifecycle management of wind farms, with a tilt towards offshore farms, a brief overview of different types of foundations was presented in chapter 2, then we discussed different types of failures encountered by wind turbines during operations, maintenance strategies that are used to mitigate these failures were analysed afterwards.

As many wind farms in Europe are reaching their end of life, so a detailed study was done about end-of-life management, including various concepts like extension of life, recycling, repurposing, and decommissioning. This thesis also explores the challenges that are related to efficient decommissioning starting from vessels accessibility to regulations and licensing.

Finally, a study was conducted encompassing failure mode effect and criticality analysis, N^2 analysis, reliability analysis for the gearbox and generator of the wind turbine, these analysis helped in understanding working of wind turbines, interconnection between different components and failures encountered. In the end of thesis cost benefit analysis was done, to give an estimate of the lifecycle costing.

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