FACULTY OF SCIENCE AND TECHNOLOGY

MASTER'S THESIS

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Abstract

Renewable energy resources such as offshore wind turbines are considered as if they do not emit greenhouse gas emissions, as greenhouse gases are not emitted from these resources during electricity generation. However, throughout the various lifecycle stages of offshore wind turbines, significant levels of greenhouse gases could be emitted. To this end, we seek to analyse the greenhouse gas emissions from offshore wind turbines.

The core objective of the thesis is to assess the major factors that result in greenhouse gas emissions from offshore wind turbines. Specifically, we study these factors from a lifecycle perspective. In this light, we investigate the major factors at each lifecycle stage of offshore wind turbines that result in greenhouse gas emissions. Moreover, we lay out several recommendations so that offshore wind turbines that are currently deployed or will be designed in the future can result in significantly lower greenhouse gas emissions.

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I am very grateful to my family, especially to my grandmother, who made my master`s degree in Norway come true. Her permanent love and confidence have encouraged me to go ahead in my study. Despite the time difference and distance, her care, unconditional support, and motivation throughout my studies are so meaningful for me. She has been the source of inspiration.

Finally, I would like to thank my love Ogün, who has shown his support though the difficult times, his moral support motivated me to keep going on with my work. I am so appreciative for his constant love, understanding and encouraging me.

List of Abbreviations

CO_2	Carbon dioxide
GHG	Greenhouse gas
IEA	International Energy Agency
HAWT	Horizontal axis wind turbine
VAWT	Vertical axis wind turbine
AM	Asset Management
LCA	Life cycle assessment
SOV	Service operation vessel

1. Introduction

In this chapter, we introduce the background and motivation for this work, and we lay out the description of the problems discussed in this thesis. Then, we discuss the scope and objectives of this work. We conclude this section with an outline of the contents of the remainder of this report.

1.1. Background and Motivation

In this subsection, we describe the global outlook for the energy sector, the importance of renewables to achieve Net Zero Scenario, and noteworthy improvements in wind energy.

Global outlook

Global warming and rising CO2 emission levels have become major issues of global concern in this century. The economic and regulatory measures to combat global warming increased the demand for renewable energy coupled with modern technologies that foster the integration of renewables. According to the IEA, the current demand for renewable energy increased by 3% in 2020 and is expected to follow this trend across all main sectors such as transport, power, and industry in 2021[1] Since the demand for fossil fuels declined, this tendency increased the interest in renewables.

The aim of the Paris Agreement, which was signed in 2015, is to reduce the energy-related CO2 emissions to approximately 3.5% per year from now until 2050 in order to keep the average global temperature well below 2 degrees Celsius (°C) in this century compared to pre-industrial levels.

On the other hand, renewable production capacity remains far below the level necessary for the Net Zero Scenario. As can be observed from Figure 1, despite all existing measures to mitigate global warming, it is estimated that the global temperature will increase by 1.5°C between 2030 and 2050 [2].

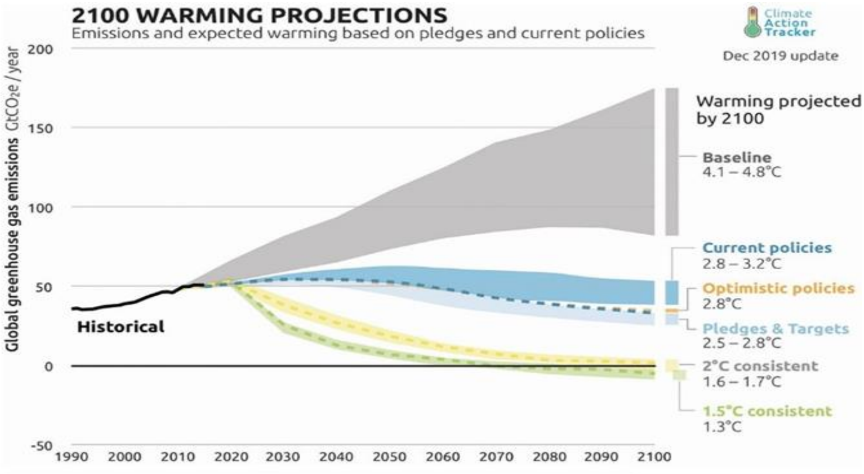

Figure 1. Emissions and expected warming based on pledges and current policies **[2]**

To ensure that the objectives set out to mitigate global warming and reach the Net Zero Scenario can be achieved within their target timelines, it is indispensable to double the installed capacity of renewables, specifically wind energy.

Wind energy is the leading renewable energy resource in terms of total installed capacity, following hydropower, with more over half a terawatt installed globally as of the end of 2018. [3]. The wind industry achieved tremendous improvement from 1982 in installation techniques and operational efficiencies (Figure 2).

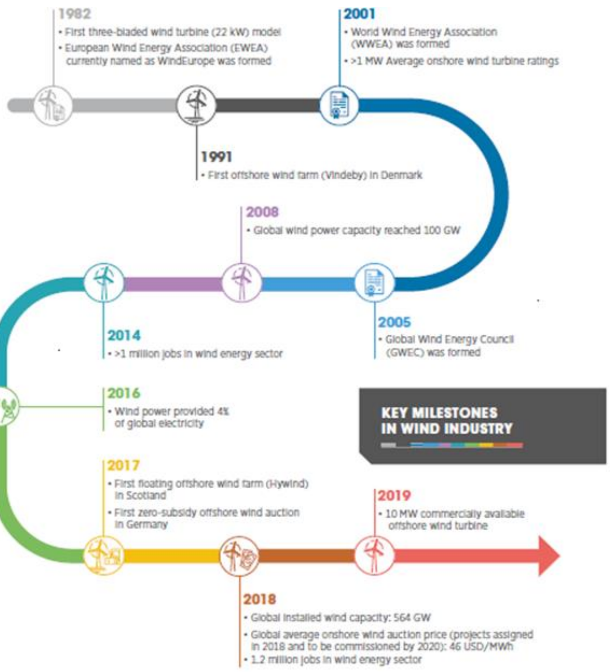

Figure 2. Overview of key milestones achieved by the wind industry since 1982 [3]

Wind turbines can convert wind to electric power without generating greenhouse gas (GHG) emissions. There are different types of wind turbines according to their axis, such as horizontal axis wind turbines (HAWT) or vertical axis wind turbines (VAWT), whereby HAWTs constitute the majority of wind turbines. In terms of location, wind turbines can be classified as onshore, offshore, and aerial wind turbines.

Offshore wind energy is an emerging renewable technology that has rapidly developed in the past ten years. It has undergone significant cost reductions, technology advancements and breakthroughs. Further, it has greatly benefited from more efficient supply chains with substantial uptakes in different markets, which in turn continue to unlock further investments.

While power generation from offshore wind turbines do not result in GHG emissions, wind turbines, throughout their life cycle, do indeed contribute to the formation of pollutants that exacerbate the global climate change. Specifically, in the production, installation, operation, and decommissioning steps, offshore wind farms result in significant amounts of CO_2 emissions. As such, a comprehensive evaluation of the benefits of offshore wind turbines in mitigating GHG emissions hinges on a thorough study, which investigates the lifecycle of offshore wind turbines and the GHG emissions associated with each lifecycle step.

1.2. Problem Description

In the light of our review in Section 1.1, we observe that offshore wind turbines possess a great potential in reducing GHG emissions associated with different sectors. Nevertheless, to accurately assess the impact of offshore wind turbines on GHG emissions, it is necessary to study the lifecycle stages of offshore wind turbines and investigate the GHG emissions for each stage.

From manufacturing to commissioning, the lifecycle stages of offshore wind turbines could result in significant levels of GHG emissions. On top of that, how much GHG will be emitted in each lifecycle stage could depend on several factors. For instance, manufacturing the components of offshore wind turbines is an intensive process that could necessitate high levels of electricity consumption. Meeting such a high energy demand will inherently yield GHG emissions. However, it is worth noting that the GHG emissions of any stage itself depends on several factors. Carrying on with the manufacturing example, the location of the manufacturing of offshore wind turbines has a major impact on the GHG emissions. For instance, manufacturing in a location connected to an electricity grid with a high share of coal-fired or gas-fired units will inevitably result higher GHG emissions, compared to a location connected to a grid with a large share of renewables. Another factor is the time of manufacturing. For instance, if the manufacturing process were to take place during a time period where there is a lot of renewable generation, a higher share of the electricity demand for manufacturing could be met from renewables, resulting in lower GHG emissions.

Such examples make clear that the GHG emissions associated with the lifecycle stages of offshore wind turbines need to be thoroughly investigated. Absent such a study, it will not be possible to accurately quantify the GHG emissions from offshore wind turbines. Further, it is necessary to study on what factors the GHG emissions associated with each lifecycle stage depends. Such a study will enable the decision-makers to take these factors into account while taking decisions and possibly optimise their decisions so as to be able to reduce GHG emissions and striking a balance between costs and GHG emissions. Motivated by these observations, in the thesis, we focus on the problem of identifying the primary factors that result in GHG emissions under each lifecycle stage of offshore wind turbines.

1.3. The scope and objectives of the thesis.

In this thesis, we set out to find the answers to the following research questions:

1. What are the salient factors in the lifecycle steps of offshore wind farms that contribute to GHG emissions? We address this problem in Chapter 3.

2. How can the identified factors that contribute to GHG emissions be classified under different stages of the lifecycle of offshore wind turbines? We investigate this problem in Chapter 4.

3. What are possible recommendations to different lifecycle stages of offshore wind turbines such that the resulting GHG emissions could be mitigated? We explore this problem in Chapter 5

1.4. Methodology

In this thesis, the most frequently utilised research methodology is qualitative. The research findings are coupled with an exhaustive literature review. Specifically, a review of books, scientific research papers, and online articles was conducted as part of the literature review. This was done in order to present a thorough overview of how the asset management concept is interlinked with offshore wind farms and each LCA stage. In the light of the reviewed work, the thesis qualitatively investigates the lifecycle stages of offshore wind farms. For each lifecycle stage, the thesis assesses the factors that influence the GHG emissions. Finally, we propose a conceptual framework that allows the representation of the identified salient factors on a consistent basis.

1.5. Limitation

There are several limitations that influenced the undertaking of this work. It is clear that quantitatively assessing the GHG emissions in each lifecycle stage of offshore wind farms requires numerical data. Nevertheless, such data is not publicly available. Although we qualitatively examined these factors, it is not possible to compare the GHG emissions of different steps on a numerical basis due to lack of data. Further, the lack of data influenced the case studies of this work as well. The factors identified in this thesis could not be fully analysed in a real-world scenario due to the unavailability of GHG emissions data associated with individual lifecycle stages in practical applications.

1.6 Outline of the thesis

The rest of this thesis is divided into six chapters:

Chapter 2 presents a literature review concerning the fundamental aspects of asset management, supply chain, and logistics. Further, it presents relevant studies on offshore wind farms and their challenges, green energy, sustainability, and carbon footprint.

Chapter 3 discusses the lifecycle steps of offshore wind farms and presents the salient factors in each lifecycle steps that contribute to GHG emissions.

Chapter 4 presents the salient factors that influence the GHG emissions associated with each lifecycle stage of an offshore wind farm.

Chapter 5 presents several recommendations about how the GHG footprint of offshore wind farms can be reduced.

Chapter 6 reviews the objectives and the deliverables of the project and the challenges faced while writing the thesis.

Chapter 7 summarises the thesis and presents concluding remarks.

2. Literature Review

This chapter presents theoretical background knowledge and insights into asset management. Specifically, we discuss life cycle thinking around asset management and provide key principles associated with asset management. We further discuss supply chain and logistics, as well as offshore wind and their classification. We present the leading and emerging market, and challenges of supply chain and logistics in the wind energy sector so as to draw upon these concepts in the subsequent sections of this thesis.

2.1. Asset Management

Asset management is described as a set of processes for an organisation to optimally utilise its sources so as to create revenue. These processes may involve resources from different departments, including Operation and Maintenance, Finance, Information Technology, and Human Resources.

Asset management may involve a holistic view that may bring together different segments of a company to accomplish common strategic goals. It is also characterised by its ability to advertise the interconnection of activities and provide them with risk-based, information-driven decision-making which promotes the consistent achievements of organisational objectives [4]. The key principles of AM according to J. Woodhouse are illustrated in Figure 1 [5].

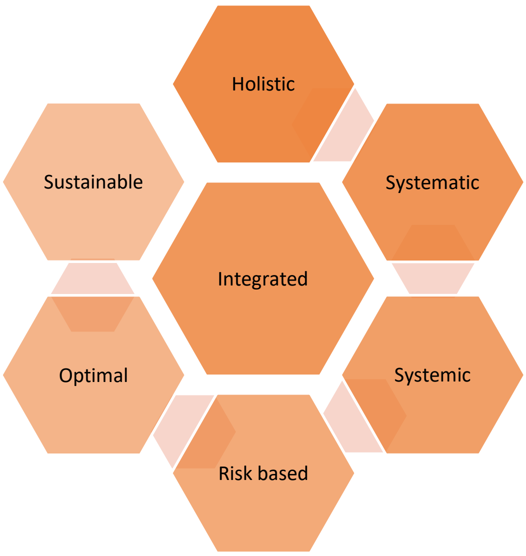

Figure 3. Key principles and attributes of asset management [5].

Engineering asset management refers to the management of physical assets. We define an asset as a physical item that has value to the stakeholder. The management process is a set of procedures, such as optimization performance, increasing outputs, maximising availability, or minimising costs to achieve the set targets. However, all such targets are fraught with uncertainties [6]. Due to current and emerging industrial conditions, it is important to focus on industrial assets in a strategic way.

There are still ongoing problems with the lifetime documentation of wind turbines since it is incomplete, not fully digitalized, and sometimes non-existent. Available data, technical incidents and the resulting operation and maintenance cost data are acquired and sorted in different systems without logical linkages. Considering maintenance software and computerised maintenance management systems (CMMS), proprietary and isolated software solutions inhibit an integrative and holistic view on complex maintenance problems. As an example of those software solutions, Shoreline Wind is an enterprise software, supplying a comprehensive life cycle asset management platform to renewable industries worldwide, from early project development and analysis to complex field service optimization in the operational phase. Another solution is model-based system engineering using CORE9. This method is used to support the requirement analysis, system design, data, or system analysis. The traditional approach to managing engineering asset management, which creates a lot of mismanagement in flow of essential communication between each department, while using that software is making it possible to track ongoing changes in one department and apply the change immediately across different departments.

To increase the cost efficiency in offshore wind energy assets, it is indispensable to create a unique context to explore complexity and linkages between engineering, business, data and operations management approaches.

2.1.1. Key benefits of Asset management

Asset management is a broad and holistic subject, in order to understand its key benefits and general understanding, Global Forum on Maintenance and Asset Management (GFMAM) established a framework that defines the core scope and boundaries of asset management.

The GFMAM framework defines asset management's scope or "core" as a mixture of asset management disciplines and asset management basics [8]. According to GFMAM’s asset management landscape framework, the knowledge of this field is becoming more accessible and available as more and more practices are getting involved. This is possible due to various yet interlinked concepts which share a common vision of the asset management discipline.

The aim of AM is to deliver a structured framework and investment planning in order to deliver service in acceptable levels that provide cost-effective solutions throughout the entire asset life-cycle at minimal risk. To be more specific, organisations would be able to gain benefit from employing a structured AM framework in the following ways:

Good business practice: This will result in better decision-making. Hence, the mission and objectives of the utility will be supported in the long term if infrastructure management is coordinated with strategic policies and directions.

Improved regulatory compliance: Implementing more efficient Operations and Maintenance as part of the asset management discipline would result in significantly improved compliance within the organisation.

Improved reliability: Evaluating the risk implications of asset failures, allows a better resource allocation toward urgent needs while potentially reducing the overall risk.

Long-term system integrity, Employing AM framework conducts visibility by providing a better overview of the system and therefore assists in building a more sustainable infrastructure that is long-lasting.

Cost saving: asset management programs that keep the whole infrastructure in a reliable state and are based on minimising life cycle costs can cut back significantly on operation and maintenance costs as well as long-term capital expenditures. A life cycle approach ensures that the utility receives the greatest value for its investment [10].

2.1.2. Life cycle of Engineering Assets

The process of "engineering asset life-cycle" starts with the identification and recognition of an asset, as well as there can be confirmation of a project, then budget forecasting and approval of it. After acceptance of the project begins should be confirmation of the designed engineering depiction, from which it is adopted, installed, and developed for getting a start, moreover, during the production process over time retiring and tempting activations begin.

To successfully accomplish life cycle management, the activities performed as part of each life cycle phase need to be carried out in full coordination with other phases. The inclusion of life cycle activities is a critical component of the whole-life strategy necessary to establish a strong asset management approach and enhance asset value [7]. A general asset life cycle structure is illustrated in Figure 2, which includes four categories: acquisition, operation, maintenance, and disposal.

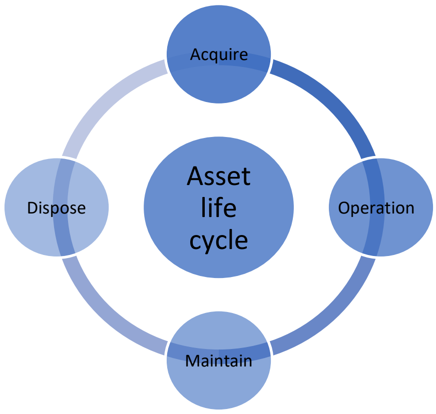

Figure 4. Asset life cycle [7].

Generally, due to the technology's reliance on various external factors, the life cycle of a wind energy asset is complex. In the design and development of offshore wind turbines, several external factors are Increased demand for wind power and other sources of renewable energy encourages more research and development in this field, which leads to an increased wider range of technical options.

2.1.3. The importance of Asset management for offshore wind power.

The importance of asset management for the wind power industry is significant, by introducing Asset management framework leads to reducing the downtime and increasing maximum production.

The largest area where asset management can save money is in the operations and maintenance (O&M) of turbines, which account for about 25% of total costs.

Decision that has made throughout development, design and construction phase can have significant impact on the project’s operation and maintenance. This may have an impact for the duration of the asset's life. The project investment return can be increased and risk minimized by choosing and implementing effective O&AM strategy [9].

In order to quantify the GHG footprint of offshore wind farms, the studies primarily consider the GHG emissions to be virtually zero as there are no GHG emissions while an offshore wind farm generates electricity. This may lead to an inaccurate characterization of the GHG emissions of offshore wind farms, as when all life-cycle stages of offshore wind farms are comprehensively evaluated, there are several factors that result in GHG emissions. In order to accurately study the GHG emissions of offshore wind farms, it is necessary to leverage asset management tools and analyse the lifecycle stages of offshore wind farms. This is required since, as explained in the rest of this thesis, several stages in offshore wind farms result in GHG emissions. As such, it is necessary to approach the problem of evaluating the GHG emissions of offshore wind farms from an asset management perspective.

2.2. Offshore Wind

If we look back at the history of wind energy development, we can see that it was mostly associated with the fluctuation of oil prices. After World War II the price of oil fell, which decreased the interest in wind energy (wind turbines). With the first oil price shock in the early 1970s, the interest in wind power increased significantly.

Nowadays, onshore winds make up a large portion of the wind energy generated now. Nevertheless, offshore wind is gaining popularity since the wind is usually stronger and more consistent at sea than on land. Moreover, as it was discussed in several research papers about the visual impacts, mechanical and aerodynamic noises caused by onshore wind turbines. To get better renewable wind energy sources and decrease the visual impact and noise effect, offshore wind is much preferable.

After the first offshore wind farm installation in 1991 in Denmark with 400-500 KW corresponding to about 5MW total capacity, it cleared the way for offshore wind farms around Europe. Vindeby, which was decommissioned in 2017 [11].

Due to policy toward the wind power industry and the Paris Agreement, the wind market has grown rapidly in the last decades, and wind turbine technology experienced significant evolution over time. According to the International Renewable Energy Agency (IRENA), offshore wind capacity would need to be increased triple by 2030 (to 228 GW) to enable the power sector change required to meet the Paris Agreement targets [3].

2.2.1. Classification of Offshore Wind Farms

As spelled out in chapter 1 – introduction part, wind turbines can be classified based on different criteria, as for their direction of the rotating axis and location. Based on location, they can be classified into onshore and offshore wind turbines. Note that offshore wind turbines are significantly different than onshore wind turbines. While onshore wind turbines are deployed inside land, offshore wind turbines are deployed within waterbodies. As a result, offshore wind turbines require major differences in their design so that they could remain stable inside water.

For offshore wind turbines (OWT) the foundation type is also a major criterion that governs the installation method. Because the cost of foundations grows significantly with depth, the sea depth is the most important factor for the feasibility of offshore wind farms. As a result, numerous types of foundations have already been produced, and others are being developed in consideration of the sea depth and other parameters. There are 2 main categories known as a type of OWF: bottom-fixed foundation types and floating wind turbines.

Fixed-bottom offshore wind turbines are similar to land-based wind turbines, but they have a more complex support structure, are larger, and are engineered to resist the marine environment [12].

Floating wind turbine foundations have been introduced to the industry in order to replace bottom-fixed foundations. It offers many advantages to the industry by allowing it to be installed in deeper water depths, which reduces visual noise, offers safer accommodation for fishing and shipping channels and obtains stronger and more stable winds. [13] [14]

Figure 5. Offshore wind turbine substructure types depend on water depths [15].

2.2.2. Technology and Future Trends and Technology Advancements

Enormous changes and technology advancements has made offshore wind technology as one of the leading renewable energy resources since the first turbines were installed in 1991 in Denmark. In recent decades, equipment manufacturers have largely focused their investment on r&d (research and development) on constructing offshore wind turbines in larger size and more powerful. The physical dimensions and rated power output of the technology have increased substantially.

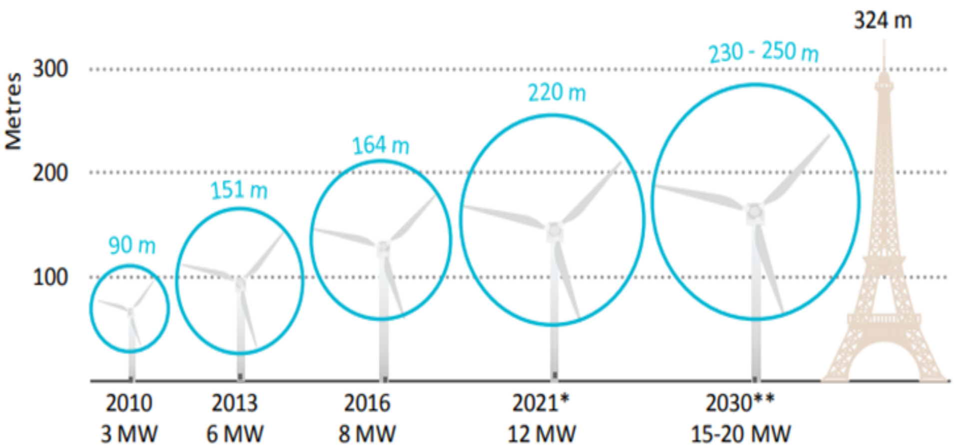

Figure 6. Evolution of the largest commercially available wind turbines IEA world energy outlook 2019 [16].

As we see from Figure 8, in 2021 announced as an expected year of commercial deployments of 12 MW size of offshore wind turbines and it is projected that it will reach almost 260 m which is approximately 80% of Eiffel Tower height. The recent demand of industry is mostly interested in further technology improvements for installation of 15-20 MW turbines for 2030. Due to the increase in the size of wind turbines it increased capital cost since larger turbines confront building constraints and demand larger foundations but it has also decreased the operation and maintenance costs, resulting in lower levelized power prices [16].

In 2017, Øydegard (2017) proposed future research on the digitalization of offshore wind that could be done in several areas, mentioning logistics as one of them. From an industrial perspective, MHI-Vestas (2018) noted that digital transformation has begun enhancing the capacities to gather, sort, and analyze data, as well as combining it with machine learning and artificial intelligence. Digital intelligence, according to recent statements from Siemens (2018), gives the company an edge over rivals. Equinor (2018) is also making investments in order to take the lead in digitalization globally [44].

2.2.3. Leading and Emerging Markets

Technological developments and digitalization accelerate the expectation of performance improvements and competitive offshore wind power costs. Recently, the majority of installed offshore wind farms are located in the North Sea and near the Atlantic Ocean, however other countries have established future objectives and plans for further offshore wind installation.

The Netherlands established a new target for offshore wind installation of more than 49 TWh, indicating a total installed capacity of 11.5 GW by 2030 [3]. Apart from the leading countries such as Germany, the USA, Spain and Denmark, China, Turkey, and Japan have made significant steps to expand their wind power capacity.

For example, in Japan, the government aims to generate up to 45 GWT which can make the 3rd largest offshore wind power generators in the world. As a solution to achieve the required target the University of Tokyo has established the “Ocean Utilization Systems” course. The aim of these lectures is to provide a complete overview of offshore wind farm projects by assessing the whole lifecycle of a socio-technical system. By using Shoreline Wind`s simulation platform it will increase the efficiency to explore infrastructure for offshore wind farms and it makes it possible to learn the state-of-art method on how to evaluate complex problems regarding cost and performance, by simplifying and visualizing the entire process [17].

Turkey reached the highest level of installed capacity in wind energy of 10 GW and aims to expand and add 20 GW of wind energy by 2030. However, all 10 GW of installed wind energy is onshore. But the government is currently looking into the prospect of growing offshore wind. Many European and International corporations have established manufacturing operations in Turkey. As a result of the constant development of the local supply chain, Turkey has all potential to grow up the installed wind capacity [18].

China has recently made tremendous progress in offshore wind, and it currently leads among the industry leaders. China installed 1.6 GW of offshore wind capacity in 2018, which is the most of any country. The plan for the installation of 5 GW of offshore wind power by the year 2020 rapid expansion and the construction of supply chains to accommodate future developments has been supported by the government`s 13th Five-Year Plan [16].

The short summary of adopted future projections for offshore wind by 2030 in certain regions such as the EU, China, United States, India, and Korea is illustrated in Table 1. Apart from those giant regions with ambitious long-term goals, Japan, Canada and Turkey are also establishing the foundation for future offshore wind expansion [19].

Country/ Region	**Future policy target by 2030**
European Union	65-85GW by 2030
China	5GW
United States	22 GW
India	30 GW
Korea	12 GW

Table 1. Different future projections by 2030 within a minimum of 10 GW of offshore wind [3].

2.2.4. Supply Chain of the Offshore Wind Farm

A supply chain refers to a global network of organizations that involves the flow of tangible and intangible resources such as materials, data, and activities that are supplied to a firm in the form of goods and services [20]. We depict in Figure 7 the key pillars of a supply chain of a company.

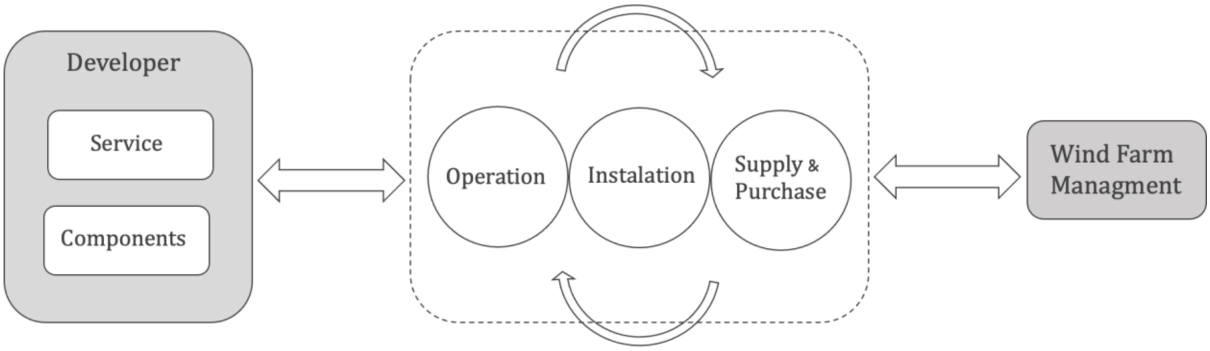

Figure 7. An illustration of supply chain of a wind farm [20].

GWEC expects that the capacity of offshore wind will increase by 260 GW between 2022 and 2030, which will drive the global capacity of offshore wind installations to 316 GW at the end of the decade. To this end, GWEC finds it indispensable that there is a "well-functioning global supply chain that is able to scale up rapidly over the next decade to meet growth". Nevertheless, the supply chain is currently under stress due to inflation, increasing commodity and logistics costs, and an unbalanced demand growth [47].

A key step in the supply chain an offshore wind farm is the procurement and material supply step. In this step, the designers, engineers, environment consultants, and project managers work together so as to procure and supply the necessary material. The steps include the supply of the blades, gearbox and main shaft, tower, bed plate, foundation, as well as the electrical generation parts. Further, the control and instrumentation components of offshore wind farms need to be analogously procured.

2.3. Challenges of Offshore Wind Energy Sector

One of the primary distinctions between offshore and onshore wind energy is that the former typically employs larger wind turbines, whereas the latter relies on entirely different technologies and competences. The extraction of raw materials and the production of steel and concrete continue to produce significant indirect emissions. Currently, the industry is considering solutions, such as making steel out of hydrogen and securing raw materials extracted using renewable energy. But for these strategies to be commercially viable, costs will need to be significantly reduced.

Throughout the scholarly literature research, a lack of sufficient research study has been done on the renewable supply chain. The literature mainly focused on supply chain and logistics. There has recently been a surge of interest in measuring and managing sustainability performance of supply chain management by Schaltegger and Burritt in 2014, and some analysis targeted specifically towards reduction of carbon emissions [21].

From the end-to-end user perspective, it is noticeable that wind energy faces logistics and supply chain issues. The research done by Poulsen and Lema in 2017, shows the study challenges in the supply chain for the deployment of offshore wind in Europe and China by highlighting that the global supply chain, specifically logistics, is not ready for a renewable transformation. There are a certain number of barriers, bottlenecks, and constraints which mentions that there is still a lack of proper legal policy for offshore wind, and the supply chain is concerned mostly onshore. Poulsen and Lema advocate for political binding for offshore wind in Europe beyond 2020, while Chinese players acquire more know-how from Europe to accelerate technology diffusion [22]. This could be a learning experience for the development of offshore wind in the United States.

According to a report published in 2018 by the IPCC (Intergovernmental Panel on Climate Change), 2010 was the first year in which the energy sector (natural gas, coal, and other sources) had the largest contribution to GHG footprint with almost 35% of total GHG emissions, which later increased to 41%, corresponding to 13.6 billion tons of CO2 [23]. Although the development of offshore wind energy will serve to reduce the GHG footprint of the energy sector, this has thus far been largely limited. Despite the fact that offshore wind energy has been around since the 1990s, most of the facilities built to date have been pilot projects, rendering offshore wind power a developing market.

Currently, however, the situation is taking a turn as offshore wind farm technology is rapidly growing. Indeed, several countries around the globe are driving its development, which points to a promising future for this technology. Nevertheless, the expansion of wind turbine capacity and wind farm scale brings a new set of challenges.

Reliability and quality lie at the cornerstone of offshore wind turbines. The construction and operation work of offshore wind turbines are very challenging compared to onshore as they take place in seas and oceans. To improve quality, operation and maintenance (O&M) needs to leverage inspections and monitoring results so that optimal schedules can be derived which minimize the expected total cost over the lifetime of offshore wind farms. For offshore wind turbines, these optimal decisions need to take into account weather windows in determining the schedules for inspections and repairs [49]. On top of that, the decommissioning of offshore wind turbines is another complicating factors. Previous studies [50] find that decommissioning of offshore wind turbines suffer from a lack of guidance, process planning and the lack of availability of vessels.

3. Greenhouse Gas Emission and Offshore Wind

The GHG emission is measured by the volume of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) in the air. Increasing the percentage of GHG emissions causes a huge impact such as global warming and climate change, consequently on agriculture, economics, immigration, and human lives. There are several factors that influence the carbon footprint of offshore wind farms.

3.1. Contributing Factors to GHG

One could list the salient factors that influence the GHG emissions as:

- Manufacturing of offshore wind turbine components
- Wind turbine design
- Wind turbine size
- Wind turbine lifetime
- Spatial characteristics of the wind projects
- Geographical location of installation.
- Manufacturing location.
- Production and manufacturing locations of offshore wind turbine components
- Supply vessels and logistics

Manufacturing of offshore wind turbine components

The majority of the CO_2-equ emissions occurs throughout the manufacturing process of the wind turbine's components. Generally, offshore wind turbines include the following major components, rotor which consists of hub, nose cone and 3 blades; nacelle with frame covers the generator, the gearbox, transformers, and the electronics; tower; foundation; and grid connection cables (Figure 8).

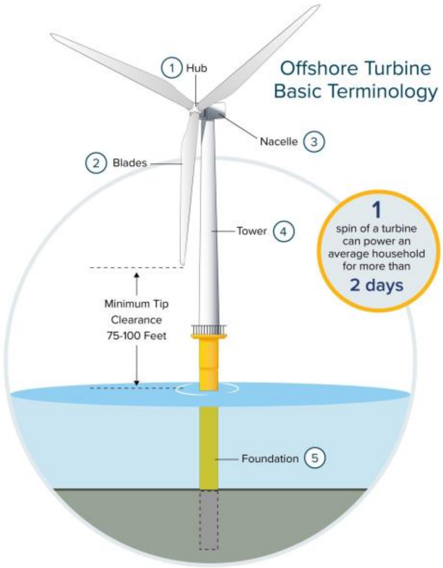

Figure 8. Wind turbine components [24].

A wide range of elements used throughout the manufacturing of the components of wind turbines emit a considerable percentage of GHG. Specifically, among the components of wind turbines, studies [25] found that steel tower was the main contributor to GHG emissions, accounting for more than 50% of the emissions. A study conducted by Siemens Gamesa on manufacturing G83 2 MW turbines indicated that steel accounts for most of the GHG emissions with 75.7%, followed by low alloy steel (15.5%), and brass (0.003%). Most of the low alloy steel is used in the tower of the wind turbine [25].

However, the tower is not the only source for the emissions. In fact, it is the preceding stage, or the material production of raw steel that ejects a high quantity of CO2-emissions during manufacturing (1.75 t/t raw steel) and accounts for 96% of the total emissions within the steel tower production process. Further, during the manufacturing of the foundation part, concrete as well as steel are primarily used. As a result, foundation has the largest contribution to GHG emissions after nacelle, while the production of blade has a contribution of just 10% [26]. Glass fiber/ Fiberglass, epoxy/polyester, PVC foam, balsa(wood), and, in rare situations, carbon fiber are typical materials that are used in blade manufacturing. These materials are typically combined to create composite materials.

The blade root of a wind turbine is the component that links the blade to the hub. High strength steel bolts are required in one of the most crucial areas of blade design. These bolts can be fitted in a variety of methods, the most frequent of which is with steel inserted in the composite root section [27]. The manufacturing of the main shaft also requires high-grade steel.

According to Guezuraga et al. [28] the production of blades consists of approximately 60% glass fibre and 40% epoxy. The material is delivered on rolls to the corresponding assembly facility where it is cut into appropriate pieces to the spar and blade. Glue material is used to assemble the blade shells and the spars [28].

The nacelle of a wind turbine contains the drivetrain components. These include components such as bearings, gears, generator, and shafts as well as the analytical and auxiliary equipment including anemometer, controller, cooling system, and sensors. The nacelle cover is mainly made of fiberglass, plastic, and steel. Further, aluminium, cast iron, copper, plastic, stainless steel, and steel alloy materials are used for the manufacturing of other components within the cover. The generator is basically made of steel and copper, while the gearbox is made of cast iron and stainless steel, and aluminium.

Based on the analysis and simulation done with the software called GEMIS (Global Emission Model of Integrated Systems) for turbine 2.0 MW-geared and 1.8 MW -gearless respectively. The results showed almost similar results, however in terms of CO2 emissions gearless design had lower GHG emissions with respect to the geared design [28].

The manufacturing of the substructures also releases a significant share of GHG emissions (25% of overall GHG emissions). Since offshore wind turbine foundations differ based on the water depth, the higher the water depth, the more the foundation structure becomes complicated, and the more material demand is required.

Raimers et al. [29] investigated the replacement of the jacket structure by a gravity foundation or a monopile structure. The results showed that the changes in the material in manufacturing jacket foundation results in higher GHG emissions rather than the monopile structure and gravity foundation, which is characterized by lower GHG emissions.

These findings show that there is a need for designing alternative methods for wind turbine manufacturing so as to reduce GHG emissions. Such methods may include the modification of the steel manufacturing process, for instance, through the use of recycled steel and electric furnace instead of a basic oxygen furnace. Rajaei et al. [30] indicated in their research that reducing the level of emissions from manufacturing may be possible by replacing Portland cement which is used in the concrete foundation with cementitious fly ash, a by-product of coal combustion.

Since a tower generates the highest percentage of GHG emissions, that is why in order to reduce the climate change contributions of turbines, steel which is used during the production of towers should be targeted for emission reduction.

Wind turbine design

There are a number of approaches that can be taken toward wind turbine design in order to reduce the GHG emission.

As it was mentioned in the previous chapter, depending on the rotation of the axis, wind turbines are divided into 2 types: Horizontal axis wind turbines and Vertical axis wind turbines. Most of the wind turbines installed worldwide predominantly are horizontal axis, which means the rotation of the centre of the rotor and the shaft is horizontal, parallel with the wind direction. VAWT`s axis rotation is completely different than that of HAWT, as the rotation is perpendicular to the wind in the vertical case. There are a lot of different types of VAWT, but the main principal feature is that either they have a drag type or lift type, the former is simpler and more inefficient than the latter.

Figure 9. Horizontal and Vertical Axis Wind turbines [31].

The design of VAWT is simpler compared to the HAWT. The complicated components of VAWT are located in the ground or sea level, whereas for HAWT these are located at the height of 100 meters or even higher. This makes the maintenance of VAWT easier and simpler compared to HAWT. In addition, the use of aluminium in wind turbine blades accelerated the deployment of VAWT technology. Since this class of wind turbines does not require the blades with twisted and tapered sections, as HAWTs, to achieve relatively high aerodynamic efficiencies. Moreover, through the use of extrusion technology, VAWT aluminium blades can be constructed quickly and relatively inexpensively [32].

Two different types of wind turbine with different sizes, 300 W Vertical axis wind turbine and 500W Horizontal Axis wind turbine were compared, where sensitivity analysis was used to estimate energy output, CO2 emissions and environmental impacts. The component materials for VAWT are primarily galvanized steel (42.5%), followed by Aluminium (13.5%), while for HAWT consists of more materials such as galvanized steel (42.1%), followed by Permanent Magnet (1.6%) and with approximately equal portions of plastic and aluminium, and the least copper [25]. The detailed sensitivity analysis and LCA study for the abovementioned two types of wind turbines showed that emissions per kWh/year in terms of GHG emissions for VAWT are much more than HAWT.

Another analysis demonstrated by Rashedi et al. suggests that offshore horizontal wind farms exhibit higher impact rates than onshore horizontal ones. However, the capacity of an offshore farm is 50% higher than an onshore farm. As a result, the per unit electricity profile of the horizontal offshore farm is more environmentally friendly than the onshore counterpart. This is due to the difference in their substructure [26].

Wind turbine size

Different studies showed that the size of wind turbines has a significant impact on GHG emissions. One of those studies compared 4.5 MW and 250 W horizontal and vertical axis wind turbines respectively. The primary energy consumption of 4.5 MW wind turbines is approximately 70.1 TJ in its life cycle and produces 11.7 GWh of electricity, while 250 W wind turbine consumes about 2.8 GJ and produces 2 MWh of electricity [27]. It was noticed that in both cases energy consumption occurs predominantly at the manufacturing stage.

Wind turbines in the MW size emit less GHG emissions per kWh of electricity generated than turbines in the kW size range.

Wind turbine lifetime

Generally, the lifetime of a typical wind turbine is assumed to be about 20 years, depending on the manufacturer it can reach 25 years as well [28]. However, in practice, it withstands 30 years and over of life. While extending the lifetime of a wind turbine increases maintenance activity, the inspection visits, transport of equipment and people from the port to the offshore field, and the component replacements result in an increased GHG emissions. Nevertheless, the emissions from these activities are relatively lower compared to other factors, such as manufacturing. The extension of wind turbine lifetime reduces the effective GHG emissions per kWh of energy generation. Since GHG emissions are mostly related to the manufacturing process, a longer lifecycle ensures that GHG emissions are spread out over a longer period [29].

Spatial characteristics of the wind projects

GHG emission is strongly influenced by the location of the wind farm, which is determined by the type of substructure, water depth, and the O&M concept in case of larger distances from shore. Wind turbines installed very close to each other cause The Wake Effect, which decreases the efficiency of wind turbine capacity and increases GHG emissions (Figure 10).

Figure 10. Wake effect [33].

Wind farms that are located far from the shore could be the solution to GHG emission reduction (at least small percentages) by applying windmill technology with higher power generation. Windmill converts wind power into rotational energy [30].

Comparing the offshore and onshore wind farms with the same capacity, throughout their life cycle, the offshore wind turbines have larger emissions and larger emission intensity. The reason for that is that an offshore wind turbine needs a floating platform fixed in the sea, in order to provide it with buoyancy and stability. Furthermore, it requires more materials which results in significant GHG emissions during the manufacturing, transportation, installation, dismantling, and disposal compared to the counterpart turbines [31].

Geographical location of installation

GHG emissions differs significantly in the region of production. Lenzen M. and Wachsmann et al. examine 5 scenarios, where it was considered 5 installation options with different locations in Germany and Brazil [34]. From those scenarios, it was concluded, a higher emission score for the manufactured components in Brazil. The reason might lie in the difference between the energy supply systems of both countries and their economies.

In conclusion, it was hypothesized that the geographical variability of wind turbine components has a significant and direct effect on GHG emissions due to "upstream supply chain effects".

Manufacturing of wind turbine components

The wind industry is growing rapidly in the last decade. As the size and complexity of wind turbines grow, the manufacturing process requirements and component transportation costs increase the need for local manufacturers who can overcome technical and logistical challenges.

The manufacturing of major components of a wind turbine consists of a complex supply chain. The centre of wind turbine manufacturing is predominantly based in Europe, with the support of national renewable energy deployment policies, in countries like Germany, Denmark, and Spain. Wind turbine manufacturing became competitive also in Asian countries such as India, Japan, China, and South Korea.

In other countries, such as Norway, the wind industry is growing rapidly in recent years. However, there is a lack of manufacturing presence. Some parts of wind turbines are coming from other countries, for instance, Denmark or Germany, which requires the supply of those components and therefore a significant increase in GHG emissions.

Transportation of the components

As the wind energy sector expands, transportation and logistics become more important. Since the majority of the wind facilities are not close enough to each other for the companies to build fixed manufacturing facilities nearby, the option of transportation method is more suitable, here.

The logistics and transportation of the components of a wind turbine such as turbine blades, towers, and nacelles from their manufactured location, is done in various ways such as via rail transport, road transport, and maritime transport. This requires extensive planning, which often takes up to a year, prior to the demand date, due to several parameters, such as road conditions, weather conditions, and in-stock supply. For those parts of the wind turbine which is being transported by road, route planning and route improvements are required (such as the removal of trees etc.)

There is still an ongoing problem with the supply chain of wind turbine components that should be overcome, also as another point all these transportation and logistics activities create a significant amount of GHG emissions. Since not all components are manufactured in the country of use, almost most of the transportation methods require fuel consumption, which is causing significant pollution. For example, if installing an offshore wind turbine in the US some of the components are shipped primarily from Europe, the weather conditions, the shipping road, and other things should be considered.

Production and manufacturing locations of offshore wind turbine components

The production of wind turbines differs based on their location. As an example, in the case of installing a wind farm in Turkey, Brazil, or Norway, one could presume that not all wind turbine components are produced in the country of the respective farm. Some parts such as the nacelle and generator are primarily produced in Germany. The production location influences the shares of the GHG emissions of the components as the electricity generation of different countries may result in different levels of GHG emissions due to the resource mix of their grids. Also, the transportation of the wind turbine components from the location of manufacturing to the location of installation is also a major factor, as different modes of transportation rely on fossil fuels, which similarly result in GHG emissions.

Labour cost in Europe is much higher compared to many other countries. For this reason, as an example, many manufacturing plants are relocated from European countries to China for a lower cost. This is a key contributing factor to GHG emissions.

Wind turbine manufacturing in different countries results in different levels of GHG emissions. Regardless of the country of manufacture, the end product (wind turbine) is the same. However, the percentage of emissions emitted during the manufacture of the same product will differ depending on the energy mix used to generate power/ electricity in each country. For example, Denmark's main source of energy comes mostly from wind power plants, while in China the main energy comes from coal fire power stations.

Supply vessels and logistics

Transportation by truck and by sea vessel are both options for getting to the location where the wind power plant will be installed. Transport therefore gives a fair representation of the current supply. For the installation of large offshore wind structures, ships with the necessary lifting capacity and height are required [41]. Offshore wind farms are constructed, maintained, and serviced using a variety of ships, such as:

Figure 11. Offshore wind farm vessels [52].

- Construction vessels:

  This is the core group of vessels that are employed in the construction of wind tower structures. They consist of the most magnificent-looking Jack-up vessels. Geotechnical vessels, stone dumping vessels, floating sheerleg cranes, barges, semi-submersible floating platforms, heavy lift vessels, and diving support vessels are additional vessels used in the construction of wind towers.

- Service vessels:

  These are different classes of vessels made up of offshore accommodation vessels (OAV) and crew transfer vessels (CTVs). Catamarans, support vessels (W2W), crew transfer vessels (CTV), surface effect ships (SES), service operational vessels (SOVs), daughter craft, SWATH and Semi-SWATH vessels, trimarans, monohulls, and RIBs are the most popular types of units of this type.

- Cable installation vessels:

Energy produced by wind turbines is transferred using specialized cable construction. Cable laying vessels, cable laying barges, barges, ROV support vessels, and multipurpose vessels are the most common special vessel types needed to lay them [43].

The effects of shipping on the marine environment are profound. About 2.6% of the world's CO2 emissions are brought on by shipping on the oceans. In 2015, these came to about 932 million tons of CO2, according to the German Federal Environment Agency [42].

The supply of electricity to vessels while vessels are in port continues is an issue that merits special attention. A large portion of these vessels run on fossil fuels, which greatly contribute to GHG emissions. To address this shortcoming, several companies in the industry set out to reduce GHG emissions from service operation vessels. One notable example is the agreement between Ørsted and ESVAGT [51], which seeks to develop service operation vessels powered by batteries and dual fuel. These vessels will be capable of operating on renewable e-methanol that is produced from wind energy and biogenic carbon. The project is expected to reduce yearly emissions by approximately 4,500 tonnes of CO_2.

4. GHG contributing factors from lifecycle perspective.

The lifecycle process chart describes the life process of an item from the start (when it is at the conception phase) to the disposal phase. The lifecycle process chart involves the stakeholders such as customers, sponsors, organizers, who are involved in the project or have an interest in the outcome of the project. It helps identify the needs of the stakeholders at each lifetime stage.

The lifecycle process chart helps to have control over the project and all the steps that must be followed during all the stages of a project. In other words, the lifecycle process chart helps plan and execute the project in a more structured way by having a better overview, so that project tasks and requirements can be handled correctly and at the right time. As a result, it ensures that a project can smoothly advance, its hurdles can be easily overcome, and generate more profits. It is also helpful to be able to maintain good communication with the stakeholders who are involved in the project, be aware of their needs and expectations, which is very important to have a successful, safe and efficient project.

Based on extensive several literature reviews, we identify the life cycle stages of wind turbines as in Figure 12:

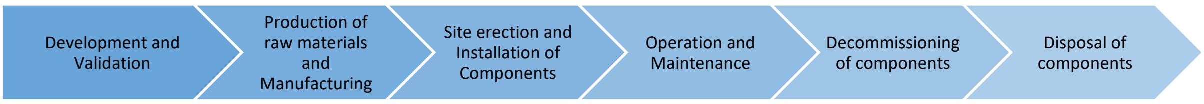

Figure 12. Life cycle stages of an OWF.

- *Development and validation phase*

Development and validation phase of an offshore wind farm starts approximately 5 years, due to the nature of offshore maritime environment. The starting point of any type of project or wind farm project is the feasibility study to better identify areas that suitable for wind farms and those that are not. The wind farm project may be created either by a wind farm developer who is looking for suitable locations, or by community contacting person in the wind sector. Throughout this phase, in order to validate and start the project, many studies, paperwork and other procedures must be accomplished to ensure the economic feasibility of wind project. The evaluation of the feasibility of the possible site would be evaluated based on the several interrelated parameters, such as:

- The average wind speed, water depth, seabed conditions
- The availability of the land
- The impact on local people and the environment
- The acceptance from community
- The distance from houses
- Consideration of local municipality development plans
- Existing and future grid infrastructure

Many of these criteria are interconnected, and more might be included depending on the project.

- *Production of raw materials and manufacturing*

The production and manufacturing phase includes the production of the raw materials used in the manufacturing of offshore wind turbine components. Further, it includes the manufacturing of wind turbine components themselves, including towers, foundation, nacelles, blades, transmission cables and transformer station. It also includes the transportation of raw materials used during the manufacturing of the components, such as steel, copper, and epoxy [41].

We noted in the previous chapter the fiberglass rotor blades have a sandwich construction, with 60% glass fibre and 40% epoxy resin as the weight ratio. The drivetrain is made up of the generator, gearbox, and main shaft components. These components are made primarily of cast iron and stainless steel. Further, a cast iron bed frame supports the entire assembly. Included in the nacelle are also, the yaw system, transformer as well as the bearings. Finally, steel is used in building the tower [29].

- *Installation and Commissioning*

The installation and commissioning phase of an OWF involves activities related to the construction of wind farms. In this phase, the installation ports and logistics is very important in supply chain management of offshore wind farms. The installation and commissioning phase includes the transportation of wind turbine components to site (onshore wind turbines) or to the offshore site (offshore wind turbines). This phase also includes the processes involved in placing the foundation, the turbines, and the internal cables, as well as installing the transformer stations and integrating them to the grid.

Modes of transportation to the site of installation of wind turbine includes transport by sea (by vessels) and land (by trucks) [41]. Transportation of the parts and construction activities require mainly carbon-based fuels for the operation of the machinery equipment.

As for the transportation and erection stage, the turbine might be produced in Denmark and transported to another destination of installation by boat and truck. The tower components are produced in a factory near the site, whilst the tower subparts again might be produced based on the location in another European country, such as Germany or Denmark and transported by boat and truck. The distance for the components from the port to the site is estimated beforehand.

Due to their size, the transportation of wind turbines is carried out in multiple batches. At the wind farm site, assembling the sections and erecting the wind turbine can take up to a week. However, depending on the weather conditions, these processes can be completed faster, such as around two days. The assembly of wind turbines are carried out using large cranes by and a team of specialized engineers and technicians [48].

The cost incurred at this stage includes those related to port, installation of the components, commissioning of the wind turbines and electrical systems, and construction insurance [30]. Therefore, in case of the delay of supply distribution, it has significant negative consequences on installation expenditures [35].

- *Operation and Maintenance*

A wind project undergoes several tests after the installation and commissioning phase before the handover to the owner/developer [48]. As part of the operations stage, the physical operation, finance, maintenance, security, and reliability of an of offshore wind farm must be managed. While in operation, wind turbines as well as their intrinsic critical components are remotely monitored on a continuous basis by leveraging a supervisory control and data acquisition (SCADA) system. This system is used while monitoring the production and the performance of a wind farm to ensure its operating efficiency. Routine maintenance is performed between two and 4 times in a year.

The wind farm owner, operations supervisor, or turbine maintenance contractor can use the SCADA system to monitor the wind farm's production and performance so as to ensure that it is operating efficiently. When a defect occurs, the computer system detects it and notifies the supervisor, who dispatches a maintenance staff to the spot. Depending on the kind of wind turbine, routine maintenance is performed between two and four times each year. Where a fault occurs the computer system will identify it and inform the supervisor who will send a maintenance crew to the site. The routine inspection can take a number of days and involves at least two service technicians to look at the condition of blades, cables and gearboxes.

As part of the operations and maintenance phase, regular inspection visits are carried out primarily with diesel trucks approximately three times a year [36]. Moreover, maintenance activities include transportation and oil and lubricant changes, while rotor blade, gearbox and generator replacement are assumed to be required once within a 20-year lifetime. Nevertheless, these assumptions might be highly optimistic assumptions as a reliability study of relatively small turbines indicate significantly higher failure rates [37].

In case of unscheduled maintenance inspection, which is also performed by maintenance specialists in reaction to replace or repair the components of wind turbine. The maintenance inspection of electrical infrastructure is routinely maintained and tested at least once in a year.

- *Decommissioning phase*

At final phase of life cycle of OWF, when it reaches the end of its lifetime, the developer will decide whether the OWF is to be decommissioned or repowered. This phase implies the complete removal of an OWF, whereas repowering entails updating wind turbines at an existing OWF by either replacing older turbines with new ones or swapping out the parts in the original turbines with new ones with more efficient technologies.

The final stage, decommissioning, implies the complete removal of an Offshore wind farm, whereas repowering entails updating wind turbines at an existing Offshore wind farm by either replacing older turbines with new ones or swapping out the parts in the original turbines with new, more efficient technologies.

For the life cycle analysis, the decommissioning phase is a very important parameter. Compared to other sources of energy the wind energy wastes are not toxic to the environment. It was assumed that around 98% of blade, 90% of grid and nacelle and 90% of tower would be recycled [38]. The decommissioning site is assumed to be around 50- 120 km away from the site (or the wind farm). The foundation is disposed on a municipal waste. Energy consumed during all decommissioning phase is assumed to be equal to the manufacturing one [39].

As there is limited data on the decommissioning of offshore wind turbines, we explored data used in specific scientific studies in the literature. In such studies, the turbines are assumed to be disassembled using a mobile crane and transported 500 km by road to a disposal facility [40]. To transport one unit of 1.5-MW wind turbine, studies foresee that nine trips may be required. For dismantling at the facility, energy requirements are further assumed to be 2625 m3 of natural gas and 26.3 MWh of electricity [40].

Table 2 depicts the possible recycling methods:

Material	Material End-of-life treatment
Concrete	Landfill 100%
Cast Iron	Recycling with 10% loss
Copper	Recycling with 5% loss
Epoxy	Incinerated 100%
Fiberglass	Incinerated 100%
Plastic	Incinerated 100%
Stainless	Recycling with 10% loss

Table 2. Possible scenarios for recycling of materials of wind turbine. [40]

After the detailed description of each phase, we can conclude that throughout the wind turbine life cycle phases must be undertaken during the examination of GHG emissions in each stage of LCA.

Life cycle assessment (LCA) must be undertaken during the examination of the carbon footprint of every item in each step. There are several factors associated with turbines that affect the environment, including the production of aluminium, steel, and other concrete materials. Fossil fuels may be utilised in the various stages of the lifecycle of a wind turbine, which must be taken into account in calculating the GHG emissions for the wind turbine life cycle [44]. To assess the carbon footprint of wind turbines, the quantity of emitted GHG in each stage of the life cycle needs to be evaluated and summed over all stages.

5. Recommendations for reducing GHG footprint of offshore wind turbines.

The analysis laid out in the previous chapters laid out several factors that contributed to increasing the greenhouse gas emissions of offshore wind turbines. In this chapter, we use the analysis conducted in the previous chapters to present suggestions on how the greenhouse gas emissions of future offshore wind turbines can be reduced. The recommendations presented in this chapter use the insights drawn from the previous chapters into the major factors that result in greenhouse gas emissions throughout the lifecycle of an offshore wind turbine.

Specifically, the recommendations presented in this chapter concern the manufacturing, installation, maintenance as well as the decommissioning phases of offshore wind turbines. For each of these phases, we consider how the existing mechanisms can be modified so that the offshore wind turbines off the future could be developed in a way that results in much less GHG emissions. In the rest of the chapter, we represent in several sections our recommendations for reducing the greenhouse gas emissions associated with the manufacturing, installation, maintenance and decommissioning phases.

5.1 Manufacturing Phase

Our analysis in the previous chapters showed that the manufacturing of wind turbines could result in major levels of greenhouse gas emissions. The resulting greenhouse gas emissions stem not only from the chemical processes required to manufacture the various components of wind turbines, but also from the massive amounts of energy that is consumed in those processes.

The manufacturing of wind turbines requires various chemical treatments and reactions on several sorts of material including iron, steel, copper, aluminium, and zinc. Throughout these chemical processes, it is imperative to work with certain ranges of temperature. Further, it is required to ensure that various interlinked processes are started, executed, and completed in a manner such that the constraints of the coupled processes are complied with.

To maintain the necessary conditions for the chemical processes, greenhouse gases are necessarily emitted. Further, in several of these chemical processes, greenhouse gasses are emitted as a by-product of the reaction.

A key recommendation to reduce greenhouse gas emissions is to utilize and manufacture materials that result in less GHG emissions. For this purpose, it is necessary to identify potential materials that can replace the existing materials currently used in manufacturing wind turbines. Specifically, the identified potential materials must involve chemical processes and conditions that do not result in significant amounts of GHG emissions. To this end, it is necessary to investigate and make advances on the use of organic components in wind turbines.

Note that since the utilized material require massive amounts of energy, the manufacturing and production of various components typically involve high levels of electricity consumption. Clearly, the required electricity consumption needs to be met by the electricity generation of the power plants located in the electricity grid of the manufacturing location. These plants however could be fossil-fired plants that run on coal, oil as well as natural gas. As a result, chemical processes that require high amounts of energy will necessitate higher electricity generation from fossil fired plants. High electricity generation from fossil fired plants will in turn increase the greenhouse gas emissions as there are greenhouse gas emissions associated with using call or natural gas to produce electricity. There are several ways to improve the sustainability of the electricity generation in the electricity grid in which the manufacturing process is carried out. For instance, the location in which the wind turbines are manufactured could be selected in electricity grits that have a large share of renewable energy sources. Such a solution will ensure that the increased electricity consumption due to the chemical processes required for manufacturing wind turbines could be met by renewable energy sources, which do not result in greenhouse gas emissions while generating electricity. If moving the location of manufacturing is not feasible, increasing the share of renewable energy sources in the electricity grid in which the manufacturing process takes place can significantly reduce greenhouse gas emissions. To do so, it will be required to make necessary regulatory and policy changes so that specific renewable energy targets will be set in places where there is significant manufacturing activity.

On a more local level, factories in which the manufacturing processes of wind turbines are carried out can make their own electricity consumption profiles more sustainable. To this end, factories can themselves install distributed renewable energy sources such as photovoltaic panels and wind turbines so that they can meet their electricity consumption by their own generation, which they know to be sustainable. For their factories can schedule the operation of energy intensive manufacturing processes such that the time periods in which there is high levels of electricity consumption correspond to the time periods where there is a high level of renewable energy generation. Such a scheduling will ensure that a larger share of the electricity consumption of manufacturing activities can be met by sustainable energy sources and less so by fossil-fired plants which will consequentially decrease the greenhouse gas emissions associated with various manufacturing processes. In addition to deploying renewable energy sources in facilities where manufacturing activities take place companies can further purchase energy storage such as batteries so that they can store their excess renewable energy when the renewable energy generation exceeds the electricity consumption of their factories. The stored energy can then later be used to meet the electricity demand of the manufacturing processes that take place in time periods during which there is not significance renewable energy generation. Overall, the combination of renewable energy sources and batteries in facilities where manufacturing activities take place will reduce the dependence of the facilities to the main power grid, which will ensure that a higher share of their electricity demand is met from sustainable energy sources and thus result in significantly less greenhouse gas emissions.

5.2. Installation Phase

We next review existing practices that can be modified so that the greenhouse gas emissions that result from the installation phase can be reduced. Our review in the previous chapters showed that there is significant levels of greenhouse gas emissions in the installation phase as several vessels are deployed to install offshore wind turbines between a time window that can span several months to several years.

In most existing practices, the vessels that are being currently deployed to install offshore wind turbines run on fuels such as diesel or oil. Clearly these fuel sources are not sustainable and result in greenhouse gas emissions when they are used. Especially, the heavy-lift vessels that are primarily used in installing the tower as well as the blades of offshore wind turbines can run several weeks in a row, carrying crews and hosting several heavy equipment. As a result, they mostly consume a lot of fuel and give rise to significant levels of greenhouse gas emissions.

In order to reduce the greenhouse gas emissions in the installation phase, it is necessary to replace the vessels that run on non-sustainable field sources by battery-powered vessels. The batteries of these vessels can be charged in ports where there is significant levels of renewable energy generation. As a result of this design choice, the source of energy for operating heavy-lift vessels will primarily come from sustainable energy sources, which will in turn mitigate the greenhouse gas emissions due to running on fuel sources such as oil or diesel. In addition, there are several vessel designs where the vessels themselves are equipped with the new energy sources. Equipping heavy lift vessels with such renewable energy sources such as wind turbines will require storing less energy in the port (where the source of energy will be mixed between renewables as well as fossil fired plants) as more of the required energy consumption can be met from the renewable energy sources that are integrated within the vessel. This will in turn result in less greenhouse gas emissions as more of the electricity demand of the heavy-lift vessels will be met from sustainable renewable energy sources.

In addition, it is necessary to optimize the transportation of the crews and arrange their shifts so that the energy consumption due to transporting crews can be reduced, which will similarly reduce the greenhouse gas emissions due to using non-sustainable fuel sources.

5.3. Maintenance Phase

Similar to the installation phase, the maintenance of offshore wind turbines entail greenhouse gas emissions due to the consumption of non-sustainable fuel sources in executing maintenance operations. Specifically, in order to transport the maintenance crews to the locations of offshore wind farms, it is necessary to deploy vessels, which, under current conditions, primarily use fossil fuels.

There are several modifications that can be executed such that the maintenance procedure can be improved. Firstly, the digitization of offshore wind turbines and collection of massive amounts of data from various wind turbine components can enable the development of intelligent predictive maintenance models. Such predictive maintenance models can be used to identify the components of offshore wind turbines that will need to undergo maintenance and optimize the scheduling of maintenance procedures. Optimal maintenance schedules as determined by intelligent predictive maintenance procedures will ensure that both the components of offshore wind turbines do not fail and that the maintenance procedures are not performed in an unnecessary frequency.

A key benefit of utilizing intelligent predictive maintenance methods is that optimal maintenance schedules will ensure that the maintenance crews are transported to offshore wind farms only as long as their transportation is both necessary and optimal. This will in turn ensure that the fuel consumption associated with transporting maintenance crews to offshore wind farms is minimized which will consequentially reduce the greenhouse gas emissions.

5.4. Decommissioning Phase

The analysis in Chapter 4 showed the intricacies of evaluating the decommissioning phase which mainly stems from the fact that the large majority of offshore wind turbines that are currently in operation have not been decommissioned. However, this also presents various opportunities as before the offshore wind turbines that are currently in operation are decommissioned, novel methodologies that will be developed can be applied during the decommissioning of the existing of offshore wind turbines and does reduce the associated greenhouse gas emissions.

We noted in the previous chapter that the material and the components of existing offshore wind turbines are unfortunately neither reused or recycled. If it were possible to reuse the components of offshore wind turbines, then the offshore wind turbines that will be developed in the upcoming years can use as components the components of the wind farms that will by that time be decommissioned. We noted in the manufacturing phase that there are large greenhouse gas emissions associated with manufacturing new components as it requires both energy-intensive manufacturing processes and also the required chemical processes entail high greenhouse gas emissions. That's why, reusing the existing components of the decommissioned offshore wind turbines will allow the manufacturing of fewer new components and thus will significantly reduce greenhouse gas emissions.

For this purpose, it is required to investigate and make advances into how the offshore wind farms that will be decommissioned in the upcoming years or decades can be utilized in developing and installing offshore wind farms in the upcoming decades. In this light, it is necessary to explore whether the components of existing offshore wind farms can in any capacity support future offshore wind farm projects.

In conjunction with exploring currently existing offshore wind farms, it is analogously necessary to consider the design of future offshore wind farms. In this regard, it is necessary to design new offshore wind turbine projects so that the components that will be included in the upcoming offshore wind turbine projects are by nature reusable and recyclable. Such a design choice will ensure that a decommissioned offshore wind farm will not result in massive non-usable chemical components but rather either support the development of novel offshore wind farm projects or other chemical processes that rely on similar material. As a result, it will reduce the greenhouse gas emissions of either future offshore wind farm projects or decrease the emissions of other manufacturing processes that utilize similar material.

Vestas, for example, leads the CETEC (Circular Economy for Thermosets Epoxy Composites) project that aims to make fully recyclable wind turbine blades. This project has been launched to facilitate the adoption of this new technology and to advance a circular economy throughout the wind industry.

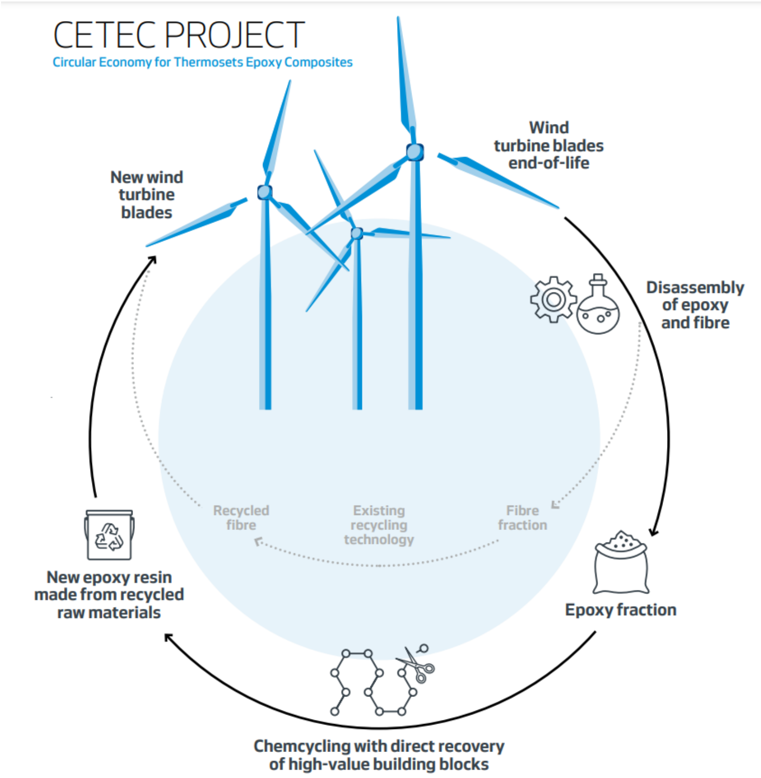

Figure 13. Vestas' CETEC project of fully recyclable wind turbine blades [46].

This innovative project consists of two steps. The first step is the separation of fibre and epoxy from thermoset composites. The following second step is the disassembly into base components which is similar to virgin materials using an innovative chemcycling process. This creates a new circularity pathway for epoxy resin as these materials can then be used again in the production of new turbine blades [45].

6. Discussion

In this thesis, we focused in the problem of evaluating the greenhouse gas emissions of offshore wind farms. The main objective of the thesis was to evaluate the several factors in the lifecycle stages of offshore wind farms that resulted in greenhouse gas emissions. Such an evaluation was necessary as existing studies mostly assume that there are no greenhouse gas emissions from renewable energy sources such as offshore wind farms, as these renewable energy sources do not emit greenhouse gases while generating electricity.

We evaluated several factors in the design, development, installation, and decommissioning of offshore wind farms which result in GHG emissions. We further approach these factors from a lifecycle perspective and studied at which lifecycle stage these factors contribute to greenhouse gas emissions. Finally, we presented several recommendations so that the offshore wind farms that are both currently in operation and that will be developed in the future will result in significantly less greenhouse gas emissions.

A major challenge in writing this thesis was the access to data. Specifically, a quantitative evaluation of the greenhouse gas emissions of offshore wind farms requires a comprehensive dataset that includes the greenhouse gas emission recordings due to each lifecycle. This, however, is not currently available, which was a key hurdle in our analysis.

7. Conclusion

In this thesis, we seek to conduct a thorough analysis of the greenhouse gas emissions associated with offshore wind turbines. Typically, renewable energy resources such as offshore wind turbines are treated to have zero greenhouse gas emissions, as greenhouse gases are not emitted from these resources during electricity generation. Nevertheless, in practice, throughout the various lifecycles of offshore wind turbines, significant levels of greenhouse gasses could be emitted. Motivated by these observations, the key objective of the thesis is to investigate the resulting greenhouse gas emissions from offshore wind turbines.

Specifically, we assessed the major factors that result in greenhouse gas emissions from offshore wind turbines and studied these factors from a lifecycle perspective. In this light, we presented the key factors at each lifecycle stage of offshore wind turbines that contribute to the greenhouse gas emissions. Furthermore, we presented several recommendations so that offshore wind turbines that are currently deployed or will be commissioned and designed in the future can entail significantly lower greenhouse gas emissions.

References:

[1] International Energy Agency (IEA) Global Energy Review 2021, Assessing the effects of economic recoveries on global energy demand and CO2 emissions in 2021.

[2] The decarbonisation fuel challenge. [Online]. Available:

https://www.eurotherm.com/de/glass-manufacture/the-decarbonisation-fuel-challenge/

[3] International Renewable Energy Agency (IRENA) Future of Wind. Deployment, investment, technology, grid integration and socio-economic aspects. Accessed from October 2019.

[4] Lloyd, C., 2010. Asset management: Whole-life mansagement of physical assets, Thomas Telford.

[5] Woodhouse, J., (2010), Asset management: The way forward, in Lloyd, C., (ed), Asset management: Whole life management of physical assets, Thomas Telfard, pp 201-221

[6] Amadi-Echendu, J. E., et.al. (2010) 'What is Engineering Asset Management', in Definitions, concepts and scope of engineering asset management. London; New York: Springer, pp. 3–16.

[7] IAM, 2015. Asset management – An anatomy. [pdf] Available at: https://theiam.org/what-is-asset-management/anatomy-asset-management

[8] GFMAM, 2014. The Asset Management Landscape (Second Edition).

[9] Integrated Asset Management for Wind Power Industry. Available at: https://www.tuv.com/content-media-files/india/pdfs/i00-wind/wind-asset-management.pdf

[10] Definitions and Benefits of Asset Management. Available at: https://www.newea.org/about-us/committees/asset-management-committee/am-resource-center/definitions-and-benefits-of-asset-management/

[11] Dutton, A. , Sullivan, C. , Minchew, E. (2019) Going-Global: Expanding-Offshore-WindTo-Emerging-Markets. Retrieved from the world

[12] Musial, W. Overview of Floating Offshore Wind. In Proceedings of the Webinar Hosted by National Renewable Energy Laboratory, Golden, CO, USA, 26 February 2020.

[13] IOP Conf. Series: Wind turbines: current status, obstacles, trends and technologies – Materials Science and Engineering 161 (2016)

[14] Lesny, K., Richwien, W., 2011. Design, construction and installation of support structures for offshore wind energy systems. Woodhead Publishing

[15] Exploring Offshore Wind and careers it offers. (Image). Available at: https://getintoenergy.org/renewable-energy/exploring-offshore-wind-and-the-careers-it-offers/

[16] Offshore Wind Outlook 2019: World Energy Outlook Special Report (2019). Available at: Offshore Wind Outlook 2019: World Energy Outlook Special Report (windows.net)

[17] The University of Tokyo uses Shoreline Wind simulation for exploring efficient infrastructure for offshore wind farms. Available at: https://www.shoreline.no/news-events/news/the-university-of-tokyo-uses-shoreline-wind-simulation-for-exploring-efficient-infrastructure-for-offshore-wind-farms/ (Accessed from: 28 June 2021)

[18] Evwind, News Menu, OpEd, Uncategorized, Wind Energy, wind energy. Turkey reaches 10 GW wind energy milestone. Available at: https://www.evwind.es/2021/09/09/turkey-reaches-10-gw-wind-energy-milestone/82307 (Accessed from: September 9, 2021)

[19] International Energy Agency (IEA) - World Energy Outlook 2019.

[20] I. J. Chen, A. Paulraj (2004) Towards a theory of supply chain management: the constructs and measurements.

[21] S Schaltegger, R Burritt - 2014. Measuring and managing sustainability performance of supply chains: Review and sustainability supply chain management framework. Accessed from 6 May 2014

[22] T Poulsen, R Lema - 2017. Is the supply chain ready for the green transformation? The case of offshore wind logistics. (Accessed from June 2017).

[23] IPCC Report Analysis: The Top Five Measures to Halve Emissions by 2030 (Accessed from August 2022).

[24] Offshore Wind 101. Available at: https://www.nyserda.ny.gov/All-Programs/Offshore-Wind/About-Offshore-Wind/Offshore-Wind-101

[25] M. Sattler (2020) Reducing the Carbon Footprint of Wind Energy What Can Be Learned from Life Cycle Studies?

[26] Oebels, K.B. and Pacca, S., 2013. Life cycle assessment of an onshore wind farm located at the northeastern coast of Brazil. Renewable Energy, 53, pp.60-70.

[27] Burton, T., Jenkins, N., Sharpe, D., & Bossanyi, E. (2011). Wind energy handbook. John Wiley & Sons.

[28] Guezuraga, B., Zauner, R. and Pölz, W., 2012. Life cycle assessment of two different 2 MW class wind turbines. Renewable Energy, 37(1), pp.37-44.

[29] Reimers, B., Özdirik, B. and Kaltschmitt, M., 2014. Greenhouse gas emissions from electricity generated by offshore wind farms. Renewable energy, 72, pp.428-438.

[30] Rajaei, M. and Tinjum, J.M., 2013. Life cycle assessment of energy balance and emissions of a wind energy plant. Geotechnical and Geological Engineering, 31(6), pp.1663-1670.

[31] Types of wind turbines. Available at: https://c03.apogee.net/mvc/home/hes/land/el?utilityname=dixieec&spc=kids&id=16214

[32] Sutherland, H.J., 2000. A summary of the fatigue properties of wind turbine materials. Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology, 3(1), pp.1-34.

[33] Optimizing energy production: Addressing rotor wakes at wind farms. Accessed from: August 11, 2016. Available at: https://www.windpowerengineering.com/optimizing-energy-production-addressing-rotor-wakes-wind-farms/

[34] Lenzen, M. and Wachsmann, U., 2004. Wind turbines in Brazil and Germany: an example of geographical variability in life-cycle assessment. Applied energy, 77(2), pp.119-130.

[35] Myhr A, Bjerkseter C, Ågotnes A, Nygaard TA. Levelised cost of energy for offshore floating wind turbines in a life cycle perspective. Renew Energy 2014;66: 714–28.

[36] Stacey L. Dolan,Garvin A. Heath. Life Cycle Greenhouse Gas Emissions of Utility-Scale Wind Power.

[37] Echavarria E, Hahn B, Van Bussel GJ, Tomiyama T. Reliability of wind turbine technology through time. Journal of Solar Energy Engineering. 2008 Aug 1;130(3).

[38] Nalukowe BB, Liu J, Damien W, Lukawski T. Life cycle assessment of a wind turbine. Technical report; May 2006. From website: www.infra.kth.se/fms/ utbildning/lca/projects%202006/Group%2007%20(Wind%20turbine).pdf.

[39] Ardente F, Beccali M, Cellura M, Lo Brano V. Energy performances and life cycle assessment of an Italian wind farm. Renew Sust Energy Rev 2008;12:200–17.

[40] Chataignere A, Boulch D (2003) Wind turbine (WT) systems, ECLIPSE—environmental and ecological life cycle inventories for present and future power systems in Europe.

[41] Razdan P, Garrett P (2018) - Life Cycle Assessment of Electricity Production from an onshore V100-2.0 MW. Wind Plant – 18th December 2015, Version 1.0.

[42] New project to drastically reduce shipping emissions. Available at: https://w3.windfair.net/wind-energy/news/39688-maersk-supply-service-offshore-developer-wind-energy-wind-power-orsted-decarbonization-maritime-industry-emissions-shipping-co2-sov (Accessed from 26.01.2022)

[43] 4C Offshore. Offshore Market Intelligence Services. Available online: https://www.4coffshore.com/ (Accessed from 18 December 2021).

[44] Chartron, Sylvain; Stein, Michael; Gaysse, Jérôme; Haasis, Hans-Dietrich (2018) : Digitalization potentials in supporting offshore wind logistics.

[45] New coalition of industry and academia to commercialise solution for full recyclability of wind turbine blades. Available at: https://www.vestas.com/en/media/company-news/2021/new-coalition-of-industry-and-academia-to-commercialise-c3347473 (Accessed from 17 May 2021)

[46] Towards a circular economy for wind turbine blades (Image). Available at: https://www.jeccomposites.com/news/new-coalition-of-industry-and-academia-to-commercialise-solution-for-full-recyclability-of-wind-turbine-blades/

[47] New Era for Offshore Wind Threatened by Supply Chain Woes. Available at: https://www.world-energy.org/article/25653.html (Accessed from 1 July 2022).

[48] Irish Wind Energy Association – Life cycle of an Onshore wind farm, March 2019.

[49] Li, R. and Wang, X., 2011, May. Status and challenges for offshore wind energy. In 2011 International Conference on Materials for Renewable Energy & Environment (Vol. 1, pp. 601-605). IEEE.

[50] Topham, E., Gonzalez, E., McMillan, D. and João, E., 2019, May. Challenges of decommissioning offshore wind farms: Overview of the European experience. In Journal of Physics: Conference Series (Vol. 1222, No. 1, p. 012035). IOP Publishing.

[51] Ørsted and ESVAGT sign agreement on the world's first green fuel vessel for offshore wind operations Available at: https://orsted.com/en/media/newsroom/news/2022/04/13648631 . (Accessed from 08.04.2022)

[52] Łebkowski, A., 2020. Analysis of the use of electric drive systems for crew transfer vessels servicing offshore wind farms. Energies, 13(6), p.1466. (Image)