Assessment of recycling potential and circularity in decommissioning of offshore wind farms

Department of Wind Energy Master Report

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DTU Wind Energy-M-0402

June 2020

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Title: Assessment of recycling potential and circularity in decommissioning of offshore wind farms

DTU Wind Energy-M-0402402
June 2020

Project period:
February – June 2020

ECTS: 30

Education: Master of Science

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Remarks:
This report is submitted as partial fulfillment of the requirements for graduation in the above education at the Technical University of Denmark.

DTU Wind Energy is a department of the Technical University of Denmark with a unique integration of research, education, innovation and public/private sector consulting in the field of wind energy. Our activities develop new opportunities and technology for the global and Danish exploitation of wind energy. Research focuses on key technical-scientific fields, which are central for the development, innovation and use of wind energy and provides the basis for advanced education at the education.

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Abstract

There has been a rise in the installation of the Offshore Wind Farm (OWF) in recent years to meet the climate targets. As the wind farms reach their design lifetime of 20-25 years, the number of wind farms required to be decommissioned will soon increase in the coming years. As the offshore wind industry is relatively young, there is only a limited amount of practical experiences in decommissioning and disposing the OWF. Thus, there rises a need for research about a more sustainable approach for decommissioning and disposing of the components and materials in an OWF. The paradigm of Circular Economy (CE) is receiving increased attention and it offers possibilities to implement the concepts of CE in decommissioning the OWF. Furthermore, the Life Cycle Assessment (LCA) of the OWF is necessary to measure the impacts of decommissioning and disposal on the environment. This thesis addresses the present research gap and develops a methodology to link the materials used in an OWF with circularity potential and environmental impacts in decommissioning the OWF.

An interactive tool was developed that links the materials used in the OWF with circularity and environmental impacts depending on the specifications of the wind farm selected by the user. The materials used can be ranked according to parameters like mass, monetary value, climate impact, criticality and recycling rate. The circularity potential of the concerned OWF is calculated based on the Material Circularity Index (MCI) indicating the extent to which the material flows are circular. Furthermore, the environmental impacts of the OWF are calculated through the LCA study conducted in SimaPro.

The results obtained are discussed for a case study of Utgrunden OWF which was decommissioned in 2018 and consisted of 7 wind turbines (Eron Wind70/1500) with 1.5 MW capacity. The steel is the most used material in the OWF and due to its quantity and high recyclability, it generates high monetary value. Cables used have a large impact on the environment and also pose a potential of high economic value due to copper contained. The magnets due to the presence of Rare Earth Elements (REE), are the most critical material used in an OWF. The criticality signifies the economic and strategic importance for the European economy. Also, due to the manufacturing process of REE, the magnets pose high environmental impacts and focus should be on recycling the magnets. Based on the recycling rates of the materials, the recycling potential of the wind turbine was 84% and that of the whole OWF was 67% indicating the fraction of materials that are currently recycled. The circularity potential of the OWF was 0.52, indicating the material flows are 52% of a fully circular system. The OWF had global warming impact with emissions of 1.2 $kg\ CO_2 - eq/kg$ material used in the wind farm.

Different scenarios with complete removal of foundations and cables and reusing components were modelled. Detailed analysis of the removal process of foundations is necessary to assess the impacts. Moreover, the components of the decommissioned OWF should be reused or repurposed for other applications. Based on the analysis conducted, it can be said that there is a scope for improving the decommissioning and material disposal process to minimize the resource use by the implementation of the CE principles.

Keywords: Offshore Wind, Decommissioning, Circular Economy, Life Cycle Assessment

Preface and Acknowledgement

This thesis was conducted between 27^{th} January and 27^{th} June 2020 at the Technical University of Denmark (DTU) as a part of a two-year Masters degree. During my studies in M.Sc. in Sustainable Energy specializing in Wind Power, I was interested in the upcoming topics in sustainability and wind power which has motivated me to write this thesis.

This thesis process has been an exciting multi-disciplinary journey where I have been reflecting on various issues and inter-linking different topics. The process involved many people without whom I would not have succeeded in the thesis.

I would like to express my deepest gratitude towards my main supervisor, Professor Niels-Erik Clausen and industry supervisor Pernille Skyt for their invaluable commitment to this project. I highly appreciate their continuous guidance and support throughout the process. The process would not have been possible without their encouragement and crucial feedback. I also thank them for introducing me to their network, where I had interesting discussions with many people.

This thesis work has been in cooperation with the DecomTools Project. The Energy Innovation Cluster is the partner of this project. I would like to thank several partners of the DecomTools project for their inputs and insights into the industry to ensure the results of this thesis are relevant.

I also want to thank the researchers at the Technical University of Denmark and people from industry who guided me by directing to the relevant studies and giving me crucial insights into the subjects and providing me with the required data.

Lastly, I thank my family and friends for their unreserved love, patience and encouragement throughout the process of this thesis.

Amogh. U. Gokhale
June 2020
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Contents

List of Tables

List of Figures

List of Abbreviations

1

Introduction

1.1. Background

The world today is now facing the adverse effects of the unprecedented human influence on the climate system. Humans have been emitting CO_2 to the atmosphere which is leading to global warming and other threats. Decarbonisation of the energy sector and reduction of carbon emissions to limit climate change is now gaining attention. Shifting away from the consumption of fossil fuels, towards cleaner renewable sources of energy is essential to meet the agreed upon climate goals. Many European countries are exploring ways to become carbon-neutral by 2050 to limit the global average temperatures to 1.5°C, to meet the climate targets according to the Paris Climate Agreement.

Wind energy has proved its significance in the world and will lead the way for transformation of electricity sector. The International Renewable Energy Agency (IRENA) predicts onshore and offshore wind combined, would generate 35% of the global electricity demand by 2050 [1]. To reach this target IRENA forecasts around 1000 GW of offshore capacity and 5044 GW of onshore capacity to be installed in the world by 2050 [1]. As of 2018, 542 GW of onshore wind and 23 GW of offshore wind capacity has been installed installed in the world according to IRENA. Recent advancements in the offshore wind industry have exhibited the potential of offshore wind to be at core of the transformation towards renewable energy. The By 2019, 22.1 GW of offshore wind has been installed in Europe and the European Commission estimates installation of 450 GW of offshore wind capacity by 2050 in the European countries [2]. The figure 1.1 shows the installation rates required to achieve the vision of installing 450 GW in Europe by 2050. Of this 450 GW, a majority of the offshore wind of around 80 GW will be installed by the United Kingdom, followed by 60 GW in the Netherlands. Denmark is planned to install 35 GW of offshore wind capacity by 2050 [2]. Till 2019, around 90% of the installed offshore wind capacity is located in the North Sea and nearby Atlantic Ocean. To meet the 450 GW target, North Sea region will be crucial with 212 GW of installed offshore wind capacity while the Atlantic ocean and Baltic sea will also have significant contributions around 85 GW [2].

The wind turbines have a designed service life of 20-25 years. After this period, they need to be eventually decommissioned. Eva Topham defines decommissioning as "*All the measures performed to return a site close to its original state as is reasonably practicable, after the projects lifecycle reaches to an end*"[3]. With a surge in installation of new Offshore Wind Farm (OWF) and due to the ageing fleet of currently operating OWF, the number of OWF required to be decommissioned will increase in the coming years. 22 offshore turbines in 2020, 80 turbines in 2022 and 123 turbines in 2023 will reach the planned lifetime of 20 years and will require decommissioning [4]. WindEurope estimates by 2023 between 3.9 and 4.8 GW of the offshore wind capacity will be decommissioned [5]. As the offshore wind industry is relatively young, there is only a limited amount of practical experiences in decommissioning and disposing the OWF. At present, not much attention is given to the decommissioning phase and the complexities in decommissioning related to regulations, process planning, vessel availability and environmental impacts. Even the decommissioning costs are highly underestimated [3]. After decommissioning, the components and the materials from an OWF need to be disposed of efficiently. Proper disposal of these materials can generate monetary benefits by selling them as scrap and also have environmental benefits due to a decrease in the quantity of new materials being produced.

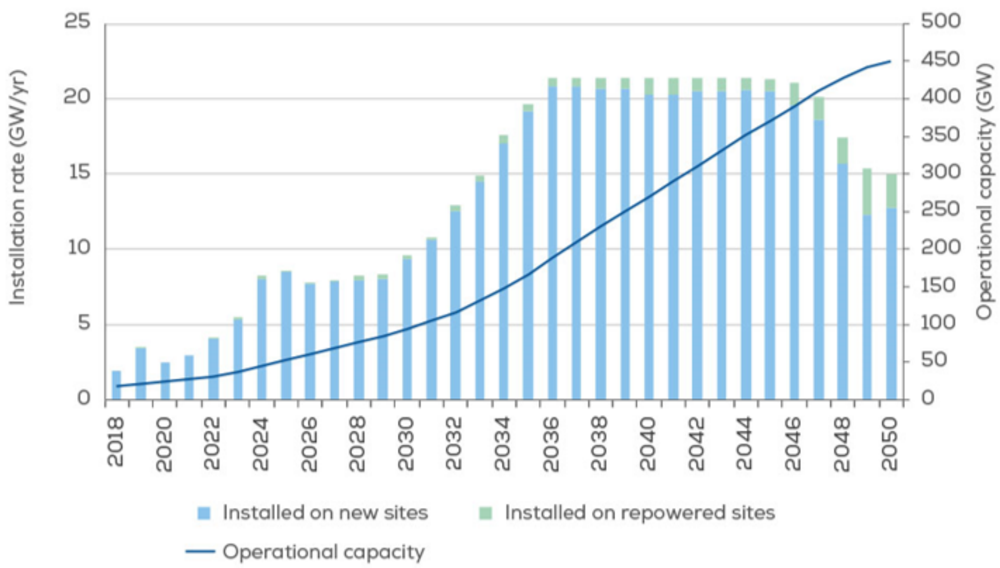


Figure 1.1: Installation rate in GW/year (left axis), and operational capacity (right axis) required to achieve 450 GW by 2050. Source: Wind Europe [2]

This increase in decommissioning the OWF and disposing the components, offers opportunities for applying more effective measures. The Circular Economy (CE) concept is receiving increasing attention worldwide. The goal of the CE principle is to make sure that the products or materials re-enter the system at the highest possible quality. Governments are considering CE model to control resource consumption and tackle climate change. EU has planned to implement the Circular Economy Action Plan to fulfil its climate goals [6]. The idea of CE is to set mechanisms to induce regenerative industrial transformations in motion that will lead towards sustainable production and consumption. It is essential to measure this transformation towards CE to track the progress and assist the decision making process. Circularity indicators measure the extent to which a system follows CE principles. At present only a few circularity indicators have been developed measuring some aspects of CE. Most of these indicators reflect upon the material flows in the system to measure the circularity potential. However, they do not necessarily take into account the environmental impact of the materials. Thus, circularity indicators alone should not be used to assess a system. Measuring the environmental impact of the material flows to complement the circularity can give further insights. Life Cycle Assessment (LCA) is a framework to assess the potential environmental impacts and resources used throughout a products life cycle. The LCA term was coined in 1990 and it is continuously being researched upon. Global databases for the processes like manufacturing, transportation, recycling etc can be used to model the processes in life cycle of the system. The impacts of these modelled processes are then calculated by methods to indicate their environmental impact. ISO 14040 [7] specifies the principles and framework for conducting an LCA study. ISO 14044 [8] mentions the requirements and the guidelines for carrying out the LCA study.

1.2. PROBLEM ANALYSIS

This thesis focuses on a relatively new area, the decommissioning of OWF. There is not much practical experience in this topic and it needs to be developed. Also, the topic of CE is gaining attention and awaits implementation. The problem today is to make the decommissioning phase of the OWF more sustainable by handling the waste generated more effectively. This offers opportunities to implement the CE paradigm and assess the environmental impacts of decommissioning and disposal of OWF. There are different materials used in components of an OWF. How these components and materials are decommissioned and disposed and what is the environmental impact and recycling and circularity potential of the OWF is assessed in this thesis. **This thesis work considers the decommissioning of the wind turbines its monopile foundations and inter-array and export cables of the OWF.**

1.2.1. MOTIVATION

This thesis work addresses an important research gap in the wind industry. Decommissioning of the OWF needs improvement and presents opportunities for implementing new measures. A connection between the topics of decommissioning, circular economy and life cycle assessment is not extensively researched at present. Further, research on measuring the circularity of a system and applying it to the case of wind turbines has not been fully developed. This thesis tries to establish a methodology to link the circularity assessment with its relation to environmental impacts in the decommissioning of OWF. Thus, the main motivation behind this thesis work is to act on this existing research gap and develop opportunities for sustainable decommissioning and disposal of OWF and improve the image of the wind turbines as a fully 'green' alternative.

1.2.2. RESEARCH OBJECTIVES

The overall objective of this thesis work is to develop an interactive tool which shows the materials used in an OWF and calculates the recycling and circularity potential along with the environmental impacts of the OWF as per the specifications of the wind farm selected by the user. This thesis work is divided into four main objectives which are as follows:

1. Development of a tool to rank the materials in an offshore wind farm based on its mass, monetary value, criticality and climate impact.

2. Assessment of circularity indicators and calculating the circularity potential of the offshore wind farm.

3. Assessment of the environmental impacts of the offshore wind farm.

4. Recommendation of practices and measures while decommissioning and disposing the offshore wind farm.

1.3. Thesis Structure

This thesis addresses several topics and the writing is structured as follows:

- In chapter 1, the background of the topic addressed in this thesis is introduced. The motivation in carrying out this thesis and the main research objectives of the work are addressed
- Chapter 2 reviews the current status of the topics of decommissioning OWF, circular economy and life cycle assessment through a literature study.
- Chapter 3 demonstrates the present experience in decommissioning of OWF and practices in disposing the components.
- Chapter 4 explains the data gathering process and addresses the first research objective of ranking the materials in a OWF. The case study which will be assessed and the developed tool is introduced in this chapter
- Chapter 5 illustrates the various indicators to measure circularity and the method to calculate the circularity potential of the OWF, covering the second research objective.
- Chapter 6 discusses the modelling for the LCA study conducted in SimaPro. The methodology in conducting a LCA study is stated. This chapter covers the third research objective of measuring the environmental impacts.
- Chapter 7 states the results obtained for the first three research objectives. Three different scenarios are compared and a sensitivity analysis is conducted.
- Chapter 8 discusses the key findings of the results and displays the final tool being developed. The final research objective of recommending practices in decommissioning and disposal are given.
- Chapter 9 mentions the conclusions of the thesis work and lists the future work to be carried out.

2

Literature review

A thematic structure for writing the literature review is chosen considering the multiple and diverse aspects of this study. This review aims to critically evaluate the background of topics linked to the study, the methodology described in the literature, identify the gaps and summarize the knowledge gained to assist the findings of this thesis. The following relevant individual topics for this study are evaluated and their interlinking with each other is discussed.

2.1. Decommissioning of Offshore Wind Farms

There has been a rise in the development of Offshore Wind Farm (OWF) by the counties in recent years to meet their climate targets. According to WindEurope, the total installed capacity of OWF in Europe was 22.1 GW by 2019 [9]. As the wind farms reach their end of life which is typically 20-25 years, the number of wind farms required to be decommissioned will increase in the coming years. The experience of decommissioning OWF at present is limited with only a few OWF decommissioned till date [3, 4]. Topham defines decommissioning as "*All the measures performed to return a site close to its original state as is reasonably practicable, after the projects lifecycle reaches to an end*"[3]. This thesis study tries to summarize the current experience of OWF decommissioning [10, 11]. The research done about the decommissioning is limited at this stage as there is no standard methodology of the decommissioning process [3]. The documents about the decommissioning of the first OWF Vindeby, states the steps carried out to decommission the turbines and results of the process [12, 13]. The basic components that need to be removed from a OWF are turbine, foundation, array and export cables, substations and scour material.

For most of the OWF projects, it is mandatory to provide with a rough decommissioning plan at the beginning of the project. The project plans describe steps of decommissioning and the costs that will be incurred for the process [14, 15, 16, 17]. In Denmark, it is mandatory to provide with a detailed decommissioning plan with selected decommissioning methods and environmental assessment to the Danish Energy Agency (DEA) [18]. At present dismantling of the wind farm is considered as a reverse of installation, however with more number of OWF to be decommissioned, more sustainable practices and cost-effective methods are required. Eva Topham in her published studies in 2019, addresses the main challenges of decommissioning as the regulatory framework, planning of the process, vessel availability and environmental impacts [19]. She states that the lack of regulatory framework causes the decisions of decommissioning to be based on economic benefits. The study predicts that the decommissioning costs account for around 2% - 3% of the total capital cost [3]. However, the costs incurred in the decommissioning process are underestimated thus there is a need for improvement of modelling the cost as per the simulation model build to forecast the decommissioning costs [20]. Few studies recommend some sustainable practices of decommissioning specific components, however the steps vary according to each wind farm [3, 11]. A study compared the complete removal of components from the wind farm site with partial removal and suggested that it is beneficial to keep the foundations in-situ [21]. However, as the process is not standard, there is not enough data to analyse the accurate environmental impacts of decommissioning process [22]. Thus more research on the environmental impacts of the decommissioning process and recommending sustainable practices on dismantling the wind farm is required for better understanding of the relatively new decommissioning of OWF.

2.2. LIFE CYCLE ASSESSMENT STUDIES

The concept of Life Cycle Assessment (LCA) was first introduced in the 1960s and was termed as Resource and Environmental Profile Analysis (REPA) by Hunt and later in 1990, 'Life Cycle Assessment' term was coined [23]. Later the concept was implemented by various companies. Today LCA is defined as "*a tool to assess the potential environmental impacts and resources used throughout a products life cycle, i.e. from raw material acquisition, via production and use stages, to waste management*" [8]. The outputs of the LCA study enables us to study the effects of a system on a holistic level. The output of the LCA studies can be implemented for governmental perspective to formulate policies, industrial perspective to calculate the impacts of their products and for consumer perspective [23, 24]. Vogtlander describes a guide to use while applying the LCA studies to the real world applications [25]. The basic phases for conducting a LCA study are as follows [23]:

- Goal and scope definition: to set the context of the study
- Inventory analysis: to collect information of the physical flows
- Impact assessment: to translate the physical flows to impacts on the environment
- Interpretation: to analyze the results.

A number of full LCA studies of wind farms have been conducted, most of them are carried out for the onshore wind farms while only a few addresses the offshore sites. The studies include the impacts of wind turbines in manufacturing, installation, operation and end of life phases. Out of the 72 LCA studies conducted by Ortegon in 2013, only 11 studies had included decommissioning aspects in detail [22]. In these phases of the life cycle in wind turbines, the manufacturing and installation phase accounts for around 70% of the emissions [26]. A study conducted by researchers at DTU discussed the application of LCA study for onshore and offshore wind farms. The environmental impact in terms of CO_2 emission was 7 g CO_2-eq/kWh for onshore and 11 g CO_2-eq/kWh for offshore wind farm site. Also, the study showed that 70% of climate impacts are caused by the manufacturing process of the raw materials used in a wind turbine and savings of around 20% - 30% can be obtained with a proper end of life treatment [27]. Davidsson compared various LCA studies on wind farms and found that they were based on varying assumptions. The ISO 14040 and ISO 14044 describes the basic principles and framework and guidelines to carry out LCA analysis [7, 8]. Still there is a need to standardize a method and calculations to be able to compare several studies [28]. Davidsson also states that most of the studies take into account the recycling credit, thus the environmental impact of materials is less, however there is no certainty that the materials will be duly recycled at the end of their life. Various LCA studies have been studied for the life cycle of a wind farm. Amongst the wind turbine manufacturers, Vestas has published several LCA studies of their wind turbines. The studies mention the materials used in a turbine and calculate its environmental impact over full lifetime [29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44]. Apart from the LCA studies published by wind turbine manufacturers, several research studies were studied. The research conducted varies with a number of assumptions made, assessment method, the wind turbine model and the sites of wind farms considered. Thus a variation in the outputs of the environmental impacts and energy payback time was observed in these LCA studies. However, these LCA studies mention the amount and types of materials used in the production of wind turbine and this data has been used in this thesis project [45, 46, 47, 48, 49, 27, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60]. As LCA is a complex process taking into account the different phases in a life cycle of a turbine, there needs to be further research to accommodate the upcoming end of life scenarios.

2.3. CIRCULAR ECONOMY

In the last few years, Circular Economy (CE) is receiving increasing attention worldwide. Governments are considering CE model to control resource consumption and climate action. EU has planned to implement the Circular Economy Action Plan to fulfil its climate goals [6]. The researchers view CE as the way to set mechanisms to induce regenerative industrial transformations in motion that will lead to achieving sustainable production and consumption [61]. The application of CE principles to various sectors like food, energy, and transport will have a positive impact on climate action goals [62]. Ghisellini recommends the need to accelerate the transition of implementing the CE in the socio-technical spheres through a multilevel and multi-framework evaluation approach [63].

Although the concept of CE is currently gaining popularity, the notion of a circular economy is based on a collection of similar ideas which were derived from scientific and semi-scientific concepts that developed for many years according to Korhonen [61]. The environmental economists Pearce and Turner first introduced the term 'Circular Economy' in 1990 based on previous work of ecological economist Boulding [64]. Later the research was carried about mainly resource management to extend the lifetime of the product giving rise to strategies of repair, remanufacturing and refurbishment. Now the concept is being researched through the policy point of view [65]. At present, the works of Ellen MacArthur Foundation are considered as the advanced representation of the CE concept. CE is thus treated as an umbrella concept with various ideologies like Industrial Ecology, Industrial symbiosis, Eco-efficiency, Cradle-to-cradle design, Blue Economy and Concept of zero-emission [65].

Due to its broad understanding, many research studies define the concept of CE differently. Most frequently the research carried out only focuses on the reduce, reuse and recycle dimensions of CE and often neglects the paradigm of a systemic shift as the essence of the concept [66]. The figure A.6 in appendix shows the different interpretations of the CE concept. Kirchherr thus analyzed 114 definitions of CE from the research conducted and proposed a definition coherently describing the concept of CE. The proposed definition is: "*an economic system that replaces the end-of-life concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro-level (products, companies, consumers), meso level (eco-industrial parks) and macro-level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of* *current and future generations. It is enabled by novel business models and responsible consumers*" [66].

The CE concept is often expressed as in terms of R-hierarchies. The basic well known of them is 3R imperatives of ‘reduce, reuse, recycle. However, the broad concept of CE expands to up to 10Rs according to Reike [67]. The 10Rs are: refuse, reduce, reuse, repair, refurbish, remanufacture, re-purpose, recycle, recover, re-mine. Very few research studies consider all these aspects. The clear distinction between the 10Rs is still lacking with minute differences between them and there is a need to make clear descriptions of these terms. The research studies use these terms interchangeably thus the definition of these terms are listed below to highlight the differences. In this thesis mainly the recycling and reuse of components is modelled.

- Refuse: “*Make the product redundant by abandoning its function or by offering the same function with a radically different product*" [66]
- Reduce: “*Eliminating the production of waste rather than the disposal of waste itself after it has been created*" [67]
- Reuse: “*Any operation by which products or components that are not waste are used again for the same purpose for which they were conceived*" [68].
- Repair: “*Repair and maintenance of defective product so it can be used with its original functions*" [66].
- Refurbish: “*Return a used product to a satisfactory working condition by rebuilding or repairing major components that are close to failure, even where there are no reported or apparent faults in those components*" [69].
- Remanufacture: “*Return a used product to at least its original performance with a warranty that is equivalent or better than that of the newly manufactured product by using the discarded parts of a similar product*" [69].
- Re-purpose: “*Use discarded product or its parts in a new product with a different function*" [66]
- Recycle: “*Any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes*" [68]
- Recover: “*Any operation the principal result of which is waste, serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function*" [68]
- Re-mine: “*Selective retrieval of parts which can be used in other products or components*" [67]

The works of Ellen MacArthur Foundation are pivotal in CE today. The figure 2.1 shows the well known butterfly diagram representation of typical flow of the technical and biological materials in a circular economy. The inner circles represent the processes like maintenance and reuse of a material or a product. These measures are more desirable to harness the maximum potential from the material or a product compared to the outer circles or recovery approach. This is because the processes or energy required to transform a recycled material back to a state where it is usable, is higher than the processes in maintaining the functionality of the product [70]. Thus, the CE approach favours re-entry of a material or a product at a highest quality (minimal effort to convert into usable product) back into the system.

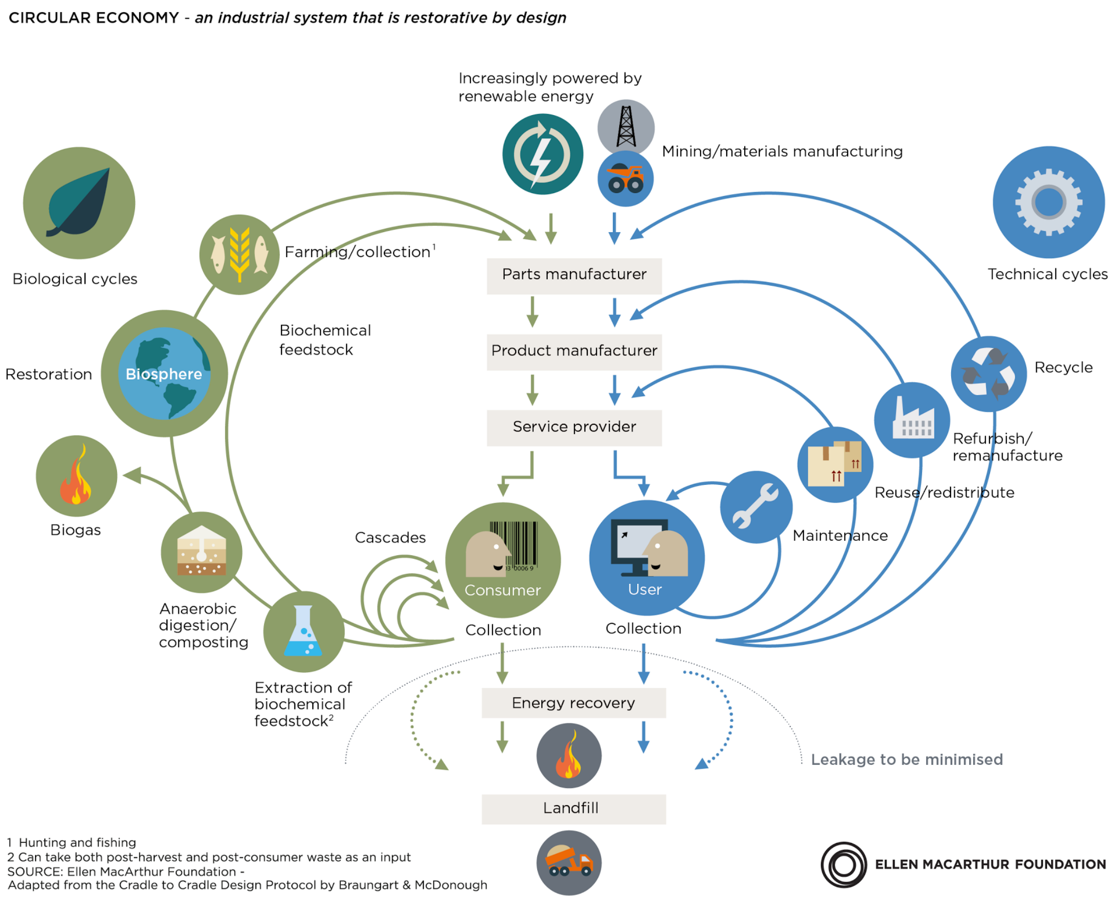


Figure 2.1: Butterfly diagram of value chain in Circular Economy. The left loops show the technical cycle that is focused in this thesis. The inner circles are favoured due to less effort in converting back to usable product. Source: image taken from [70]

Studies conducted show that the concept of CE should be implemented in case of Wind turbines to increase resource efficiency and potentially make them more sustainable. NIRAS showed the potentials of converting the OWF material chain into a more circular system by reselling the wind turbines and closed-loop recycling of blades [71]. The main focus of making wind turbines more circular is on the wind turbine blade disposal by effective recycling or re-purposing the blades for other applications [72]. Hao compares the carbon fibre and Glass-Fiber-Reinforced Polymer (GFRP) as the materials used in wind turbine blades to make the blades more circular by recycling the materials in the blades [73].

2.3.1. CIRCULARITY POTENTIAL

With an increase in the steps towards the implementation of CE principles in various sectors, there is a need of assessing the circularity of a product for a company to track the progress, support internal decision makings and design business policies. Circularity essentially indicate the extent to which a system follows a fully regenerative circular flows. There have not been many advances in developing the indicators to measure the circularity, particularly on a micro-level

[74]. Recent studies have mentioned the important characteristics of the indicator to represent the circularity. The required characteristics that the indicator can account for according to these studies are reduction in input use, increase in renewable energy share, reduction in emissions, reducing valuable material loss and increasing value of durability [74]. A recent review study analyzed the existing circularity indicators that represent the circularity degree of a system and the circularity assessment tools that measure the value created by the circular system. The indicators analyzed were New Product-level circularity metric, Circ(T), Material Circularity Index (MCI), Circularity index, Global circularity metric, Circular Economy Indicator Prototype and Circular economic value [75]. These indicators take into account various parameters while calculating the circularity. The analysis showed that the MCI accounted for the maximum number of parameters to give the output circularity index. However, to fully represent the circularity of the system the MCI should be linked with LCA studies to account for missing environmental impacts [75]. Advantages and limitations of using MCI are also supported by another study comparing 3 indicators [76].

The works of Ellen MacArthur Foundation describe the methodology of implementing MCI which is dependant on the recycling and reusing rates, and the process efficiencies and recycled and reused content in a product [77]. Not much research has been done on implementing the MCI on a case study of Wind Turbines. Vetas in 2017 first tried the basic implementation of the MCI to measure the circularity in their LCA studies they publish [30]. The indicator was chosen to give more insights into the material flows of the turbine, highlighting the potential to improve the circularity. The indicator was calculated only for the turbine based on aggregated data.

2.4. MATERIAL DISPOSAL IN A WIND TURBINE

After decommissioning the wind turbines, the material from the wind turbines needs to be disposed of efficiently. The materials if disposed of properly lead to monetary benefits by selling them on the scrap market and reduce the environmental impact by decreasing the amount of material required from primary production [78]. The recycling rate of major metals like Iron, copper, aluminium is more than 50% in the world, however when compared to the fraction of recycled content in total metal input, there is still need of improving the recycling of metals [79]. The wind industry will be exposed to huge supply risk in the transition towards wind energy with a big concern of Rare Earth Elements (REE) used in magnets for the turbine, thus extracting the materials from the secondary material supply is crucial [80] [81].

Andersen projects the quantity of total waste material from Wind turbines in Sweden to increase by an annual rate of 12% till 2026 and 41% annual rise until 2034 compared with the value in 2016 in Sweden [82]. Liu projects that by 2050 there will be 43 million tonnes of blade waste worldwide [83]. Thus reusing and recycling these waste streams is required to increase the resource efficiency and reduce the environmental impact by reducing primary production of materials [82]. Implementing CE principles to effectively dispose of the materials from wind turbines by selling the wind turbine in the second-hand market, repurposing the materials in a turbine and recycling are discussed by Andersen [84]. At present, there is more focus on recycling aspects of these materials, however, the effectiveness of renewing the value and quality of the material depends on different approaches undertaken. Upcycling converts the materials into something with a greater value than it was earlier. Recycling converts the material similar to its earlier value and downcycling converts the material to a lower value than its earlier. For example, crushing the blades and using them as cement filler material can be considered as downcycling, converting them back into fibres is recycling and using the blades for a higher purpose application like bridges can be considered as upcycling. However, there is no clear distinction between these approaches and the intrinsic value changes depending on the application which makes modelling each approach difficult. This thesis models the recycling of materials into similar properties.

Recycling of steel, cast iron, copper and aluminium as the common metals in a wind turbine is well known with processes similar to other industries. However, recycling of wind turbine blades is still under research with no clear commercially viable solution being implemented on a large scale. Various government-funded projects like FiberUSe, Dreamwind, GenVind and REACT have been carried out to focus on recycling of composite materials [85]. Research has been carried out to find the best method to handle the composite materials used in a wind turbine blade. The studies compare the mechanical processes of grinding blades to powder to use it as filler materials and reinforcements, thermally incinerating the blade or pyrolysis to harness the energy and get pyrolysis oils and thermochemical processes like solvolysis to obtain the resins and fibre [85, 86, 87, 88]. Implementing these solutions on a commercial scale is required to effectively dispose of the materials in a wind farm.

2.5. GAP ANALYSIS

The research on decommissioning of wind farms is gaining traction as the number of wind farms to be decommissioned is rising. There is still not much experience in decommissioning of big OWF, however the policies implemented by most of the governments ensure that a decommissioning plan is submitted during the planning of a OWF. There is a need for implementing the general principles of CE in decommissioning to increase resource efficiency and gain maximum monetary and environmental benefits, however, there lacks research of real case implementations. Moreover, there are not many studies to measure the circularity of a wind farm. Thus research on indicators that measure the circularity of implementing certain strategies is needed to move towards the path of CE.

The existing indicators of circularity do not reflect the impacts on the environment. Also, a highly circular system does not necessarily imply an environmentally better system. Thus there is a need for linking the circularity indicator with LCA studies to provide estimates of the overall environmental impact. Linder also states that a fully functioning metric can be used to examine the relationship between product circularity and other variables [76]. Thus although the individual topics are under research there needs to be a link connecting the materials used in a wind turbine with circularity potential and with its environmental impacts. These gaps are addressed in this thesis which also forms the motivation of this work.

2.6. THESIS APPROACH

The figure 2.2 shows the approach taken to address this research gap and to fulfil the research objectives of this thesis. It shows the simplified representation of the approach implemented to fulfil the objectives. Initially, data for different parameters of materials used in a wind turbine is gathered along with the values of reused and recycled content. The material data is used to formulate a model to predict the mass of materials in a wind turbine (explained in chapter 4). Circularity potential is calculated based on the data of materials obtained and the recycling and reusing percentages (shown in chapter 5). LCA modelling is done based on the data gathered and process defined in SimaPro (explained in chapter 6). At the end general recommendations on decommissioning are given based on the results obtained (addressed in chapter 8). Thus, a missing link between the materials, circularity and environmental impacts is established through this thesis work which is explained in detail in next chapters.

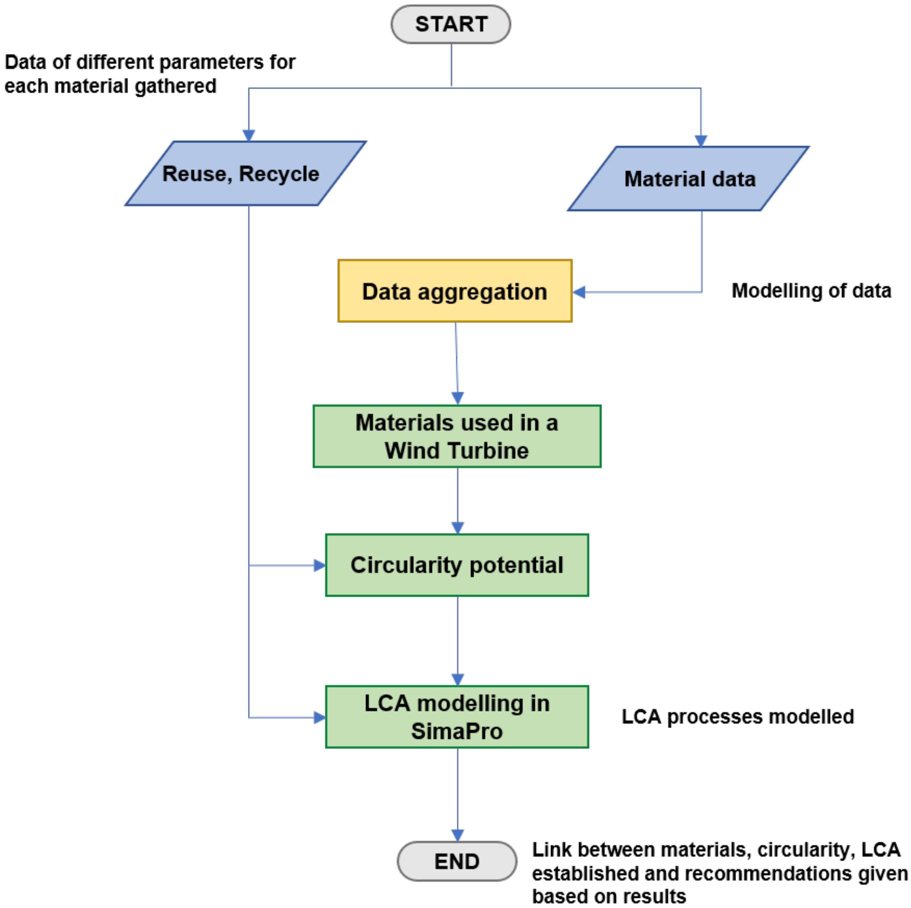


Figure 2.2: Simplified representation of the approach undertaken to fulfil the objectives of this thesis. The blue icons represent the basic data gathered, and green icons show the modelled research objectives.

3

Decommissioning of Offshore Wind Farms

This chapter discusses the decommissioning of Offshore Wind Farm (OWF). The current decommissioning practices established from the limited experience in decommissioning of OWF are highlighted. Potential bottlenecks in the current process are analyzed. The costs associated with the whole decommissioning phase are reviewed. A focus on the disposal of waste from decommissioned wind farms and the prospects of implementing Circular Economy (CE) practices in the process is also indicated in this chapter.

In the coming years, a large number of OWF will reach the end of their initially planned service lifetime which is between 20 and 25 years. The wind farm owner then has to plan the end-of-life scenario of the wind turbines and decide between lifetime extension of the asset, repowering the site or decommissioning. The present physical condition of the wind turbine is evaluated through monitoring of components and inspections. If the structural condition of the wind turbine allows for its continued operation, financial analysis of potential costs incurred due to maintenance and repair of components in its extended use is carried out. If this results in a feasible continued operation, the wind farm owner can decide for lifetime extension of the wind turbines. The wind farm owner can also decide repowering of the site which refers to the replacement of the existing turbine with a more powerful turbine. This ensures cost reductions compared to a new project, better integration with electricity grid and using the wind resource at potentially the best sites. Fulfilment of any new regulations and environmental permitting are required to plan the repowering of the site. In all the cases, decommissioning of wind turbines will always happen at some point. Figure 3.1 represents the number of offshore wind turbines that will reach the 20-year operational lifetime each year in Europe. There will be 22 wind turbines in 2020, 80 turbines in 2022 and 123 turbines in 2023 that will reach the 20-year lifetime [4]. After 2030 there will be a big increase in the offshore turbine to be decommissioned indicating the challenge in decommissioning OWF will soon rise in the next decade. Thus, further exploration of the decommissioning procedure based on the existing experience is essential.

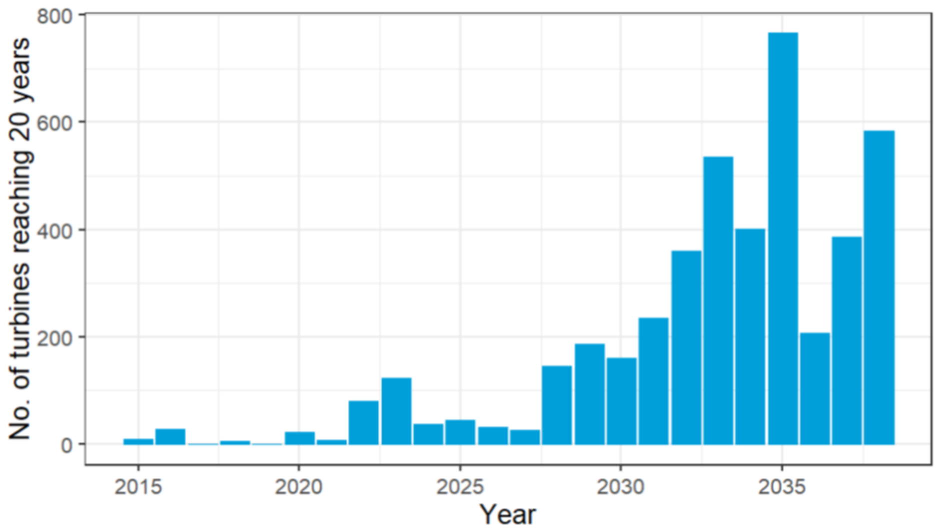


Figure 3.1: Number of offshore wind turbines reaching the 20-year lifetime annually in Europe. The number of wind turbines requiring decommissioning will soon increase. Source: image taken from [19]

3.1. DECOMMISSIONING EXPERIENCE

Since the commissioning of the first OWF in 1991, the offshore wind industry has come a long way. Now the old OWF installed are facing the decommissioning decisions. The table 3.1 shows the list of decommissioned OWF in the world. Yttre Stengrund wind farm installed in Sweden was the first commercial offshore wind farm that was decommissioned in 2015. After 15 years of its operation, Vattenfall decommissioned the OWF. Vindeby (Denmark) was the world's first OWF installed back in 1991 and it was finally decommissioned in 2016 after 26 years of its operation. The decommissioning plan of the Beatrice Demo with Jacket foundations was approved in 2019 and it is expected that the turbines will be fully decommissioned between 2024 and 2027 [89].

Table 3.1: List of the decommissioned Offshore Wind Farms till date. Yttre Stengrund was the first OWF to be decommissioned in 2015. Table based on the data from [19]

Wind farm	Country	Capacity and no. of WTs (MW)	Foundation type	Years of operation	Decommissioned year
Yttre Stengrund	Sweden	10 (5 x 2MW)	Monopiles	15 (2001-2015)	2015
Lely	Netherlands	2 (4 x 0.5MW)	Monopiles	20 (1994-2014)	2016
Vindeby	Denmark	4.95 (11 x 0.45MW)	Gravity-Base	26 (1991-2017)	2017
Utgrunden	Sweden	10.5 (7 x 1.5MW)	Monopiles	18 (2000-2018)	2018
Blyth	UK	4 (2 x 2MW)	Monopiles	13 (2000-2013)	2019
Beatrice Demo	UK	10 (2 x 5MW)	Jacket	8 (2007-2015)	2024-2027

The decommissioning is the last phase in a project's lifecycle and it refers to all the measures undertaken to return the site closer to its original state. The decommissioning involves several steps as depicted in figure 3.2. The 3 main stages in order are highlighted by green and the tasks in that stage are represented in red.

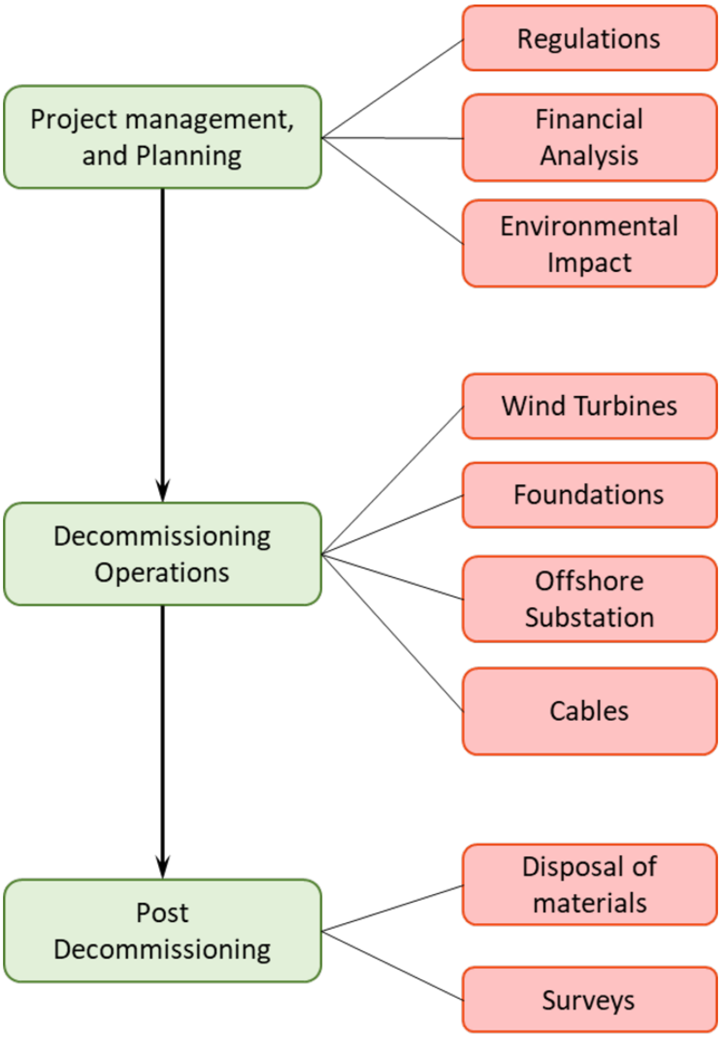


Figure 3.2: Decommissioning process breakdown. The main stages are planning, decommissioning operation and post decommissioning. The tasks in that stage are highlighted by red. Source: Author's own illustration based on [3]

The stages through which the full decommissioning process undergoes are briefly described below:

1. **Project management and planning**
   This stage corresponds to the Pre-decommissioning preparations. It includes the submission of the decommissioning plan well before actual decommissioning. In European countries like Denmark, Netherlands and the United Kingdom, a decommissioning plan has to be submitted to fulfil the regulations to carry out the decommissioning. A detailed plan of processes for removal of each component and the required time duration and costs is carried out. The availability of the vessels and other equipment required for the removal process is also planned. The environmental impact of the removal process is also assessed. This plan is then followed to do the actual decommissioning of OWF.

2. **Decommissioning Operations**
   This stage corresponds to the removal of structures in the wind farm. The wind farm is initially de-energised and isolated from the grid before the removal process. The structures are removed by carrying out processes reverse of installation. There are different

ways to remove the wind turbine based on the process chosen. The 3 blades can be removed individually by separate operations and then the nacelle and tower sections can be removed. Instead of individually removing the 3 blades, the rotor and nacelle assembly can be dismounted directly as well. The process of turbine removal depends on the size of the turbine and vessel and crane being used to decommission. A large enough crane can even remove the complete turbine in a single lift. The foundations are either removed completely or are cut at seabed and the rest is left in situ depending on regulations and environmental impact. The offshore substation is divided into two parts topside and foundation and the removal process is similar to the turbine. There is no clarity about removing the offshore inter-array and export cables so they are either completely removed or left in situ depending on the regulations. Different techniques to cut the structures that are implemented are diamond wire cutting, water jet cutting and use of controlled explosives. Author's recommendations on sustainable processes of decommissioning the OWF are discussed further in section 8.2.

3. **Post Decommissioning**
   This stage corresponds to the disposal and maintenance of the decommissioned site. After the components of the OWF are removed from the site, they are collected onshore. These components have a number of mixed materials present which can be of value. Care should be taken to dispose the materials in such a way that causes a minimal environmental impact. The removed components can be reused, remanufactured or recycled. Effective disposal of these materials is further discussed in section 3.2. A survey after decommissioning is done to see the impact of the whole process and ensure that the site is brought close to its original condition.

Although the typical basic steps in the decommissioning process are same, the decommissioning plan changes with every OWF due to reasons like governing regulations, locations of the site, type of structures and scale of decommissioning. Thus, the decommissioning process is found to be highly uncertain. Through the limited experience of decommissioning of OWF, main challenges in decommissioning have been identified as the regulatory framework, logistics, environmental impacts and overall planning of the process. These challenges are briefly discussed below.

- **Regulatory framework**
  The decommissioning process for the whole offshore industry at present is insufficiently regulated and lacks clear recommendations on practices. In the European Union (EU), Denmark, Britain and the Netherlands have their own offshore windfarm decommissioning plans, while most of the other countries apply the same oil and gas decommissioning procedures. The wind farm owners are expected to provide a decommissioning program including the operations and cost implications for approval to the construction of OWF. However, the plans are found to be rather simplistic and underestimate the decommissioning costs. Under Danish regulations, the developer must provide with a financial guarantee to the Danish Energy Agency (DEA) for decommissioning the OWF before bidding. Also, the owner must provide with a detailed decommissioning plan with environmental impact assessment to the authorities before 2 years of decommissioning [90]. The regulations in countries are not harmonized and this may interfere in planning of the OWF. There are no clear directives governing the removal of cables. In Denmark, it is required to remove the buried cables unless there are strong reasons to keep them in situ, while in the Netherlands there are no clear recommendations. The decision about partial or full removal of structures is still mainly based on economic reasons. There is a need to

integrate the offshore wind farm decommissioning policy in EU framework to make it homogeneous.

- **Process planning**
  The decommissioning process of the OWF varies with each wind farm depending on the size of the turbine, distance from the nearest port, type of foundations and any other factors relevant for that wind farm. Also, the planning of decommissioning is expected to be done many years before the actual decommissioning takes place. This increases the uncertainty of the technical feasibility of carrying out the decommissioning. Further, a plan of full or partial removal of some components needs to be analyzed. The decommissioning process also varies depending on the availability of the necessary vessels.

- **Vessel availability**
  Specialized vessels with heavy lifting and specific stability are required in the decommissioning process. Also, the water depth, sea bed condition and distance to nearby shore varies the type of vessel that can be used. The availability of the required vessel can be a crucial task due to the steep increase in the installation of new offshore projects, operation and maintenance of the existing OWF and decommissioning of oil and gas facilities. Availability of a specific vessel due to its deck capability, work versatility and speed governs accounts for a large part of the total decommissioning costs. Thus, optimizing the decommissioning processes is more uncertain due to the availability of the vessels. Different types of vessels like liftboat, jackup barges, Self-propelled installation vessel (SPIV) and heavy-lift vessels are required for different applications and different wind turbine capacities.

- **Environmental impact**
  The environmental impact of decommissioning, particularly partial or full removal of the structures is still a highly debated and uncertain topic in decommissioning of OWF. Some recent studies show the environmental benefit of partially removing the foundations. These substructures could have become a habitat for the offshore flora and fauna over the operation period of the OWF. Also, the impact on marine life during the decommissioning activities is not fully known. Moreover, the sustainability of the full decommissioning process depends on the disposal of the materials obtained from the removed structures. Proper disposal of the material components involving reuse or recycling measures is essential for sustainable decommissioning phase.

3.1.1. DECOMMISSIONING COSTS

The cost of decommissioning includes the cost associated with the preparation of offshore site, removal of structures, vessel mobility and disassembly of the removed components. These costs typically account for 2% to 3% of the total capital costs of the project at present [3]. Due to less experience and high uncertainty of the process, the decommissioning costs are underestimated. The process of removal of structures and transporting them to ports form a major part of the total decommissioning costs. It includes the travel of the vessels and equipment from the port to the decommissioning site, removal operation of the structures, loading on the vessels and return to the nearby ports. These costs are dependant on the time required for the vessels in operation and also the capability of the vessel. Thus, an optimization model with different type and capacity of vessels and time required in offshore operation is normally performed by the companies to obtain optimal decommissioning costs. Analysis of various models like the use of a single-propulsion vessel, multivessel transportation, support vessel is carried out for each specific OWF to minimize the costs with travel time, removal time, vessel day rate and vessel capacity as the parameters [11].

A detailed analysis of the decommissioning costs is out of scope for this thesis work. Recent studies carried out by DNVGL have showcased that the total decommissioning costs account between 200,00 €/MW to 600,00 €/MW [91] for the present OWF. These costs can be reduced with gained experience in decommissioning. Another way to reduce these costs is by proper disposal of the materials obtained from decommissioned components. About 20% of the decommissioning costs can be recovered by recycling of the materials from the components [3].

3.2. POST-DECOMMISSIONING: DISPOSAL

After the implementations of various processes for removal of the structures from OWF, the components need to be disposed of efficiently. The disposal of these decommissioned structures can add monetary value and environmental benefits if done effectively. The decommissioned turbine contains a mixture of various materials in its components that needs to be handled differently. The main materials that need to be disposed are cast iron, steel, copper, aluminium, fibreglass, epoxy and neodymium and dysprosium magnets. At present, most of the materials that have a monetary value are recycled. Steel mainly used in the foundations and the tower sections of the wind turbine forms the bulk of the material obtained. Steel being highly recyclable, most of it is disposed as scrap steel for recycling purposes. Cast iron is primarily present in the main drive shaft, generator and gearbox in the nacelle. Similar to steel, cast iron is mainly recycled. The copper and aluminium from the cables and the generator have a high monetary value, thus recycling is the preferred option. The magnets used in the wind turbine which consists of Neodymium and Dysprosium poses technological challenges for recycling them. However, the fibreglass and epoxy resin used in the blades and the hub are of a primary discussion in the industry, This importance for safe disposal of blades is mainly to make wind turbines as a fully 'green' alternative.

Proper disposal of the fibreglass is one of the most challenging aspects due to the size of components, recycling complexity and low market value. The composites in the blades consist of various materials with different properties. The Glass-Fiber-Reinforced Polymer (GFRP) used is a thermoset composite and in a curing process where the polymers are cross-linked, it undergoes an irreversible process which causes difficulty in recycling. For many years the wind turbine blades are landfilled in the United States, due to complexities in recycling them [92]. The EU policy is now taking steps towards prevention of landfilling of the blades and develop commercial processes for their disposal. Various EU funded projects like ReFibre, Dreamwind, Genvind and LIFE BRIO focus on the investigation of new processes for proper disposal of blades [85]. The size of the blades pose further challenges, mechanical treatment by using jaw cutter, circular saw or wire saw is done to reduce the size of the blades for ease of transportation. At present most of the blades are incinerated as an alternative to landfilling and the energy from combustion is used for other purposes. The blade sections are combusted at high temperatures up to 800 °C and the heat is used for energy recovery. However, the composites in blades have a low heating value thus limited energy recovery and around 60% of the scrap is left as ash which is harmful. Another common practice is to burn the reinforced plastic in cement kilns for cement production. About 10% of the input fuel is replaced with blades [93]. The fibreglass can also be treated with fluidised bed gasification operating at about 450 °C for better energy recovery. Or the pyrolysis technology of heating the blades in a reactor vessel under pressure in an inert environment can help recover the fibres for further low-level use. Solvolysis process is used to break the bonds of the carbon fibre usually at temperatures between 300 °C and 650 °C to recover the fibres with similar strength. Further research is carried out for viable commercial applications. Heating glass fibres above the temperature of 250 °C is shown to degrade their mechanical properties, thus the recovered fibres cannot be used in manufacturing wind turbine blades [94]. Hence, apart from the recycling of materials, other potentially better disposal measures should be undertaken. The recent study conducted by WindEurope suggests that increasing circularity in disposing of the blades is key to achieve sustainability in wind turbine blades [95].

3.2.1. CIRCULAR ECONOMY PERSPECTIVE

As discussed earlier, with proper disposal of components, the monetary and environmental benefits can be gained. At present recycling of the materials is the only major focus of the wind industry. But the principles of CE suggest to widen the scope and maximize the potential in disposal of the decommissioned components. The goal of the CE principle is to make sure that the products or materials re-enter the system at the highest possible quality. The figure 3.3 shows the preferred approach according to the CE principles in disposing of the components. The prevention of resources being consumed or reducing the quanitity of materials being used is the preferred option to reduce the waste at disposal. The figure 2.1 showcased different entry points to the system like with maintenance (repair), reuse, remanufacture and recycle of the product at the end of its life. Each of this step requires more processing compared to the previous step. For example in case of recycling of a product after its life, the material in the product is recycled to get raw materials, further processing and energy is required to convert this raw material into a usable product. However, it is much beneficial to repair the product or reuse it maintaining its usability with minimal effort.

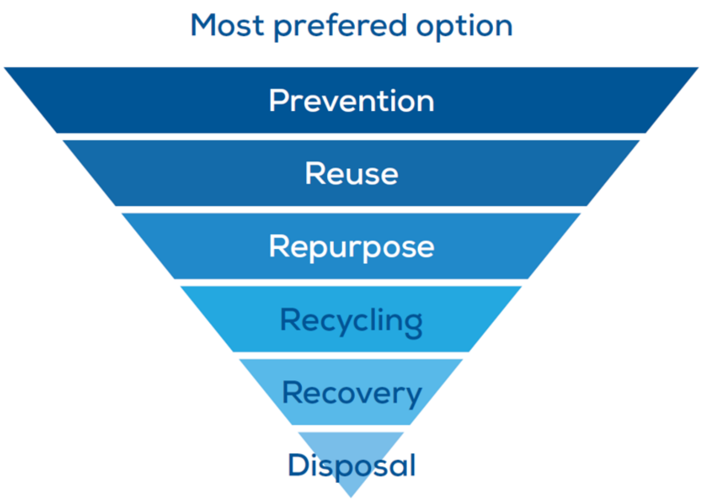


Figure 3.3: Waste hierarchy according to CE principles for sustainable waste management. Preventing waste generation is most preferred while disposing material to landfill is least preferred for sustainable waste management. Source: image taken from [95]

In the case of wind turbines, the primary focus should be on to reduce the amount of waste being generated, this can be achieved by a mass reduction in the components and minimize the waste during production. During the operation phase, the wind turbine should be duly maintained and required repairs should be done to increase its lifetime. When further repair work turns unfeasible, the working components can be reused directly for other wind turbines. Remanufacturing should be done if some major components need replacements, functional parts from other turbines can be used to rebuild a working wind turbine. Also, the components after some processes can even be repurposed for applications other than a wind turbine. If the component as a whole cannot have a functional use, the materials in it are recycled to obtain a raw material. If the recycling is not feasible, the energy from the component can be harnessed to utilize for other processes by incinerating the material. Lastly, landfilling of the material or incinerating without any recovery is least favoured while disposing of waste. The ability to implement these stages depends on how the wind turbines are decommissioned and disassembled.

The experience in decommissioning of OWF is limited at present and there is a need to implement more sustainable practices as the number of wind farms to be decommissioned increases. A holistic view in solving all the challenges in the decommissioning phase is vital to develop new concepts in handling the wastes generated more effectively. Implementation of the CE practices right from the designing phase of the wind turbines to the efficient use of the decommissioned components is pivotal to make OWF as the most sustainable alternative in its entire life cycle. For implementing these changes, a thorough study about the materials used in manufacturing the OWF is required which is done in the next chapter.

4

Materials used in a Wind Farm

This chapter explains the methods used out to gather the required data for the thesis. It further shows the aggregation of the data to be implemented in the model developed in this thesis work. The first research objective of this thesis which is to develop a tool to rank the materials used in an Offshore Wind Farm (OWF) is addressed and the tool is showcased after analysing data of several parameters. Further, this chapter introduces to the case study of Utgrunden OWF which will be analysed throughout the thesis results. Lastly, the relevant data for the materials are collectively represented as a sheet in the interactive tool developed.

4.1. Data Gathering

The work carried out in this thesis addresses the practical as well as theoretical research related problems. Required data for the analysis is gathered from various possible sources. Mainly the approach of quantitative data collection was implemented by collecting the majority of the data from the published articles, journals and websites. Qualitative validation of the collected data and more insights into the topic was done through email correspondence with the people working in the wind industry. As the topic of decommissioning OWF is relatively new for the wind industry, this validation of the collected data, verified the relevance of the data to the real values in the wind industry. Data from multiple sources was analyzed to cross-check the values and analyze the variation. Several studies were considered, to give a more aggregated view of the data wherever required. The sources for the data were diverse from research publications to the published reports from the wind turbine manufacturers. The basic assumption of considering the offshore wind turbine material content same as the onshore wind turbine was made in this thesis work unless specified otherwise. This was assumed as there is not much data available specifically for offshore turbines. Also, as the turbine components (Rotor, Tower, Nacelle) in both the turbine types onshore and offshore, have similar materials and quantities this further makes it a valid assumption. The construction of foundation which differs for an onshore and offshore turbine was specifically taken into account. Also, the difference in the cabling network of the wind farm which varies depending on onshore or offshore location was considered in the analysis. As generally there is a single offshore substation for a OWF, and the processes and materials of the offshore substation can be related to the structures of the wind turbine, the offshore substations were not considered in this thesis. The data gathered for various parameters is discussed below. Sensitivity analysis is carried out later and presented in section 7.2 to account for the uncertainty of the analyzed data.

4.1.1. MASS

Different materials present in the construction of the OWF forms the starting point of this thesis work. The main materials used in manufacturing of the wind turbine components and for the foundations and cables are considered. A decision was taken to choose the following materials: steel, cast iron, aluminium, copper, fibreglass, epoxy, magnet for this thesis work. These materials represent up to 98% of the total mass of the materials in a wind turbine. Also, the mentioned materials represent materials with significant economic and environmental impacts. At present, there is no database specifying the mass of materials used in a wind farm according to wind turbine specifications. Thus, the data about the mass values are gathered from several published studies. The studies referred mainly consisted of the Life Cycle Assessment (LCA) studies carried out by researchers and companies for various wind farms in different locations. These studies specify the parameters of the wind farm into consideration and enlist the mass of materials present in the wind turbine as a bill of material. Effort was taken to include a maximum number of published studies.

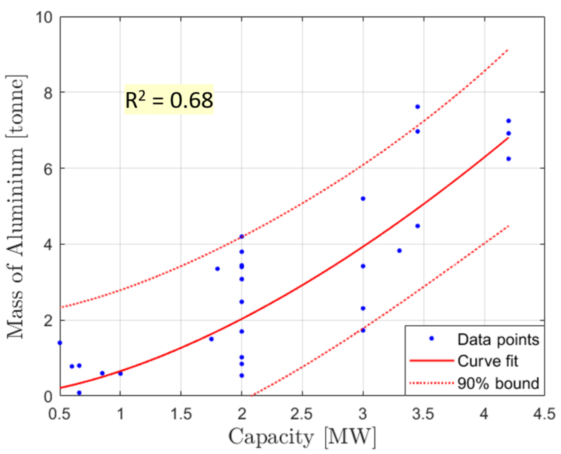
Several published LCA studies were analyzed to aggregate the values. Most of these LCA studies conducted refer to an onshore wind farm however, the data of materials in a wind turbine are used due to the similarity between onshore and offshore turbines. A total of 32 LCA studies were seen to be relevant with sufficient details in the data of mass of materials that could be used in this thesis. Out of these assessed studies, 15 Vestas published LCA were used [29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43]. These studies published by Vestas specify the mass of materials used in a wind farm with various Vestas wind turbines. These studies indicate the aggregate of materials used for all wind turbines in the considered wind farm, thus a conversion was made by dividing it with the number of turbines to obtain the mass of materials used for a specific wind turbine. Similarly, 4 research published LCA studies were used which specified the mass of materials in a wind turbine as a whole [48, 45, 47, 46]. Remaining 13 research published LCA studies specifying the mass of materials in a wind turbine split into its main components like Rotor, Nacelle and Tower were used [49, 27, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60]. The missing data about the mass of certain materials in some studies was rectified by taking average values from other turbines with same specifications. The variation of the values of mass of materials in a wind turbine was assessed with respect to the main specifications of a wind turbine namely capacity, rotor diameter and hub height. The values of mass for a turbine with similar specifications varied in different LCA studies. Thus, an aggregate curve fit model is formulated to signify the quantity of materials present in the wind turbine based on the stated specifications.

The work of Sieros et al in the theoretical and practical upscaling of wind turbines have suggested that power equation signifies accurate distribution of materials [96]. The power form 4.1 used is governed by curve fit coefficients a and b, while M represents the mass value of the material and X is the wind turbine specification parameter. The power equation was used as it resulted in a better curve fit for the mass of materials with a lower R^2 values.

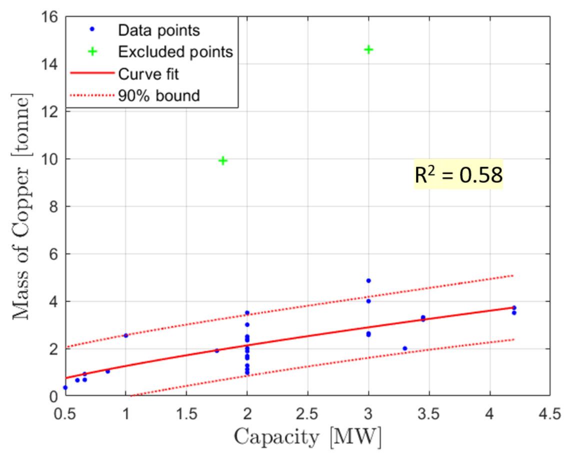
$$M = a \cdot X^b \tag{4.1}$$

Analysis done to aggregate the mass of materials with respect to different turbine specifications is presented in the following figures. The graphs show the mass of materials in tonne and the curve fit line highlighted in red. The coefficients of power form of the curve fit are stated later in the section. This aggregated curve fit equation is used to predict the mass of materials depending on the specifications of the turbine later in this thesis. The dotted red lines in the following graphs represent the spread of uncertainty of the fitted coefficients. 90% of certainty bound is depicted by the two dotted lines signifying lower and upper bounds. The 'goodness of fit' is shown by the R^2 value for each curve. The value shows how well the curve fits the given data.

The figures 4.1a and 4.1b show the variation of mass of aluminium and copper present in the wind turbine with respect to wind turbine capacity. As both aluminium and copper are mainly present in the nacelle of the wind turbine, the capacity rating of the turbine is used as the decisive scaling factor. In case of aluminium, $R^2 = 0.68$ is achieved by the curve fit. The mass of copper in a wind turbine is highly dependent on the technology of the turbine whether it is geared or direct-drive. In the case of direct-drive turbines, the generator required is larger hence more copper is necessary for the windings. However, most of the studies found were for the geared turbine also because geared turbine technology forms a majority in the current fleet of offshore wind turbines in the world. The two outlying points highlighted by green cross in the figure are discarded for a better curve fit as they belong to the direct-drive technology. A value $R^2 = 0.58$ was obtained for the curve fit of copper mass.

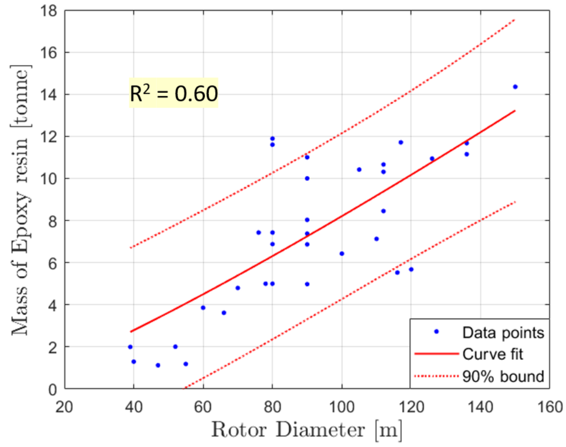


(a) Spread of aluminium mass in tons varying with the capacity rating of a wind turbine. Curve fit calculated in MATLAB

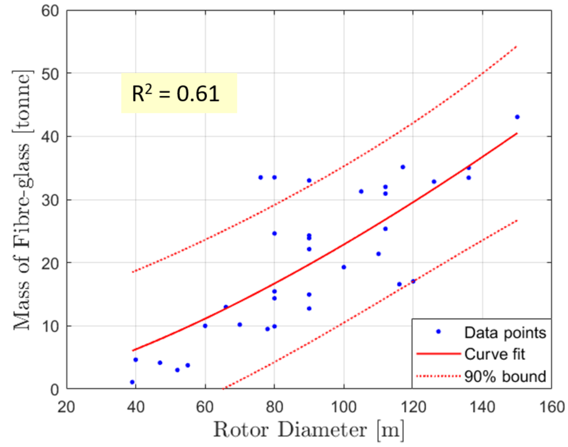


(b) Spread of copper mass in tons varying with the capacity of a wind turbine. The 2 points shown in green are excluded as they belong to wind turbines with a direct-drive generator. Curve fit calculated in MATLAB

The figures 4.2a and 4.2b depicts the variation of the mass of epoxy and fibreglass in a wind turbine. As epoxy and fibreglass are mainly used in the blades, rotor diameter is decided to the decisive scaling factor. Some LCA studies analyzed, lump together these materials together as 'blade material'. In such cases, distribution by weight of 65% reinforcing fibre and remaining 35% epoxy resin is assumed based on industry averages [97]. The values of $R^2 = 0.60$ and $R^2 = 0.61$ are obtained for epoxy and fibreglass curve fitting.

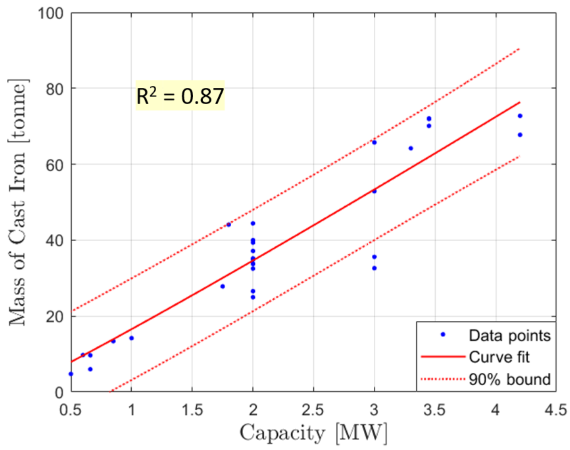


(a) Spread of epoxy mass in tons varying with Rotor diameter of wind turbine. Curve fit calculated in MATLAB

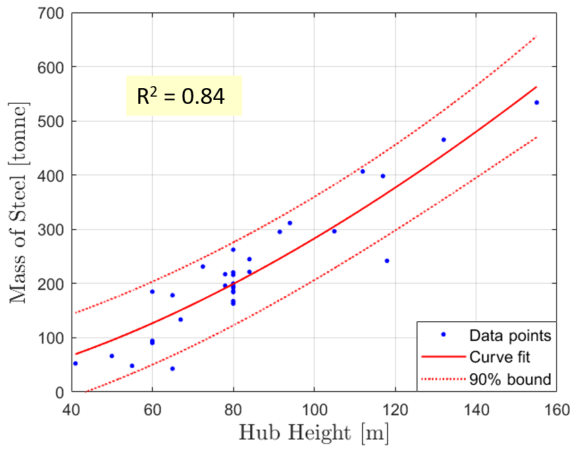


(b) Spread of fibreglass mass in tons varying with Rotor diameter of wind turbine. Curve fit calculated in MATLAB

The figures 4.3a and 4.3b shows the variation of the mass of cast iron and steel in a wind turbine. In case of cast iron, as it is mainly used in the nacelle, capacity rating of the wind turbine is selected as the scaling factor and $R^2 = 0.87$ is obtained from the curve fit. While almost 80% of steel is used for manufacturing a tower of the wind turbine, thus the hub height is chosen as the scaling factor. Goodness of fit value of $R^2 = 0.84$ is obtained for the curve fit of steel.



(a) Spread of cast iron mass in tons varying with the capacity of a wind turbine. Curve fit calculated in MATLAB



(b) Spread of steel mass in tons varying with the hub height of a wind turbine. . Curve fit calculated in MATLAB

The main difference between the onshore and offshore wind farm related to the type of foundation. As most of the analyzed LCA studies represented onshore wind farms, separate studies referring to the foundations of offshore turbines were analyzed. The most common types of foundations used for an offshore turbine in order are monopiles, jacket, gravity, tripods, tripiles and floating. Monopile foundations are the most installed type, with 4258 offshore turbines (81%) using monopiles till 2019 [9]. Thus this thesis has assessed the mass of a monopile foundation. Steel is primarily used in the monopile foundation. A study by Vicente et al lists the weight of monopile foundations for various OWF [98]. The data was used to model the variation of the mass of monopile foundation with respect to the capacity of the offshore wind turbine as seen from figure 4.4. The excluded points highlighted by green belong to OWF installed at water depths of 35m which is not the case for OWF installed before 2010 which will be soon decommissioned. The value of $R^2 = 0.81$ is obtained for the curve fit of monopile foundations.

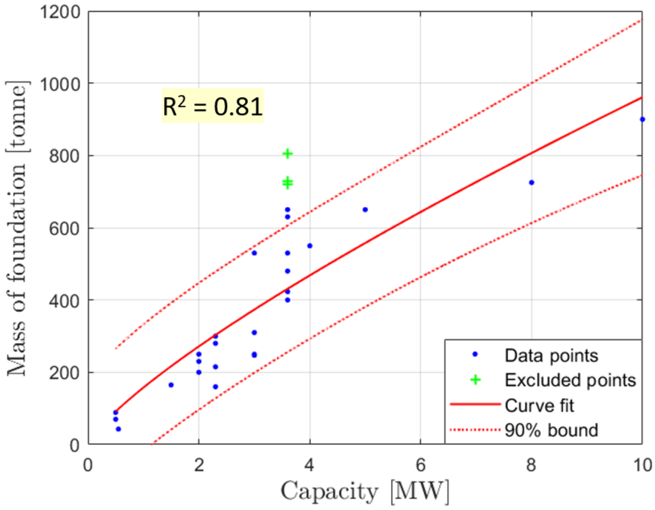


Figure 4.4: Spread of steel mass in tons used in monopile foundations varying with the capacity of a wind turbine. The excluded points belong to the OWF installed at water depth of more than 35m. Data used from study of monopile foundations [98]

The aggregation of the mass of materials is done in MATLAB curve fit toolbox, table 4.1 shows the coefficients a and b in the power equation form 4.1 for the materials. Also, the values of R^2 representing goodness of fit are shown for an overview of curve fitting.

Table 4.1: Coefficients of the power form equation $M = a \cdot X^b$ and goodness of fit (R^2) of the curve fitting in MATLAB done for the mass of material gathered from LCA studies

Material	***a***	***b***	R^2
Steel	0.2043	1.571	0.84
Cast Iron	16.55	1.065	0.87
Fibre glass	0.03469	1.41	0.61
Epoxy	0.03642	1.76	0.60
Aluminium	0.6554	1.631	0.68
Copper	1.262	0.754	0.58
Foundation	157.7	0.785	0.81

PERMANENT MAGNET MASS

Magnets in the generator help to generate electricity. They are used in wind turbines with different technology like geared and direct-drive. At present of all the wind turbines installed in the world, 26.6% use direct-drive technology while the rest use geared systems [1]. However, with overall benefits in reduced maintenance, high reliability and reduced weight, the increase in using direct drive technology using permanent magnets is likely. Thus, the magnets used in a wind turbine are considered. Several types of permanent magnets like AlNiCo (Aluminum-Nickel-Cobalt), ferrite, SmCo (samarium cobalt), NdFeB (neodymium-iron-boron) and SmFeN (samarium iron nitride). Of these types, NdFeB magnets are most commonly used due to its superior performance. These magnets contain about 30% of REE like Neodymium. The mass of magnets used in a wind turbine depends on the technology used and size of the generator. On average the total mass of magnets used in a wind turbine is 600kg/MW [99]. This value was used in the tool developed in this thesis.

CABLE MASS

In an OWF, inter-array cables connect each wind turbine to a transformer platform and an export cable connects the wind farm to the onshore grid network. Optimizing cable layout is a highly complex issue which depends on the availability of the cable type, costs, spatial distribution of the wind turbines, number of wind turbines and their capacity. This optimization is out of scope from this thesis work, and the mass of cables is based on previously conducted studies. However, based on certain assumptions of type of cable and costs, the mass of cables can be predicted. A constant of $11\frac{Tonnes}{MW\cdot km}$ for inter-array cables and $0.854\frac{Tonnes}{MW\cdot km}$ for export cables was suggested by Juan Andrés Pérez-Rúa, a researcher at DTU through email correspondence, based on their research [100]. Due to high capability to withstand the extreme environment and high material flexibility, copper cables are mostly used in the OWF. Thus, a copper cable is assumed as the preferred type with 66% of the mass being copper and the remaining 33% mass of plastic in a cable. Average spacing of 7D (Rotor Diameter) between the offshore wind turbines was assumed based on the study [101]. The mass of the cables is calculated as shown in 4.2.

$$\begin{aligned} Cable_{Array} &= 11 * Capacity * Number\ of\ Turbines * Spacing \\ Cable_{Export} &= 0.854 * Capacity * Number\ of\ Turbines * Spacing \end{aligned} \tag{4.2}$$

Where capacity of the wind turbine is in MW, and the spacing is calculated as 7 times the rotor diameter of the wind turbine in kilometres.

MATERIAL SPLIT

The curve fitting was done for the materials used in a wind turbine as a whole. However, during the decommissioning phase, the turbine is disassembled at a component level, and the mixture of materials in those components are disposed. Hence for better clarity during disposal and to see the environmental impacts of each component, the mass of material is split in each component. The offshore wind turbine is divided into 3 main components, namely the Rotor, Tower and Nacelle. Certain materials like steel, cast iron and fibreglass are used in multiple components of the turbine. Few LCA studies mentioned the materials into each component [49, 27, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60]. Percentage of material in the 3 components of the turbine was assessed and the average values were applied to the aggregated materials through curve fit. The table 4.2 shows the materials in each component of the wind turbine and the percentage of the material in that component. The percentage split depicts the percentage of that specific material highlighted with the same colour, into these components. The split found is also validated by a similar range found in the research study about quantification of waste [82].

Table 4.2: Split of materials in a wind turbine into components obtained through the data from LCA studies. The percentage values of the materials highlighted in same colour add up to 100%

Component	Materials	Split (%)
Rotor	Cast Iron	31.3%
	Steel	3.3%
	Fibre glass	79.4%
	Epoxy	100%
Tower	Steel	76.6%
Nacelle	Aluminium	100%
	Copper	100%
	Magnet	100%
	Steel	20.0%
	Cast Iron	68.7%
	Fibre glass	20.6%

The curve fit equations presented in the table 4.1 are used to predict the mass of the materials in a wind turbine as a whole. This mass of materials is further divided into each component based on the split percentages shown in table 4.2. This modelling of the mass of materials is incorporated in the developed tool predicting the mass of materials depending on the specifications of the wind farm. The aggregated data is validated by comparing the mass values with Vestas turbines of various specifications. Qualitative validation of the mass of materials has also been carried out through email correspondence with contacts working in the wind industry.

4.1.2. MONETARY VALUE

The materials from the decommissioned components possess a monetary value gained through its reuse, remanufacturing and recycling. At present most of the materials are recycled by selling them as scrap. These materials are traded on a scrap market to the recycling facilities. The London Metal Exchange is the most commonly used platform for selling the scrap metals through a regulated market with buyers and sellers [102]. The scrap value of the metal varies depending on the supply and demand and many other factors, thus it is difficult to forecast the scrap value. The historical scrap prices of steel, copper and aluminium from June 2017 are shown in the Appendix A.1 A.2 A.3. In this thesis work, the daily scrap market prices from the London Metal Exchange market are linked with the developed tool. Daily exchange rate is also considered for conversion in Euros. The table 4.3 shows the scrap value of materials as assessed on 5^{th} June. The values of steel, copper and aluminium are taken from the London Metal Exchange. For fibreglass and epoxy mainly present in the blades, on average the wind farm owner needs to pay for the disposal of blades which is around 150 EUR/tonne. This amount primarily highlights the cost of transportation and gate fees if any [103] and varies depending on regulations of that country. The magnets have valuable REE in them, and a large concentration in a wind turbine results in a monetary value of between 11-12 USD/kg for magnets [65]. However, there are only limited commercial companies that recycle the NdFeB magnets, thus the scrap value might vary depending on the availability of recycling facility. Cable recycling is gaining attention in Europe, with the scrap value around 2464 EUR/Tonne [104]. This relatively high value is due to the presence of copper in the cables (array and export). The monetary values shown in table 4.3 are the costs that the OWF owner can receive by selling the components to the recycling facilities, it does not include the costs associated with recycling materials. These costs aid in reducing the decommissioning costs of the OWF.

Table 4.3: Monetary values of materials incurred by the wind farm owner by selling these materials to the recycling facilities. The values correspond to the scrap market on London Metal exchange on 5^{th} June

Materials	Monetary Value (EUR/Tonne)
Steel	234
Cast Iron	178
Fibreglass	-150
Epoxy	-150
Aluminium	1364
Copper	4847
Magnet	10222
Cable	2464

4.1.3. CLIMATE IMPACT

The different materials used in a wind turbine require energy to produce them. The UNEP study mentions the energy consumed by the metals in primary and secondary production (from scrap). Primary production of aluminium is intensive with 190-230 MJ/kg required for every kilogram of aluminium production. Energy consumption for copper is between 30-90 MJ/kg and for steel, it is 20-25 MJ/kg [105]. Average Green House Gas (GHG) emissions from the production of the materials in a wind turbine are shown in the table 4.4 based on the ecoinvent database of Idemat [106]. As production of recycled glassfibres and magnets from recycled metals are still not commercial processes, no data was available. Production of epoxy resin by recycling interestingly emits more greenhouse gasses in the process due to extra processes to convert it back compared to virgin production. The net GHG emissions considering the recycling rates of the materials are represented in the tool as seen in figure 4.7. Magnets have the highest CO_2 emission with 12.51 $kg\ CO_2/kg$. Detailed environmental impact of the components in an OWF are discussed in chapter 6

Table 4.4: Average greenhouse gas emissions in primary and secondary production of materials. Recycling of epoxy emits more CO_2 compared to virgin production, due to extra processes. Data taken from Idemat [106]

Materials	kg CO2-eq / kg
Steel (Primary)	2.31
Steel (Secondary)	0.53
Cast Iron (Primary)	1.52
Cast Iron (Secondary)	0.35
Fibre glass (Primary)	5.82
Fibre glass (Secondary)	-
Epoxy (Primary)	2.56
Epoxy (Secondary)	4.12
Aluminium (Primary)	7.27
Aluminium (Secondary)	2.53
Copper (Primary)	3.60
Copper (Secondary)	2.24
Magnet (Primary)	12.51
Magnet (Secondary)	-
Cable (Primary)	2.05
Cable (Secondary)	1.64

4.1.4. CRITICALITY

The criticality of various materials has been analyzed by the EU. The criticality is a measure of how a certain material is economically and strategically crucial for the European economy. Out of the 61 materials analyzed in 2017, 26 raw materials were found to be critical in the European context [107]. The criticality of material is assessed based on the economic importance and supply risk. Raw materials with high importance to the EU economy and with high risk associated with their supply are addressed as critical materials. The economic importance is calculated based on the importance of a given material in the EU economy in terms of end-use applications and the value added in various sectors. The supply risk represents the disruption of the supply chain of the materials to EU. It is based on the concentration of the primary supply from countries and their governance. It is measured extraction or production of material which presents the highest supply risk for the EU. Availability of substitute materials that can be feasibly replaced for the same purposes, and secondary production of raw materials by recycling reduces the criticality of the material. Thus, a special focus on measures required for critical raw materials used in a wind turbine should be taken. Out of the materials in an OWF considered in this thesis, REE used in the magnets are in the list of critical materials by EU.

The table 4.5 shows the rank of the criticality of materials used in an OWF. The EU report on critical materials does not rank the critical materials, thus the ranks in the table are author's analysis based on the values of supply risk and economic importance in the report [107]. The rank 1 denotes the most critical material while 5 denotes the least critical material under consideration. The NdFeB magnets are the most critical material used in an OWF. China produces almost 95% of the global REE required for the magnets, thus it poses a huge supply risk. Also, low recycling of REE at present further adds to the criticality. Extensive use of cast iron and steel in all the sectors in EU makes them the next critical material. The synthetically produced fibres and resins can be produced anywhere, thus they are at a lower fourth rank. Whereas, a low supply risk in manufacturing copper makes it the last ranked critical material under consideration. So considering the future scenarios and risks to supply chain disruption, the wind industry needs to focus on the critical raw materials by increasing the recycling and finding substitute materials.

Table 4.5: Ranking of criticality of materials with 1 as highly critical and 5 as least critical material. Ranking is based on the author's analysis of EU Critical raw materials report [107]. The magnets due to REE are most critical material in an OWF

Materials	**Criticality Rank**
Magnet	1
Steel	2
Cast Iron	2
Aluminium	3
Fibre glass	4
Epoxy	4
Cables	4
Copper	5

4.1.5. RECYCLING RATES

Recycling of the metals is the primary method to dispose of the decommissioned wind turbine. The United Nations Environmental Program (UNEP) analyzed the global average recycling rates of various metals. The end of life recycling rate of steel varies between 70% to 90%, and that of aluminium is between 40% to 70% and copper around 50% [79]. The rate varies according to the quality of the metal, concentration in a component and available infrastructure. In the case of wind turbines, due to large quantities of materials in its components, the recycling rates are high compared to the global averages. The table 4.6 shows the recycling rates of materials in an OWF based on the analysis done in the report on recycling wind turbines [84]. At present, most of the blades are disposed to cement kilns for incineration, **this approach is considered as a recovery and not included as recycling in this thesis**. Thus, 15% of fibreglass and epoxy is assumed to be recycled back into similar fibre material. Currently in case of monopile foundations, during decommissioning, foundation below the seabed is kept in situ, thus a 50% recycling rate is assumed indicating partial removal. Further, in section 4.3 the aggregated recycling rate for the whole turbine is calculated by the equation 4.3. This portrays what part of the wind turbine can be recycled.

$$Recycling\ potential = \frac{\sum \left(Recycling\ rate * mass\ of\ material\right)}{\sum mass\ of\ material} \tag{4.3}$$

Table 4.6: Recycling rates of the materials used in an OWF. Data based on [84] report. The current disposal of fibreglass and epoxy in cement kilns is considered as 'recovery' thus a lower 15% is assumed. 50% recycling rate of foundations signify partial removal

Materials	**Recycling rate (%)**
Steel	92%
Cast Iron	98%
Fibre glass	15%
Epoxy	15%
Aluminium	95%
Copper	98%
Magnet	5%
Foundation	50%
Cables	90%

4.2. REFERENCE CASE OFFSHORE WIND FARM

The developed tool was used to analyze a case study of an already decommissioned OWF. The Utgrunden OWF located on the Swedish east coast was used as a representative OWF. Figure 4.5 shows the location of the decommissioned Utgrunden OWF.

Figure 4.5: The location of the decommissioned Utgrunden OWF used as a reference case study in this thesis.

The Utgrunden OWF, owned by Vattenfall was decommissioned in 2018 by ZITON. The Utgrunden OWF had Enron Wind 70/1500 wind turbines with monopile foundations [108]. The OWF operated for 18 years before decommissioning. The figure 4.6 represents the specifications of the considered OWF. This dialogue box allows the user to model any OWF to be considered in the developed tool.

Utgrunden, Sweden

Please choose:		
Wind turbine Capacity	1.5	**MW**
Rotor Dia	70.5	**m**
Hub height	65	**m**
Number of Turbines	7	-
Capacity Factor	34%	
Lifetime	18	**years**
Distance of WF from shore	5	**km**

Figure 4.6: Dialogue box of the tool to choose the specification of the OWF in consideration. The values displayed are for Utgrunden OWF collected from [108].

The compilation of the data gathered, as explained in section 4.1 are represented for the case of Utgrunden OWF in section 4.3. **Further results obtained in this thesis are represented for the case study of Utgrunden OWF unless specified otherwise.**

4.3. MODEL FORMULATION

The data gathered in the earlier sections were used to develop a tool which specifies the materials used in a wind turbine. It allows user to rank the materials depending on various parameters like mass, monetary value, criticality, GHG intensity and recycling rate. This fulfils the methodology for the first objective of the thesis. The figure 4.7 shows the screen-shot of the tool listing the materials used in an OWF along with the parameters. The materials are specified according to each component of the turbine and for the monopile foundation and cables (array and export). The last two rows show the total values for a wind turbine and including its foundation and cables. The row 'TOTAL (1 turbine)' shows the total values for one wind turbine, while the last row 'TOTAL (1 turbine + foundation + cables)' shows the total values for one wind turbine, its foundation and cable for that turbine.

The 'Mass' column states the mass in tons per wind turbine (Cable mass presented is the fraction for one wind turbine in the OWF). The mass of the material is calculated based on the specifications of the Utgrunden OWF and by using the aggregated curve fits and material split discussed in section 4.1. The mass of materials is shown per wind turbine basis and the total mass of materials in an OWF can be calculated by multiplying with the number of wind turbines. Figure 4.8 illustrates the combined mass of materials used in a wind turbine (Rotor, Tower, Nacelle). The wind turbine has a total mass of 193 tons. Also, the mass of each individual component in an OWF is illustrated by the pie chart, where the total mass of materials in the whole Utgrunden OWF is 2969 tons. Steel is the primary material used in a wind turbine with 75% of the total mass. The 'Monetary value' column lists the data gathered as explained in section 4.1.2. The recycling rate of materials is listed based on the data gathering as explained in section 4.1.5.

Table below shows the materials used in an offshore wind farm per wind turbine

	Components	Materials	Mass (ton)	Monetary value (EUR/ton)	Monetary value (EUR)	Recycling rate	GHG intensity. (ton CO2-eq / ton)	Material Criticality Rank
TURBINE	Rotor	Cast Iron	7.98	178	1394	98%	0.37	2
		Steel	4.76	230	1009	92%	0.67	2
		Fibre glass	11.11	-150	-1667	15%	5.82	4
		Epoxy	5.43	-150	-815	15%	2.80	4
	Tower	Steel	110.37	230	23371	92%	0.67	2
	Nacelle	Aluminium	1.27	1408	1698	95%	2.77	3
		Copper	1.71	5206	8740	98%	2.27	5
		Magnet	0.90	10259	462	5%	12.51	1
		Steel	28.86	230	6111	92%	0.67	2
		Cast Iron	17.51	178	3062	98%	0.37	2
		Fibre glass	2.89	-150	-65	15%	5.82	4
	Foundation	Steel	216.80	230	24949	50%	1.42	2
	Cables	Array cable	8.14	2473	18122	90%	1.68	4
		Export cable	6.41	2473	14254	90%	1.68	4
	TOTAL (1 turbine)		193		43300	84.29%	1.15	
	TOTAL (1 Turbine + foundation + cable)		424		100625	66.96%	1.30	

Figure 4.7: Screenshot of the developed tool showing the materials used in an OWF and its parameters per wind turbine. The displayed values are modelled for the Utgrunden OWF

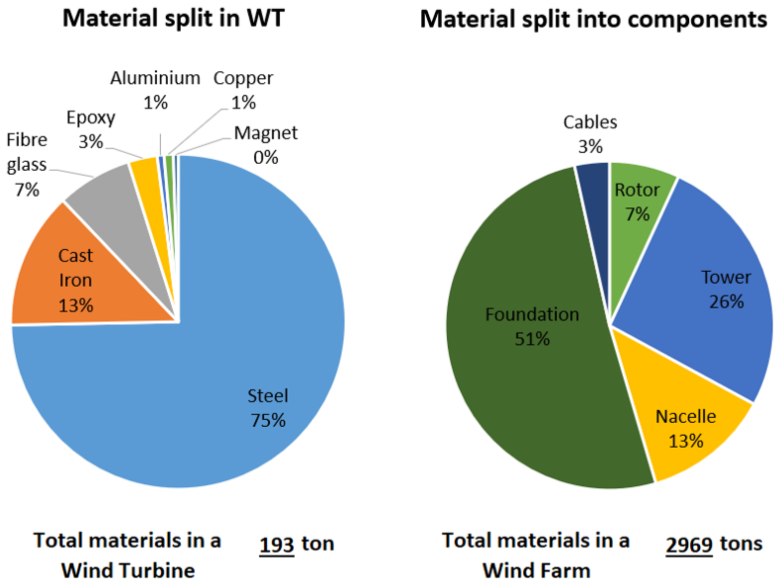


Figure 4.8: Illustration of percentage of materials used in a wind turbine and percentage of material used in individual components in the whole OWF

The column 'GHG intensity' represents the net emissions calculated based on the emissions from primary and secondary production of materials as shown in table 4.4. The equation 4.4 shows calculation of the net GHG emissions for a specific material with a certain recycling rate.

$$Net\ GHG = GHG_{Primary} * (1 - RR) + GHG_{Secondary} * RR \tag{4.4}$$

Where RR represents the recycling rates of material and the GHG emissions for primary and secondary production are calculated given in table 4.4. Due to low recycling rate of the magnets, they are seen as high GHG emitting material with emitting 12.5 $ton\ CO_2$ per ton of magnets used in a wind turbine. The average GHG emission intensity for the turbine is calculated by multiplying the mass and GHG intensity of that material and dividing by total mass of a turbine as 193 tons. Thus on average, 1kg of material used in a wind turbine emits 1.15 $kg\ CO_2 - eq/kg$ of GHG. However, this value obtained is based on the average values and takes into consideration only recycling of materials. A detailed assessment of the environmental impacts by LCA modelling is carried out in chapter 6.

The base results obtained from this developed tool are further used for analyzing the circularity potential of the OWF and for LCA modelling in SimaPro in the next chapters. The results obtained from this model are discussed in chapter 7.

5
CIRCULARITY POTENTIAL

This chapter addresses the current gap in the research in the measurement of the circularity potential. Second research objective of this thesis of *assessment of circularity indicators and calculating the circularity potential of the Offshore Wind Farm (OWF)* is addressed in this chapter. Circularity essentially is a measure of how circular (following Circular Economy (CE) principles) is the assessed system. However, as CE is a broad umbrella concept promoting responsible and cyclical use of resources, what to measure to capture the sense of CE by circularity indicators is still debatable [109]. This chapter discusses a few other circularity indicators developed and explains the implementation of Material Circularity Index (MCI) for calculating circularity of the OWF.

The term *'circularity'* goes far beyond just *'recycling'* a material, circularity encompasses a broad spectrum of ideas to maintain the highest value of a product or material through extended use, minimal resource consumption and increasing resource efficiency. The CE paradigm being widely explored, the industries are making a transition from linear to circular models. Thus, there is a need for measuring the effectiveness of these transformations with the help of some indicators. Due to a broad spectrum of CE, the indicators do not measure every aspect of CE. Some of the currently developed circularity indicators are discussed in the following section.

5.1. CIRCULARITY INDICATORS

A study done by Blanca et al in 2019, analysed various circularity indicators developed and assessed the validity and extent of measurement of these indicators [75]. On a broad level, an indicator should have the following requirements like Validity (the metric accurately measures what it is intended to measure), Reliability (consistency and robustness of the metric) and Utility (practical use of the metric). In the case of current metrics indicating the extent to which CE principles are followed, several ideologies are implemented. Circularity measuring indicators indicate a numerical scale to represent a circularity degree. On the other hand, circularity assessment tools measure the burden of value created by a circular system. The development of the circularity indicators is based upon certain assessment frameworks methodologies like Life Cycle Assessment (LCA), Material Flow Analysis (MFA) and Input-Output analysis. The full life cycle of a product/system is analysed to evaluate the benefits of CE strategy. The MFA takes into account the state and changes of each material flow in a system, over time. It only takes into account the mass balances and disregards the quality of the material. Lastly, the Input-Output analysis takes a top-down approach to analyse the interdependence between different economic sectors within a region thus mainly used in policymaking. Several indicators are developed upon these framework ideologies. These indicators are developed to measure certain progress areas as stated by Blanca et al [75]. Reduction in input resource use, increase in renewable energy share, reduction in emissions, reduction in material loss/waste, maximizing utility and durability, creation of jobs and increasing social wellbeing are certain indications of progress that can be achieved through the implementation of CE and ideally the indicators used should portray these advancements. Certain circularity indicators developed addresses some of these progress signs.

The *'New product-level circularity metric'* developed by Linder et al in 2017 is based on a very narrow view that circularity is a fraction of a product that comes from used products [76]. Similarly, indicators like *'Circ(T)'* and *'Global Circularity Metric'* are based on a mono-dimension circularity of merely material recirculation, not focusing on the quality of the material. *'Global Circularity Metric'* measures circularity based on the share of cycled materials as a part of total material inputs into the global economy. *'Circ(T)'* builds on the MFA framework to measure the cumulative mass of a material present in a system over a period of time. The *'Circularity Index'* indicator is based on material circulation and includes a notion of quality as the ratio of energy required for material recovery to the energy required for primary production. This approach prohibits the risks of achieving resource circularity by increasing energy use. The *'Circular Economy Indicator Prototype'* is calculated based on answers to the 15 questions based on product design, manufacturing, commercialization, in-use and end of life of a product. However, a broad circularity assessment approach, covering maximum progress signs is implemented in the *MCI*.

The MCI developed by the Ellen MacArthur Foundation and Granta Design is a micro-level indicator that can be used in designing new products, assessing the implementation of CE strategies, rating the companies, and benchmarking products. The MCI is built upon a complex definition of product circularity which is *"the extent to which linear flow has been minimised and restorative flow maximised for its component materials, and how long and intensively it is used compared to a similar industry-average product"* [77]. The four main principles that the MCI focuses on are:

1. using feedstock from reused or recycled sources
2. reusing components or recycling materials after the use of the product
3. keeping products in use for a longer time (e.g., by reuse/redistribution)
4. making more intensive use of products

As MCI comes close in analysing the true extensive nature of CE, thus the indicator was chosen to measure the circularity potential of the OWF in this thesis. The implementation of the MCI on the considered OWF is discussed in the next section.

5.2. MCI CALCULATION

The MCI is essentially constructed from a combination of three product characteristics: the mass of virgin raw material used in manufacturing, the mass of unrecoverable waste that is attributed to the product, and a utility factor that accounts for the length and intensity of the product's use. Through these characteristics, MCI measures the extent to which the linear flow has been minimized and the restorative flow maximized for a component. A linear flow model is built upon ‘take-make-dispose’ ideology, where a product is made from virgin materials that end up in landfills, resulting in depletion of finite resources. The figure 5.1 below represents the diagrammatic representation of the material flows and the extent to which they are assessed in MCI. A product can be manufactured by using the material from a virgin feedstock or from recycled materials or by reusing components. A virgin feedstock means a material that has not been previously used or consumed or subjected to processing other than for its original production [77]. After the use phase of the product, the components can be reused or the materials can be collected for recycling or sent to landfill or energy recovery. It should be noted that the dashed lines in the figure represent that the methodology does not require a closed-loop in which the used products/materials come back to the same manufacturer to be used in a similar product. However, the feedstock, in this case, can be sourced not only from the same product after use, but also it can be obtained through global market from any product. Thus, recycling materials is not necessarily tackled by the wind industry alone, but it depends on the infrastructure of society as well. All the wastes generated during the processes and remaining materials are disposed and considered as materials lost from the system. The efficiencies of the recycling processes add to the wastes generated from the system.

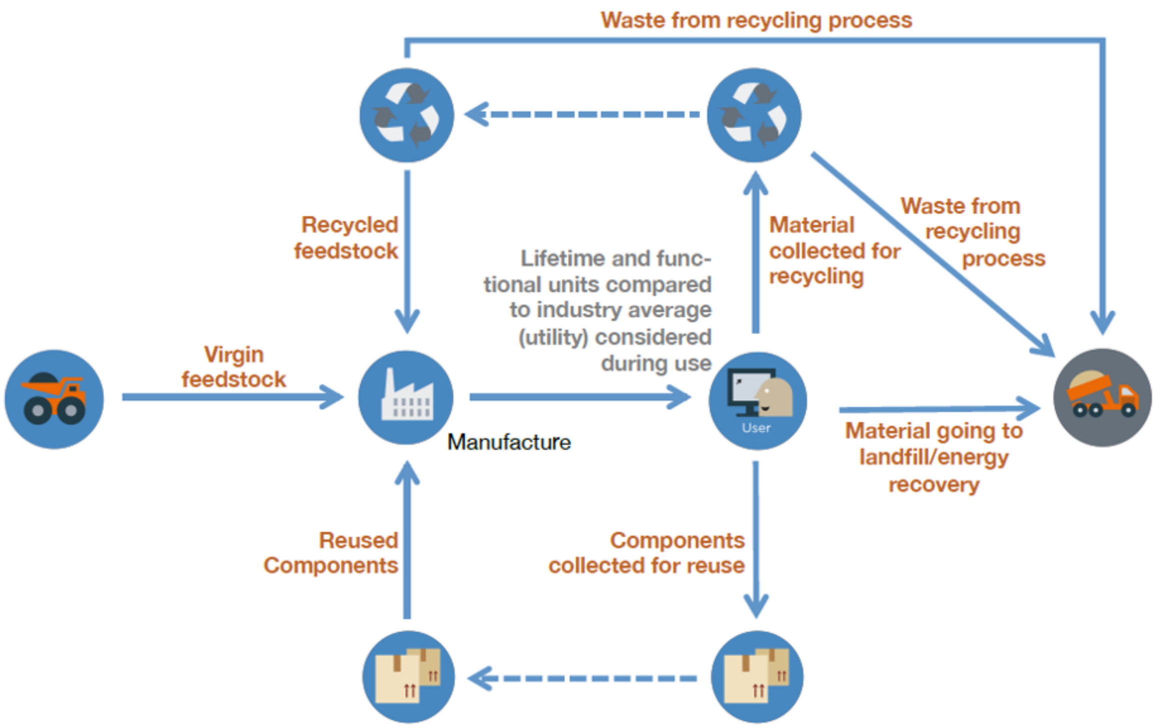


Figure 5.1: Diagrammatic representation of the flow of materials in a system considered while calculating the MCI as depicted in the methodology report of MCI. The dotted lines signifies an open system allowing sourcing of material/components from open market. Image taken from [77]

Based on these material flows, the MCI measures the level of circularity between 0 to 1. Where 0 signifies a fully *‘linear’* product in which it is made purely from virgin material and completely goes to energy recovery or landfill after its use. A fully *circular’* product, on the other hand, contains no virgin feedstock in its manufacturing, it is completely collected for material recycling or component reuse at the end of life and the recycling efficiency is 100% with no waste from the system. A fully *‘circular’* product is represented by 1 in MCI. Thus, MCI closer to 1, representing a circular model is preferred in a system.

The MCI is calculated for a turbine and the OWF in consideration. As the OWF is made up of several components and materials, the MCI is calculated for each material and then aggregated to give the circularity of the whole OWF. This makes it possible for a higher level of detail in material specific flows. The data about the mass of each material, their recycling rate is taken from the aggregated tool 4.7 as explained in the previous chapter. The calculation process of MCI, as suggested in the methodology report of MCI is explained in the following steps [77]. The steps are performed for each material individually indicated by subscript (x) in the formulae.

1. **Calculating Virgin Feedstock**
   Initially the mass of the material from virgin feedstock (primary production) is calculated by subtracting the fraction of material from recycled and reused sources.

$$V_{(x)} = M_{(x)} \left(1 - F_{R(x)} - F_{U(x)}\right) \tag{5.1}$$

   Where, $V_{(x)}$ is the mass of the virgin feedstock used.
   $M_{(x)}$ is the mass of the material.
   $F_{R(x)}$ is the fraction of material's feedstock from recycled sources.
   $F_{U(x)}$ is the fraction of material's feedstock from reused sources.

   The total amount of virgin material V in a wind turbine is then calculated by summation of virgin material for individual materials

$$V = \sum_{x} V_{(x)} \tag{5.2}$$

2. **Calculating Unrecoverable Waste**
   Unrecoverable waste is generated from the material flows through efficiency losses in the recycling process and while producing recycled feedstock and material disposed to landfill, where the material is no longer recoverable. No waste generation from component reuse is assumed in the methodology. The waste flows are calculated according to these equations

$$W_{0(x)} = M_{(x)} \left(1 - C_{\mathrm{R}(x)} - C_{\mathrm{U}(x)}\right) \tag{5.3}$$

   Where, $W_{0(x)}$ is the waste from the material disposed of to landfill or any other process which does not lead to material being recovered.
   $C_{\mathrm{R}(x)}$ is the fraction of mass of a material being collected to go into recycling process.
   $C_{\mathrm{U}(x)}$ is the fraction of mass of a material going into component reuse.

$$W_{C(x)} = M_{(x)} \left(1 - E_{C(x)}\right) C_{R(x)} \tag{5.4}$$

   Where, $W_{C(x)}$ is the waste generated in the process of recycling parts of a product.
   $E_{C(x)}$ is the efficiency of the recycling process used for the portion of a material collected for recycling.

$$W_{F(x)} = M_{(x)} \frac{\left(1 - E_{F(x)}\right) \cdot F_{R(x)}}{E_{F(x)}} \tag{5.5}$$

   Where, $W_{F(x)}$ is the waste generated when producing recycled feedstock for a product.
   $E_{F(x)}$ is the efficiency of the recycling process used to produce recycled feedstock for a material.

The total amount of unrecoverable waste (W) from the system is given by the equation 5.6. It should be noted that a 50:50 approach is implemented to give equal emphasis to the waste generated from recycling material in a product ($W_{C(x)}$) and the waste generated from producing recycled feedstock ($W_{F(x)}$). This 50:50 approach also makes sure that the waste quantities are not doubly accounted in the calculation.

$$W = \sum_x \left(W_{0(x)} + \frac{W_{F(x)} + W_{C(x)}}{2} \right) \tag{5.6}$$

3. **Calculating Linear Flow Index**
   The Linear Flow Index (LFI) measures the proportion of material flowing in a linear fashion, that is, sourced from virgin materials and ending up as unrecoverable waste. It is calculated by dividing the total amount of material in a linear flow by the sum of the amount of materials flowing in linear and restorative fashion. The term $W_{C(x)}$ is neither a part of the linear flow or restorative flow, thus it is subtracted, while $W_{F(x)}$ is not a part of the mass of the product (M), but is needed additionally to create recycled feedstock, thus it is added in the equation 5.7.

$$LFI = \frac{V + W}{2M + \sum_x \frac{W_{F(x)} - W_{C(x)}}{2}} \tag{5.7}$$

4. **Calculating Utility Factor**
   The utility factor X has two components, one accounting for the length of the product's use phase (lifetime) and another for its intensity of use. The utility factor is applied for a whole product, so in this case, it applies for the whole OWF. It is calculated as shown in equation 5.8.

$$X = \left(\frac{L}{L_{av}} \right) \cdot \left(\frac{U}{U_{av}} \right) \tag{5.8}$$

   Where, L is the actual lifetime of the product.
   L_{av} is the average lifetime of a similar industry-average product.
   U is the average number of functional units achieved during the use phase of a product
   U_{av} is the average number of functional units achieved during the use phase of an industry-average product of the same type

   The lifetime component accounts for an increase in the lifetime as a reduction in wastes for that period. The intensity component signifies a product that achieves the functional units in a certain duration. The average lifetime is assumed to be 20 years and product intensity is assumed to be equal to the industry averages, however, effects of change in these factors are further discussed in chapter 8.

5. **Calculating Material Circularity Index (MCI)**
   Lastly, the MCI is calculated as shown in the equation 5.9. The MCI methodology suggests to use a constant 0.9 signifying the interdependence of lifetime and intensity of the product [77].

$$MCI = \left(1 - LFI * \left[\frac{0.9}{X} \right] \right) \tag{5.9}$$

The figure A.4 in the appendix shows a flow chart with material flows of the system with the abbreviations mentioned in the above calculations for better clarity.

The data used for calculating the MCI for the case study of Utgrunden OWF can be seen from figure 5.2. The values of the mass of materials and their recycling rates are the same as presented in figure 4.7. The other values highlighted in blue are based on the average values from the literature and can be changed by the user of the tool. The first row namely 'Aggregated Wind Turbine' calculated the MCI if that data aggregated for a wind turbine is known. As the values vary for each material in a wind farm, a more detailed analysis is done in this thesis. As most of the materials are recycled, a lower collection reusing rate ($C_{U(x)}$) is assumed for materials. The efficiencies for recycling process of materials collected ($E_{C(x)}$), and the efficiency of the process to prepare recycled feedstock ($E_{F(x)}$) are assumed to be equal. The efficiency values are taken from the average European database, but there is uncertainty in these values which is addressed further in chapter 7. [110]. The recycled content ($F_{R(x)}$) represents the amount of material coming from secondary sources. The values are taken from the ecoinvent market processes from SimaPro database, which shows the average percentage split between primary and secondary sources when manufacturing a material. For example, 40% recycled content of steel means that 40% of steel is manufactured by using recycled iron ore while the rest 60% is primarily produced. It should be noted that in case of fibreglass and epoxy, as the current technology does not allow for using recycled fibres to make blades, $F_{R(x)}$ is considered as 0%. Reused content ($F_{U(x)}$) in a wind turbine is at a component level, where certain parts of the components can be reused directly while manufacturing a new wind turbine. As at present very few components from a wind turbine get reused, lower percentages around 3% are assumed. The lifetime factor represents the lifetime of the OWF in consideration with respect to the average lifetime of 20 years. As the Utgrunden OWF was decommissioned in 18 years, the lifetime factor is 0.9 (18/20)

Components	Materials	Mass (M) (ton)	Collection Recycling rate (Cr)	Collection Reusing rate (Cu)	Recycling product efficiency (Ec)	Recycling feedstock efficiency (Ef)	Recycled content (Fr)	Reused Content (Fu)	Lifetime factor
Aggregated Wind Turbine		193	84%	2%	80%	80%	40%	5%	0.9
Rotor	Cast Iron	7.98	98%	2%	95.0%	95%	35%	3%	
	Steel	4.76	92%	2%	95.0%	95%	35%		
	Fibre glass	11.11	15%	0%	50.0%	50%	0%		
	Epoxy	5.43	15%	0%	50.0%	50%	0%		
Tower	Steel	110.37	92%	4%	95.0%	95%	35%	5%	
Nacelle	Aluminium	1.27	95%	3%	85.0%	85%	33%	3%	
	Copper	1.71	98%	3%	85.0%	85%	44%		
	Magnet	0.90	5%	0%	30.0%	30%	0%		
	Steel	28.86	92%	2%	95.0%	95%	35%		
	Cast Iron	17.51	98%	2%	95.0%	95%	35%		
	Fibre glass	2.89	15%	0%	50.0%	50%	0%		
Foundation	Steel	216.80	50%	3%	95.0%	95%	35%	5%	
Cables	Array cable	8.14	90%	2%	75.0%	75%	30%	3%	
	Export cable	6.41	90%	2%	75.0%	75%	30%		

Figure 5.2: Screenshot of the tool developed by the author, showing the data assumed while calculating the MCI of wind turbine based on the case study of Utgrunden OWF. The values of highlighted in blue can be changed by the user of the tool to calculate the MCI under different scenarios.

Certain assumptions are made while calculating the MCI. It is assumed that the recovered material at the end of its use can be processed to a similar quality as the original virgin material. It is assumed that no material losses take place in preparing collected products for reuse. In this thesis, the MCI is calculated for a wind turbine and also for the OWF as per the method explained and the data stated in figure 5.2. The results obtained are discussed in chapter 7.

5.3. LIMITATIONS OF MCI INDICATOR

The MCI provides an indication of the circularity potential of a product based on material flows. In most of the cases, higher circularity implies a more sustainable product. However, MCI alone cannot be the basis for determining a sustainable alternative. MCI does not take into account the economic implications of carrying out the processes. MCI also neglects the energy consumption and environmental impact in manufacturing and recycling the materials. This could give rise to cases where a higher circularity has more burden on the environment. For example, a product with 99 kg of steel and 1 kg of magnets where all steel is recycled and magnets are landfilled. If this product is changed to have the same total mass but with 98 kg of steel and 2 kg magnets, this will not drastically change the MCI value as most of the product is still being recycled after its use, however, there might be a huge environmental impact due to increased use of magnets. To overcome this bias, MCI should be assisted with other complementary indicators. Monia et al suggests in her study in 2019, to couple the circularity indicators with life cycle based indicators [111]. Thus, in this thesis LCA study of the wind farm in consideration is undertaken to assess the environmental impacts and to give further insights complementing the MCI in the next chapter.

6
LIFE CYCLE ASSESSMENT

This chapter addresses the third objective of this thesis work which is *Assessment of the environmental impacts of the Offshore Wind Farm (OWF)*. The environmental impacts of the decommissioning and disposal of OWF are calculated by Life Cycle Assessment (LCA) modelling. The methodology and the process of conducting a LCA study for the case study of Utgrunden OWF are discussed in this chapter, also the underlying assumptions in conducting the LCA study are stated. The study is conducted to assess the environmental impacts to complement the circularity potential discussed in the last chapter.

6.1. LIFE CYCLE ASSESSMENT STUDIES

The LCA is defined as "*a tool to assess the potential environmental impacts and resources used throughout a products life cycle, i.e. from raw material acquisition, via production and use stages, to waste management*" [8]. The outputs of the LCA study enables us to study the effects of a system on a holistic level. Thus LCA analysis was conducted in this thesis to assess the environmental impacts in decommissioning the OWF, focusing on the disposal of the materials. Conducting a LCA is a broad and a complex process and ISO 14040 [7] specifies the principles and framework for conducting an LCA study. ISO 14044 [8] mentions the requirements and the guidelines for carrying out the LCA study. This standard procedure was referred to while conducting the LCA in this thesis. Even with these standards, the exact procedure to conduct the LCA study varies with cases and the goal of the study and requires certain assumptions. Particularly, ISO 14044 procedures to handle recycling are ambiguous and have led to numerous and deviating guidelines [112]. Uncertainty in considering the benefits of recycling is still debated and varies depending on case studies [112].

In this thesis, LCA of the system is conducted in *'SimaPro'* software. SimaPro is a leading LCA software to collect, analyse and monitor the sustainability performance data of the system. The software is linked with the *'ecoinvent'* database for the processes. The LCA framework operates in four methodological phases: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation. These phases and the underlying assumptions are discussed in detail as follows.

6.1.1. GOAL AND SCOPE

Defining the goal and scope of the study is the first phase of a LCA. The goal determines the purpose of a study in detail and scope determines what product systems are to be assessed and how this assessment should take place. The goal of this study is to compare and evaluate the potential environmental impacts associated with disposing the materials from decommissioned OWF and to support decisions in choosing various disposal scenarios. This study implements a cradle-to-cradle approach with the main focus on disposal. The figure 6.1 shows the system being considered for the conducted LCA study. **The installation and operation phase of the OWF is considered to be out of the scope for this LCA**. The conducted LCA study takes into account the impacts from producing the materials and their disposal (steel, cast-iron, copper, aluminium, fibreglass, epoxy, magnet, cables). A wind turbine and its foundation and cables are defined consisting of these materials. The impacts caused by the removal process of the OWF (cutting and lifting substructures and the cranes required for removal) are not considered, as the data of these processes is still not well documented. The transport of components from the OWF location to the onshore recycling facilities is considered in the analysis. Different scenarios for disposing the components for recycling, reusing and incineration are modelled in this LCA study. The impacts of the mineral extraction for making materials are out of the scope of this analysis. However, the impacts of all the disposed materials either by recycling, incineration, reuse or landfill are considered in the analysis.

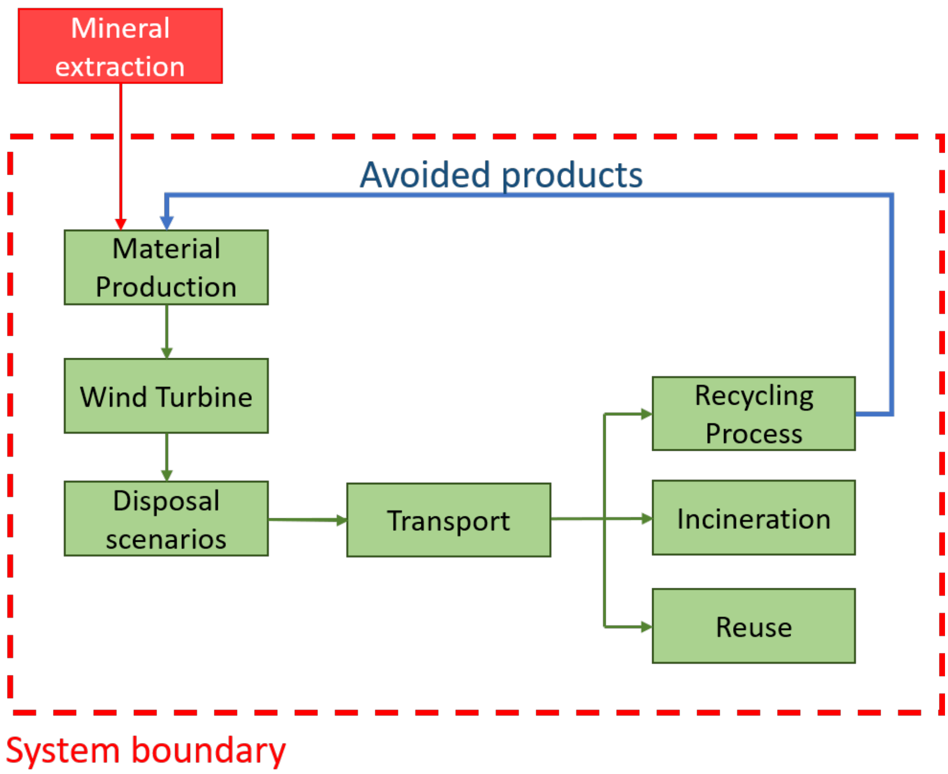


Figure 6.1: System boundary considered in analyzing the life cycle of the OWF. Impacts from manufacturing materials in an OWF and from its various disposal scenarios are assessed in this thesis.

The functional unit for the LCA study is defined as: *'1 kg of material used in a wind turbine, its foundation and cables of the offshore wind farm.* This LCA study follows an attributional process-based approach as it suits the objectives of this thesis. An attributional approach quantifies the relevant environmental impacts of the wind power plant based on physical material and energy flows. On the other hand, a consequential approach rather aims at the indirect impacts in relation to operating the wind farm.

6.1.2. LIFE CYCLE INVENTORY

In the Life Cycle Inventory (LCI), inputs and outputs throughout the entire life cycle are estimated, according to the chosen system boundaries and method. Based upon the decided scope, inventory analysis collects information about the physical flows in terms of input of resources, materials and the output of emissions, waste and valuable products for the product system. The input data of the material quantities, their recycling rates and efficiencies and the processes associated with manufacturing, transport and disposal forms the LCI of this study. The 'ecoinvent v3 database' is used for the process in this LCA study. The ecoinvent is a Swiss database that contains approximately 12,500 processes related to transport, energy and material production. The 'Ecoinvent 3 - allocation, cut-off by classification' library is used for this thesis. The cut-off system model is based on the approach that the primary production of materials is always allocated to the primary user of a material (in this case wind turbine manufacturer). If a material is recycled, the primary producer does not receive any credit for the provision of recyclable materials. The consequence is that recyclable materials are available burden-free to recycling processes and secondary (recycled) materials bear only the impacts of the recycling processes. Also, producers of wastes do not receive any credit for the recycling or re-use of products resulting out of any waste treatment [113].

As the functional unit of the LCA study is 1kg of material, the mass of materials used in the components of an OWF as shown in figure 4.7, are directly used without any scaling required in the LCI. The processes for manufacturing these materials are used from the ecoinvent database. The table A.1 in appendix shows the processes from the ecoinvent database that are selected for the specific operations. The European 'market' process models a manufacturing mix with different technologies used to produce the material and average transportation to the consumer. These processes simulate buying a specific material from the open market in that region. The transportation of the components from the OWF to the nearby port is accounted through transoceanic ship and barge. The transportation of materials from the port to the recycling facility which is assumed to be at an average distance of 100km is modelled as freight lorry transport. The waste treatment processes, recycling the materials are used from the ecoinvent database, however, they are not well developed in the database.

The materials produced from the recycling process are modelled as 'avoided products' to the system. Avoided products signify the amount of the recycled material that replaces the primary production of material. Recycling efficiency signifies the fraction of material produced from the input scrap. It acts as the amount of the primary material being replaced by the recycled material. In the developed model, the efficiency is chosen as a product of the recycling process efficiency ($E_{C(x)}$) and the recycling feedstock efficiency ($E_{F(x)}$) as shown in figure 5.2. This is considered so that it accounts the losses in converting the scrap material back into material used in a wind turbine. As at present the fibreglass and epoxy in the blade are mainly used in the cement kilns, it is not considered as recycling according to the definitions in section 2.3 and is treated as energy recovery with incineration process.

6.1.3. LIFE CYCLE IMPACT ASSESSMENT

The Life Cycle Impact Assessment (LCIA) is the third phase while conducting a LCA. LCIA translates the physical flows and interventions of the product system into impacts on the environment. As the impact of the OWF on various parameters was required, a method fulfilling multiple impact categories was chosen. ReCiPe 2016 midpoint (H) method was selected. The ReCiPe method is one of the common methods found in the LCA studies and also is researched heavily by the LCA community. The method consists of 18 midpoint indicators, each focusing on a single environmental problem which are then aggregated on a higher level with the 3 endpoint indicators. The figure 6.2 represents the relationship between these indicators. Each of these midpoint indicators measures an environmental issue. The indicators which are found to be relevant to the conducted LCA study are addressed in chapter 7. The details of the remaining indicators can be found in the method report of ReCiPe [114].

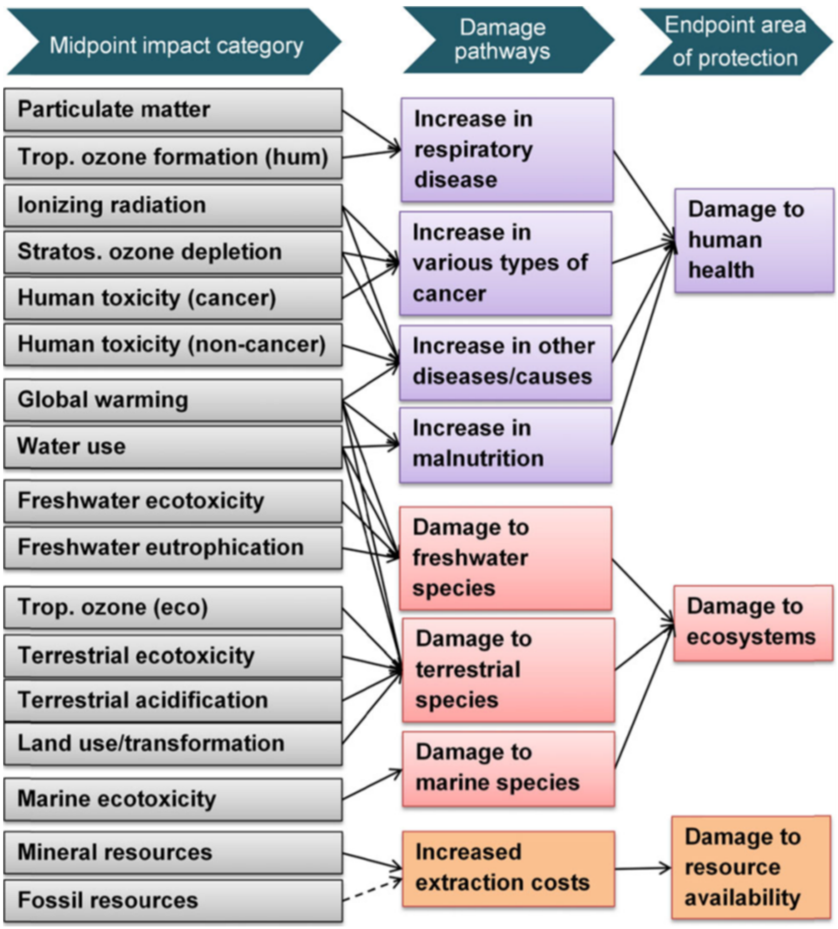


Figure 6.2: Representation of the relationship between the midpoint impact categories and the endpoint indicators covered in the ReCiPe2016 method. Source: image taken from [114]

6.1.4. INTERPRETATION

Interpretation is the final phase while conducting the LCA which fulfils the goal of the study. The areas of the biggest impact in the system are identified through the impact assessment. Sensitivity analysis is performed to guide the conclusion of the LCA study. The interpretation of the obtained results is discussed in chapters 7 and 8.

6.2. MODELLING IN SIMAPRO

The LCA methodology explained earlier is applied while conducting the LCA of the Utgrunden OWF. The wind turbine is modelled as an assembly with the components Rotor, Tower, Nacelle, Foundation and Cables as its sub-assemblies. The processes for material production are then used for the materials in respective components. The disposal scenario of the wind turbine is modelled along with transportation from the OWF to the port and further linked to disassembly for each specific component. Here the whole wind turbine is disassembled into separate components and transported from the port to the recycling facility (100km distance assumed). In case of foundations being left under the seabed, no impacts are considered for the part left as it is in the sea. However, as the SimaPro requires mass from input of the system to be equal to the outflow (mass balance), an empty process was created to make sure the fraction of foundation in the seabed has no environmental impact. Each disassembled component is then reused to a certain extent and the rest is linked to recycling scenario. The materials get recycled depending on the recycling rates of each material in the recycling scenario. The remaining material is sent for incineration. The credits (benefits) for recycling are modelled as a factor of recycled material replacing the primary production through 'avoided products' approach. As material cannot be recovered from incineration, no credits for primary production are accounted in that case. Also, no heat recovery by incineration is modelled. By considering the reuse of a component, SimaPro reduces the equivalent materials required, thus there are environmental benefits of reusing the components. The figure 6.3 shows a tree diagram in the modelling of the disposal scenario. The white squares represent the transport processes. The green coloured arrows depict the savings in the emissions by recycling or reusing compared to primary production. The arrows towards the left are liked to the production processes. The figure A.7 in the Appendix shows the complete network tree of the modelled LCA system.

The faculty version of the SimaPro that was used in this thesis does not allow linking with Excel, so the data about the mass of materials, their recycling rates and the efficiencies should be inserted manually. However, for the ease of usage, parameters are defined in the SimaPro software to change the values only once at a single location in the software.

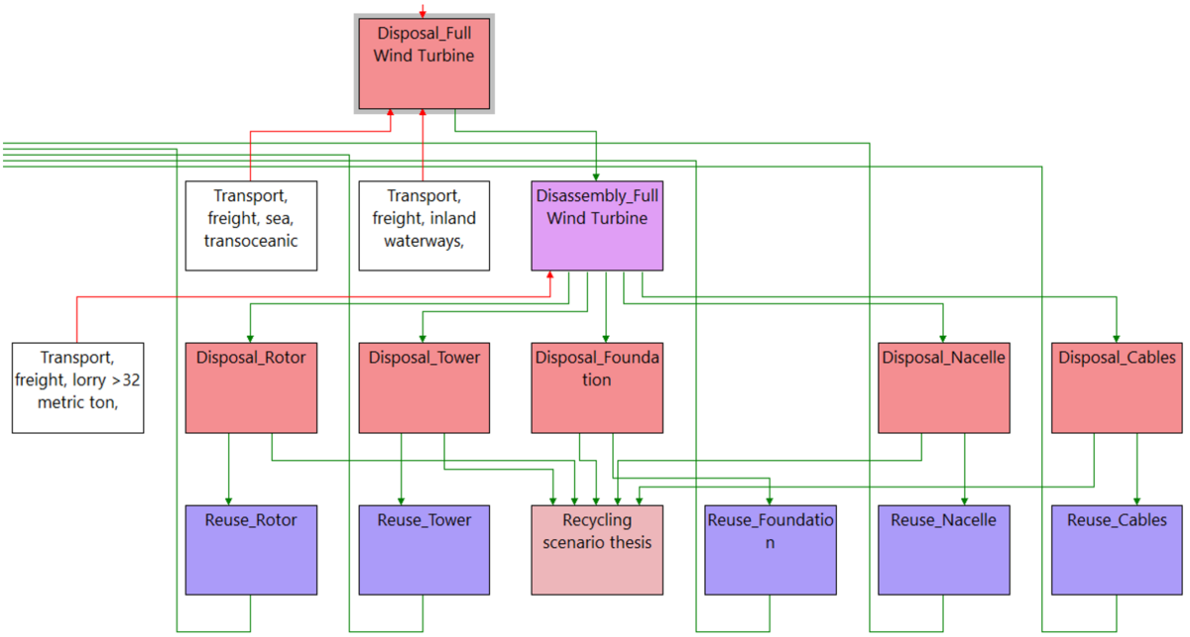


Figure 6.3: Network diagram depicted in SimaPro software for the disposal scenario of the OWF. The green arrows signify savings in emissions due to reduced primary production by reusing components and recycling materials. The white squares represent the transportation form OWF location to the onshore recycling facility.

This presents the modelling of the LCA study done to assess the environmental impacts from decommissioning and disposing a OWF. By changing the values of mass of materials, recycling and reusing percentages and other specifications of the Utgrunden OWF, the results were modelled. The obtained results from the LCA study conducted are discussed in the chapters 7 and 8.

7
Results

This chapter presents the results of the modelling done as explained in the previous chapters. Aggregating the data for various parameters of materials used in an Offshore Wind Farm (OWF) is explained in chapter 4. Using this data, method to calculate circularity potential is discussed in chapter 5 and lastly Life Cycle Assessment (LCA) methodology is addressed in chapter 6. Three different scenarios are analyzed in this chapter for the case study of Utgrunden Offshore Wind Farm (OWF). The uncertainty in modelling and possible variations in the input parameters are later addressed through the sensitivity analysis.

The case study of Utgrunden OWF, located in West Sweden with 7 wind turbines each with 1.5MW capacity is assessed in this thesis. Firstly, the mass, recycling rate, monetary value and criticality of the materials in a wind turbine, its foundations and cables were aggregated to predict the mass of materials for the Utgrunden OWF. This data is then used to calculate the circularity of the OWF by using Material Circularity Index (MCI). To complement this indicator to give further insights, LCA is performed in SimaPro with main focus on disposal phase.

7.1. End of Life Scenarios

After the decommissioning of OWF, the structures are transported to the nearby ports and the components are dismantled and further might be sent to the recycling facilities where the scrap materials will be recycled. This phase of disposing of the components presents opportunities to implement Circular Economy (CE) principles to increase resource efficiency. Three different scenarios namely Baseline Scenario, Full Removal Scenario and Reuse focused scenario are developed portraying the different approaches in decommissioning that could pan out in future.

7.1.1. Baseline Scenario

The baseline scenario represents the current practices in the wind industry and is modelled for the Utgrunden OWF. At present, mostly the wind turbine foundations are removed above sea-bed and the rest is left under the sea-bed, thus 50% of the foundation mass being recycled is assumed. Also, most of the cables buried under the sea-bed are removed, thus it is assumed that 90% of cables are being recycled. As the Utgrunden OWF was decommissioned after 18 years, the operational lifetime of 18 years is taken into consideration. The mass of the materials in the OWF is obtained by the tool being developed and the values for a wind turbine and its foundations and cables are displayed in figure 4.7.

RANKING OF MATERIALS

The first objective of this thesis of developing a tool to rank the materials with respect to parameters like mass, monetary value and criticality is partly addressed in the chapter4. The table 7.1 below ranks the materials used in the complete Utgrunden OWF from largest to lowest mass. Steel is by far most used material with 2525 tons, followed by 178 tons of cast iron. The cables both including the array and export cables, account for 102 tons. Magnets with 6.3 tons account for the lowest mass of materials used in a OWF.

Table 7.1: Mass of the materials in tonnes, used in the Utgrunden OWF presented in decreasing order. The amounts corresponds to Utgrunden OWF with 7, 1.5MW wind turbines and their foundations and cables (array and export cables combined)

Materials	Mass (tonne)
Steel	2525.60
Cast Iron	178.42
cable	101.83
Fibre glass	98.01
Epoxy	38.01
Copper	11.99
Aluminium	8.89
Magnet	6.30
Total	**2969.04**

The table 7.2 shows the monetary value that can be salvaged by the wind farm owner by selling these materials as scrap on the scrap market to recycling facilities. The values are based on the data of scrap values taken from London Metal Exchange, as displayed in table 4.3. The monetary value of the materials that can be salvaged depends on the percentage of material being collected for recycling. It is calculated as below, where the monetary value per ton and recycling rates for materials are stated in tables 4.3 and 4.6.

$$Monetary\,Value\,(EUR) = Mass\,(ton) * Monetary\,value\,(EUR/ton) * Recycling\,rate\,(\%)$$

This gives a maximum value of 226,194 € that can be achieved by recycling cables, this provides an incentive to remove all the cables. However, cable recycling infrastructure and process vary depending on location, so the monetary value can vary. Steel, even with its low monetary value per ton, due to the amount of steel being used in a wind farm, 215,902 € can be recovered by selling steel scrap. At present, magnets are not recycled on a large extent, with the assumed 5% recycling rate for magnets, they generate 3225 €. However, with a more focus on recycling magnets in the near future by assuming a 90% recycling rate, magnets can salvage 58055 € with just 6.3 tons being used in the OWF. Disposing of fibreglass and epoxy primarily in blades incur costs for the wind farm owner. These costs vary depending on the regulations of the countries, with a cost of 150 €/ton, disposing of the blade materials would cost a total of 20403 € (fibreglass and epoxy combined). Thus new measures to effectively dispose of these materials should be investigated. A total of 704714 € can be recovered by selling the materials from Utgrunden OWF.

Table 7.2: Potential monetary value of materials that can be generated by the wind farm owner by selling the materials to recycling facilities. Materials arranged from highest to lowest value.

Materials	Monetary Value (EUR)
Cables	226194
Steel	215902
Foundations	176802
Copper	60001
Cast Iron	31134
Aluminium	11859
Magnet	3225
Epoxy	-5702
Fibre glass	-14701
Total	**704714**

The ranking of materials based on its criticality is displayed in table 4.5. The criticality is a measure of how a certain material is economically and strategically crucial for the European economy. The NdFeB magnets are the most critical material used in an OWF due to complete dependence on China for the Rare Earth Elements (REE) required for the magnets.

Recycling potential of the wind turbine is calculated by the equation 4.3. It portrays the percentage of the wind turbine that is recycled. With the recycling rates stated in the table 4.6 and the mass of materials shown in table 7.1, **the recycling potential of the wind turbine is 84%**. This indicates the fraction of wind turbine being recycled. With an increase in the recycling of fibreglass and epoxy, higher recyclability can be achieved, If the foundations and cables are included, **the recycling potential of the whole Utgrunden OWF is 67%**. This reduction in the percentage is mainly due to the foundation being left below the sea-bed.

CIRCULARITY POTENTIAL

The circularity potential for the Utgrunden OWF is calculated based on the method explained in chapter 5. The Utgrunden offshore wind farm operated for 18 years before being decommissioned, this duration is a bit less than the industry average of 20 year lifetime, thus the utility factor defined in equation 5.8 is 0.9 (18/20) in case of Utgrunden OWF. **The circularity potential as given by the Material Circularity Index (MCI) is 0.60 for the wind turbine** alone. This portrays that the material flow in manufacturing and disposing of the wind turbine is 60% of a fully circular system. If the foundations and cables are also taken into account, the MCI value of the whole OWF drops to **0.52**. This indicates the material flows of foundations and cables needs to be improved for higher circularity of the wind farm. The Vestas has included the MCI indicator as a circularity indicator in their LCA reports from 2017. The MCI calculated in Vestas reports is limited to wind turbine and uses aggregated data for a turbine as a whole. A MCI value of 0.62 for V120-2MW wind turbine functioning for 20 years is obtained [32] which is comparable to the MCI value obtained in this thesis.

LIFE CYCLE ASSESSMENT

A LCA of the Utgrunden OWF is conducted in the SimaPro software. The chapter 6 explains the process to carry out the LCA. The input parameters of the conducted LCA for various scenarios are stated in table A.2 in the Appendix. The input parameters include the mass of materials, recycling rates, reusing rates of components, and transportation distances that are used to model the LCA in SimaPro. The ReCiPe 2016 Midpoint (H) method is used to calculate the impacts on the environment. This method analysis the 18 impact indicators shown in figure 6.2. The results obtained from SimaPro for all these indicators are presented in figure A.8 in the Appendix. Out of these indicators, a few indicators relevant for this case study and which showcased higher variation in relation to scenarios and sensitivity analysis are selected. The indicators were also so chosen that they reflect on different aspects of the overall impact. The explanation of what these indicators actually measure is discussed below based on the ReCiPe method manual and LCA book [23, 115, 116, 35, 114]. The functional unit for this LCA study is defined as: *'1 kg of material used in a wind turbine, its foundation and cables of Utgrunden offshore wind farm located in west Sweden for its 18-year lifespan with a capacity factor of 34%'* The total environmental impacts of the OWF and in per functional unit (1 kg of material) are also stated in the following section

1. **Global warming potential**:
   The short-wave radiation from the sun is partly absorbed by the Earth's surface and partly reflected as infrared radiation. The reflected part is absorbed by Green House Gas (GHG) in the atmosphere resulting in warming of Earth. The global warming potential is calculated in carbon dioxide equivalents ($CO_2 - eq$) meaning the green house potential is given in relation to CO_2. This indicator measures the increase in these GHG expressed in $kg\ CO_2 - eq$. **The Utgrunden OWF, has a global warming potential impact of 3490** $ton\ CO_2 - eq$ **or 1.2** $kg\ CO_2 - eq/kg$**.**

2. **Freshwater eutrophication:**
   Eutrophication is the enrichment of nutrients in a certain place. In an aquatic environment, it is the emissions of phosphorus or nitrogen, leading to an increased biomass production of algae which results in the reduction of oxygen production, which results in fish dying. The freshwater eutrophication measures the fate of phosphorus (P) emissions in freshwater and expressed as $kg\ P - eq$. **The Utgrunden OWF, has a Freshwater eutrophication impact of 5367** $kg\ P - eq$ **or 1.8** $g\ P - eq/kg$ **.**

3. **Mineral resource scarcity:**
   With an increase in the primary resource extraction, the concentration of desired minerals in the ore (ore grade) decreases over time. This results in additional efforts for extracting the same amount of resources. The Surplus Ore Potential expresses the average extra amount of ore produced in the future caused by extraction of mineral resources. It is expressed as $kg\ Cu - eq$. **The Utgrunden OWF, has a Mineral resource scarcity impact of 150** $ton\ Cu - eq$ **or 50.5** $g\ Cu - eq/kg$**.**

4. **Marine ecotoxicity:**
   The Ecotoxicity potential aims to measure the damaging effects of chemicals on an ecosystem. It is based on the potential toxicity of a substance and its interaction with the potential target. The ecotoxicological effect represents the change in Potentially Disappeared Fraction (PDF) of species due to a change in the environmental concentration of a chemical. It is expressed in kg 1,4-dichlorobenzene-equivalents $kg\ 1,4 - DCB$. **The Utgrunden OWF, has a Marine ecotoxicity impact of 1367** $ton\ 1,4 - DCB$ **or 460.7** $g\ 1,4 - DCB/kg$**.**

5. **Human carcinogenic toxicity:**
   The human carcinogenic toxicity also represents the effect of chemical concentration on human health. It takes into account the emitted quantity of chemicals, their mobility and persistence and exposure patterns to humans. Human carcinogenic toxicity measures the risk increase in cancer disease incidence and is expressed as $kg\ 1,4 - DCB$. **The Utgrun-**

den OWF, has a Human carcinogenic toxicity impact of 1645 $ton\ 1,4-DCB$ **or 554.1** $g\ 1,4-DCB/kg$**.**

These impacts from the OWF are generated by separate components and processes namely Foundation, Tower, Cable, Rotor, Nacelle and Transportation. The figure 7.1 displays the percentage split between the components of the discussed impact indicators. The impacts displayed are including the benefits of recycling the materials, portraying the net impact of the component. The impacts of the selected indicators only from manufacturing the components are shown in figure A.9. In general transportation of materials form wind farm location to the recycling facilities do not have much impact on all the indicators. On the other hand, the foundations due to large mass have big impacts on certain categories.

The net impact on global warming is highest from the foundation accounting for 43% and 25% from rotor. However, if impacts from only manufacturing of these components are considered, the foundations correspond to 40% of CO_2-eq emissions (seen in figure A.9), followed by 20% emissions from tower, while rotor and nacelle correspond to 16% and 18% respectively. In the case of freshwater eutrophication, cables have the most impact accounting for 53%. This high impact is mainly due to the phosphate emissions by the 'sulfidic tailing' process of copper. The tailings are the materials left over after the process of extracting minerals from the ore. In the case of copper ores, these tilings can account for up to 95%, thus it poses a severe threat of leaking into the freshwaters. In the case of marine ecotoxicity as well, cables account for maximum share with 63% of the total impact. This is due to the emissions of zinc and copper through the same 'sulfidic tailing' in the process of manufacturing copper used in cables. Human carcinogenic toxicity impacts are dominated by foundations accounting for 73% and tower with 10%. This is due to emissions of chromium, nickel and lead in the manufacturing of steel used in the monopile foundations and tower. Mineral resource scarcity is mainly governed by the materials being recovered through recycling. The foundations correspond to 55% and the cables 27% of the total impact on mineral resource scarcity.

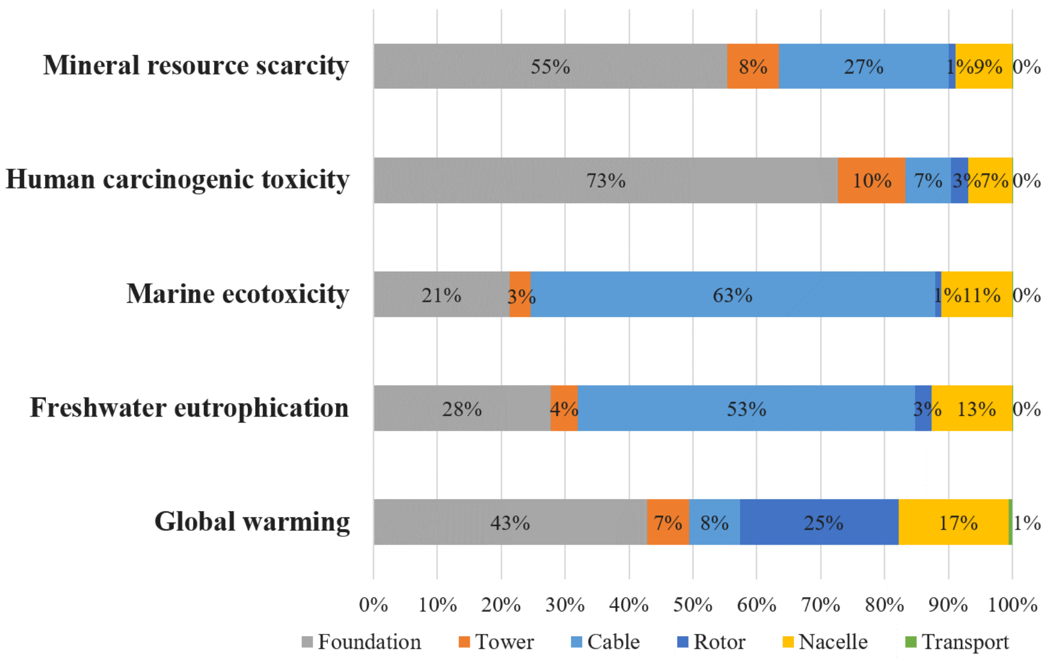


Figure 7.1: Environmental impacts of the different components of the OWF for baseline scenario. Results of the selected indicators obtained from SimaPro.

7.1.2. FULL REMOVAL SCENARIO

A full removal scenario was modelled to simulate the approach that could be undertaken by the wind industry in the near future. As at present, the monopiles are mostly removed from above the seabed, and removal of cables depends on the specific case and legal requirements. However, there might be regulations undertaken that allows no residue is left in the sea, (cable removal is now mandatory with exceptions in certain cases in Denmark). The full removal scenario focuses on complete removal of foundations and the cables. The scenario is built upon the input data of baseline scenario with only difference in the recycling rate of foundations and cables as below.

- Foundation recycling - 100%
- Cable recycling - 100%

The table A.2 shows all the parameters for this scenario.

Note: The environmental impacts of the removal process of foundation and cables are not included as the data of the processes are not available.

7.1.3. REUSE FOCUSED SCENARIO

This scenario focuses on the disposal of the components by reusing them instead of recycling the materials. Different components of the OWF can have a different remaining lifetime. A decommissioned wind turbine is dismantled at the port and some components can be reused with minimal or no extra effort. The individual components then can be used for a second-hand wind turbine. Older onshore wind turbines with low capacity are now resold at a lower price to the developing countries. The websites like Dutch wind and global wind market place allow for selling whole wind turbine and individual components [117, 118]. The changed parameters with respect to input data of baseline scenario are as:

Note: No extra process of repairing and converting these reusable components is considered. The reuse of a component is modelled as a reduction in equivalent material production.

- Reuse Rotor - 15%
- Reuse Nacelle - 15%
- Reuse Tower - 30%
- Reuse Foundation - 30%
- Reuse Cables - 50%

Note: The reuse of these components is considered only in case of wind farms, using these components for other applications is not modelled.

The reuse percentage values signify the fraction of the components from the OWF that can be reused again in manufacturing a wind turbine, the remaining part is recycled as per the baseline scenario. For example, 30% reuse of foundations signifies that for the whole wind farm, 30% of all foundations can be reusable, as it depends on the quality of the components. As the blades cannot be used again for a wind turbine due to the loads it has been acted upon, a lower percentage value is assumed, similarly due to the intricate design of the nacelle, 15% of reuse is assumed. Tower and foundations sections could possibly be used for a wind turbine, Cables have a lifetime of around 40 years, thus they could be reused for a different wind farm. The reuse percentage is changed in the 'reused content' parameter while calculating the MCI.

However, these are just estimates and no exact data on the percentage of components being reused is found. Thus, two further scenarios with high reuse and low reuse are modelled to see the effect of change in reusing percentage of components. The changed input parameters compared to the baseline scenario are stated below. In case of LOW reuse scenario, half of the reuse percentage is assumed, while a double the percentage of reuse is assumed in HIGH reuse. The 100% reuse of cables actually assumes that the same cables can be used for twice the lifetime of a OWF. The results of these two reuse scenarios are shown in figure **??** addressed in chapter 8.

LOW Reuse

- Reuse Rotor - 7.5%
- Reuse Nacelle - 7.5%
- Reuse Tower - 15%
- Reuse Foundation - 15%
- Reuse Cables - 25%

HIGH Reuse

- Reuse Rotor - 30%
- Reuse Nacelle - 30%
- Reuse Tower - 60%
- Reuse Foundation - 60%
- Reuse Cables - 100%

Note: The modelling is done only for a single reuse, how the components are disposed of after reusing is not modelled

7.1.4. SCENARIO COMPARISON

The figure 7.2 represents the results of the 5 important impact indicators and the MCI when compared with the baseline scenario. The comparison is done to give insights of the changes in disposal approaches. The value of the parameters corresponding to the baseline scenario is considered as a reference with 100%, the percentage variation in comparison with baseline scenario is observed from the figure. The comparison of the scenarios with 18 impact indicators is shown in the figure A.10 in appendix. Overall the impacts of full removal scenario have big reductions in the impacts in which foundation dominates the category. The reduction in impacts in the full removal scenario is due to the increase in the quantity of steel in monopile foundations being recycled. On a component level, the impacts from foundations reduced and an increase in the impacts of transportation was seen due to increased material to be transported in the full removal scenario compared to the baseline. The reuse scenario has lower impacts on the indicators which are mainly caused by the cables. Freshwater eutrophication and marine ecotoxicity impacts are lower for reuse scenario due to an increase in reuse of the cables. A big difference is observed in the human carcinogenic toxicity with very low impact in the full removal scenario due to steel recycling benefits. The full removal scenario gives marginally better wind farm circularity compared to the reuse scenario. The MCI of the wind farm is 0.65 in case of full removal and 0.64 in reuse scenario. The variation in the MCI with different reuse scenarios is addressed in the chapter 8. The processes of removal of the components are not considered in this thesis due to data unavailability, however, these process in reality can have some environmental impacts, thus the impacts of the full removal scenario could be higher than the obtained result.

Note: Detailed assessment of the removal process of the structures should be carried out to

select the sustainable alternative.

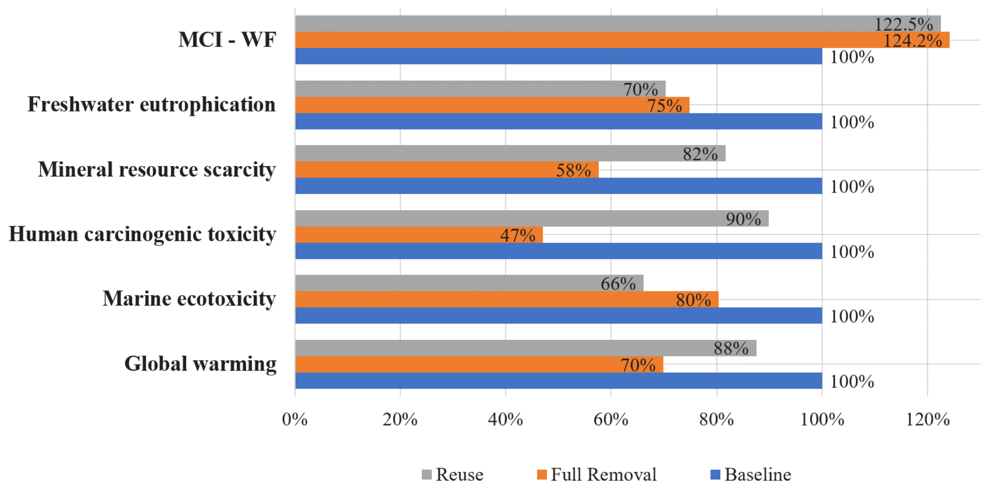


Figure 7.2: Comparison of the scenarios with the baseline scenario as a reference with 100%. Full removal scenario giver marginally better circularity. Reuse scenario has lower impacts in Freshwater eutrophication and marine ecotoxicity compared to the full removal scenario.

7.2. SENSITIVITY ANALYSIS

The uncertainty in the modelling is addressed through sensitivity analysis in this section. As the thesis was based on gathering data through literature reviews, the uncertainty in the collected data is also checked. Sensitivity analysis of the following input parameters is seen relevant.

7.2.1. MASS OF MATERIALS IN AN OWF

As the data of the mass of the materials were collected through the LCA studies published, and a curve fitting model was developed on top of it, the mass of materials is seen to have uncertainty. Also, the LCA reports have been published online and might not accurately state the mass of wind turbine. Thus to account for these uncertainties, a sensitivity analysis with a mass of all the materials in each component of the wind farm is conducted. The mass values with an increase of 20% and a decrease of 20% compared to the baseline mass of materials are considered.

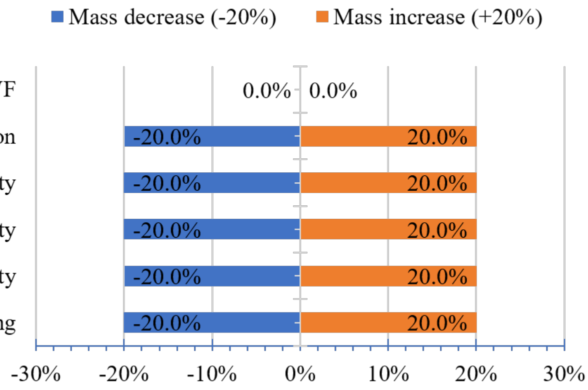


Figure 7.3: Sensitivity of the impact indicators and circularity, in the baseline scenario with a change in the mass of materials. Note that MCI is independent of the mass

The figure 7.3 shows the sensitivity of the selected 5 impact indicators and MCI with respect to a change in the mass of materials. All the impact indicators vary in the same direction with a change in the mass. With a reduction in mass of materials by 20%, all the emissions reduce by 20%. It should be noted that the MCI does not have any impact on a change in the mass. This is because, MCI measures the circularity, which is based on the material flows, so even with the changes in the mass going through the system, the flow remains same, giving the same MCI value.

7.2.2. EFFICIENCY OF RECYCLING

The efficiency of the recycling process depends on the quality of the input materials, and the process used. The recycling efficiency is particularly important in the developed LCA model, as it the fraction of the recycled material that substitutes the primary production of the material. With the advancements of technology, the recycling efficiencies of the process can increase. Sensitivity analysis is performed with an increase and decrease of 5%, compared to the baseline scenario (baseline $\pm$ 5%). In case of MCI calculations, as there are two efficiencies E_C and E_F corresponding to recycling process efficiency and efficiency of making recycled content, 2.5% is added or subtracted for a net result of 5% variation.

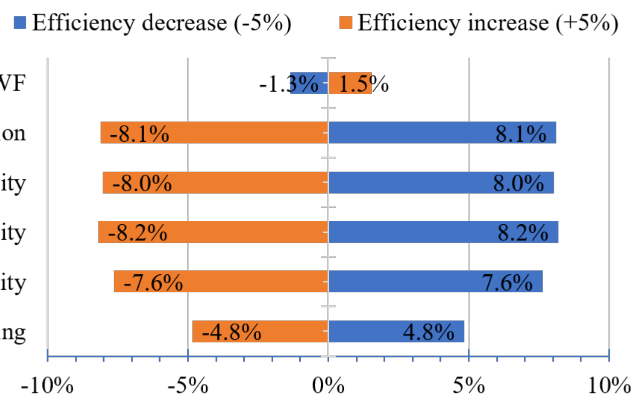


Figure 7.4: Sensitivity of the impact indicators and circularity, in the baseline scenario with a change in the efficiency of recycling materials.

The impact categories are sensitive to a variation in recycling efficiency. As seen from figure 7.4, the indicators vary around 8% with a 5% change in the recycling efficiency. Thus effort should be given on improving the recycling efficiencies of the processes. The change in the recycling efficiency value had less impact on the MCI value.

7.2.3. TRANSPORT DISTANCE

The transportation of materials and components from the OWF site to the nearby port and from the port to the recycling facility changes with respect to location. In future, a centralized high-tech dismantling and recycling facility could be built where the components are disposed of efficiently. Also, the wind farms would be built with a larger distance from shore. Thus a sensitivity is conducted on transportation distances. The distance from port to the recycling facility in the baseline scenario is assumed to be 100km, a 10 times increase in this distance is assumed to see the effects. Also, the distance from shore to the OWF is 5km, which is also increased by 10 times. On the other hand, sensitivity with half the distance from the port to the recycling facility is considered (50km), the distance of OWF from shore is kept the same (5km).

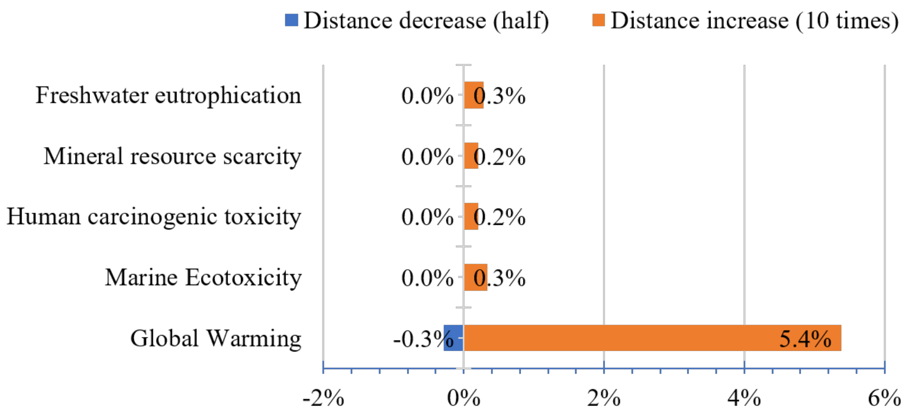


Figure 7.5: Sensitivity of the impact indicators in the baseline scenario with a change in the transportation distance from OWF to recycling facility.

Effect of change in the transportation distance is negligible. Global warming has a relatively large variation with a 5.4% increase, with 1000% increase in the transportation distance.

7.2.4. OPERATIONAL LIFETIME

The wind farm owner tries to maximize the operational lifetime of the OWF]. In the case of Utgrunden OWF, it was decommissioned after 18 years, which is considered in the baseline scenario. The experiences of the previously decommissioned OWF (shown in table 3.1) shows a big variation in the operational lifetime. Yttre Stengrund OWF was decommissioned after 15 years and Blyth was decommissioned after just 13 years of operations, however, on the other hand, Vindeby was decommissioned after 26 years. As the wind industry is moving towards increasing the lifetime of the OWF a sensitivity analysis with 15 and 30 years of operational lifetime is considered. The variation in the operational lifetime is incorporated as a change in the utility factor 5.8 while calculating the MCI. As the average lifetime of the wind turbine is considered as 20 years, a 15 year lifetime leads to a utility factor of 0.75 (15/20) and a lifetime of 30 years results in utility factor of 1.5 (30/20). In case of the LCA impacts, the lifetime of the OWF changes the electricity produced by the OWF throughout its operational phase. Thus the impact indicators are calculated in terms of per kWh externally (in Excel sheet), to take into account the variation in the lifetime. The emission values in per kWh are calculated by dividing the impact values with energy produced in the lifetime of the OWF as shown in the equation below.

$$Impact\ per\ kWh = \frac{Impact}{8760 * No\ of\ WT * Capacity(kW) * Capacity\ factor * Lifetime}$$

This results in a global warming potential of 6.2 $g\ CO_2 - eq/kWh$ for the baseline scenario. Similarly, other indicators are calculated and the variation is shown in figure 7.6.

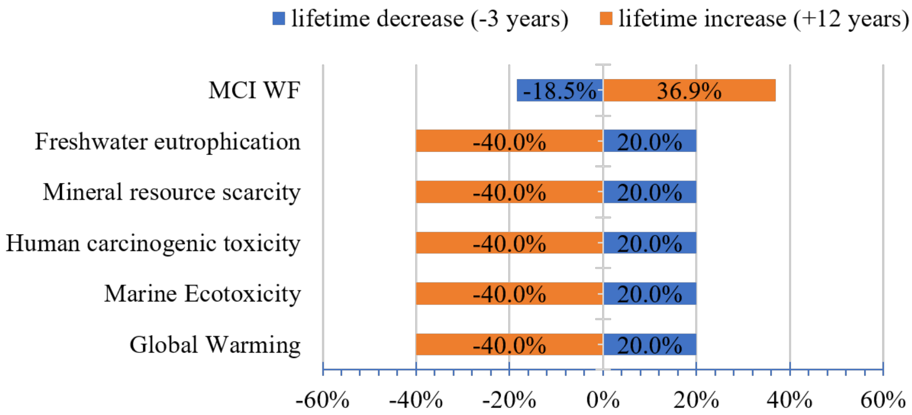


Figure 7.6: Sensitivity of the impact indicators and circularity, in the baseline scenario with a change in the operational lifetime of the OWF. The baseline lifetime is 18 years

The figure 7.6 shows the big impact of the change in the operational lifetime of the OWF. The impacts decreased by 40% when the lifetime was increased by 12 years (66% increase compared to baseline of 18 years). Increase of 20% in the impacts was observed with a reduction of lifetime (16% decrease in lifetime compared to baseline of 18 years). Thus, a reduction in lifetime has large life cycle impacts. Change in impacts is due to the fact that longer the wind farm is in operation, it produces renewable electricity, thus the overall impacts from the manufacturing phase of the wind farm is relatively reduced because of higher electricity production. Also, the circularity increased with an increase in the operational lifetime. This is because in terms of CE, extending the lifetime is equivalent to a reduction in wastes and resources consumed during that extended period. The impact indicators reduced by 20% when the lifetime was decreased by 3 years (16% decrease compared to baseline 18 years). This shows that a reduction in a lifetime is more sensitive. Thus the wind farm owner should implement means to extend the operational period of the OWF.

The main results of ranking the materials used in case study of Utgrunden OWF, its recycling potential and circularity potential indicated by MCI and the LCA of different scenarios is presented in this chapter. The results related to the first three research objectives are mentioned in this chapter. The next chapter further discusses the key ndings and their potential implications for the future decommissioning of offshore wind farms.

8

Discussion

This chapter further discusses the key results presented in the previous chapter. The full tool developed in this thesis to give the materials used in an Offshore Wind Farm (OWF) and calculate its recycling and circularity potential and complement it with Life Cycle Assessment (LCA) impact is addressed. The fourth objective of the thesis, which is to recommend the practices and measures while decommissioning, is fulfilled in this chapter.

8.1. Integrated Excel Tool

A tool was developed in this thesis that allows a wind farm owner to enter the OWF specifications and get the split of materials used in a wind turbine and its foundations and cables with several parameters of the materials like the mass, monetary value, recycling rate, climate impact, and criticality. The tool calculates the recycling potential and circularity potential of the selected OWF and provide an estimate for its impact on the environment.

The figure 8.1 shows screen-shot of the main page of the tool. The values presented are for the case study of Utgrunden OWF. The dialogue box on the top left-hand side allows the user to select the specifications of the OWF in consideration, by choosing the number of wind turbines, their capacity, rotor diameter and hub height. The capacity factor of the OWF the operational lifetime and average distance from shore can also be selected. The user can select the average source of materials coming from either recycled materials or reuse of components for a wind turbine as a whole, to give the circularity estimate of the wind turbine, for a detailed circularity assessment values of each material should be changed. The pie charts illustrate the quantity of materials used in a wind turbine and quantity of each component in a wind farm. The output values at the bottom right represent the recycling potential and circularity of the wind turbine and wind farm.

Note: As most of the data gathered for mass of materials mainly correspond to wind turbines up to 5MW capacity, this tool should not be used to predict the mass of materials in larger wind turbines (>5MW).

Analysis of materials in an OWF with respect to various parameters like mass, monetary value, Green House Gas (GHG) emissions and criticality has highlighted the importance of materials under different parameters. Due to the high percentage of quantity of steel used in an OWF, and high potential economic benefits, steel is an important material for the wind farm owner. Magnets comprising of Rare Earth Elements (REE) exhibit very high climate impacts, also they are a highly critical resource due to huge supply risks and have a high monetary value. Thus, more research on recycling of magnets to get recycled material to reduce the supply risks, reduce climate impacts, and gain monetary value should be carried out in the future. The cables used in the OWF contains valuable copper and have high monetary value potential, so the cables should be removed from the seabed and further research on recycling cables is required. Also, the cables dominate the impact indicators obtained from LCA, thus extra attention should be given on cables. Lastly, the fibreglass and epoxy which are mainly used in blades should be further researched to dispose of sustainably. This is of particular importance to change the image of wind turbines to a fully ‘green alternative’.

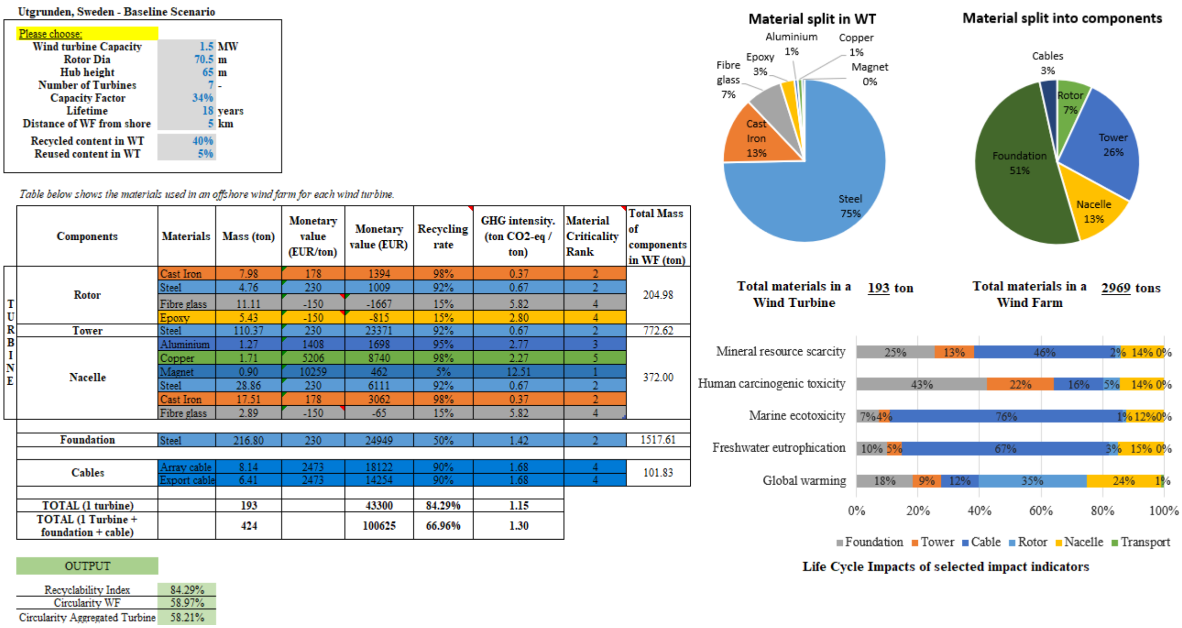


Figure 8.1: Main page of the tool developed showing different parameters of each material (mass, monetary value, GHG intensity, criticality, recycling rate), circularity potential of the Wind farm and environmental impacts. The values presented portray the case study of Utgrunden OWF.

The figure 8.2 shows the circularity potential given by the MCI for the assessed scenarios and extra reuse scenarios. The circularity is calculated for a wind turbine and also for the whole wind farm. MCI value of 0.52 is obtained for the wind farm in the baseline scenario. When all its foundations and cables are removed, the MCI increases to 0.65. This is because the quantity of materials in the foundation and cables, is now recycled and not lost from the system. In the reuse scenario, the circularity of the wind turbine calculated is 0.69 while that for the wind farm is 0.64 which is marginally lower than the full removal scenario. However, the two reuse cases highlight the variation in the MCI due to a change in the component reuse percentage. With half of the reuse fraction in the ‘Reuse LOW’ case, the MCI for wind farms is 0.57, while by doubling the percentages in ‘Reuse HIGH’ case MCI for wind farm reaches 0.78. Thus, recycling the components after use can be seen as lower hanging fruits, however, variation in the reuse leads to a big change in the circularity. Thus, the focus should be to reuse the components whenever feasible which is inline with the CE principles.

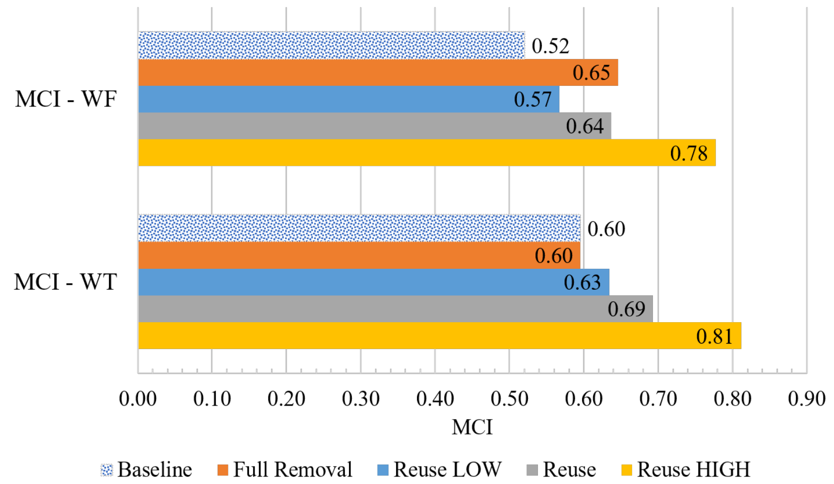


Figure 8.2: Circularity of a wind turbine (WT) alone and wind farm including wind turbine and its foundation and cables (WF) for different scenarios and Reuse cases

The figure 8.3 shows the LCA results and the MCI value for the reuse cases. The 'Reuse LOW' and 'Reuse HIGH' cases assume half and double of the reuse percentage values of the Reuse scenario respectively, as defined in the previous chapter. The impacts of one reuse cycle are accounted for by a reduction in the material required for manufacturing a reused component. A higher reuse percentage offers lower impacts in all the categories. The cables which dominate certain impact indicators, if reused for one more lifetime of the OWF, they reduce marine ecotoxicity and freshwater eutrophication by 50%. A higher reuse of components is preferred, however, it poses challenges in the feasibility of reusing the same component in a technologically advanced product and interchangeability with other manufacturers of wind turbine. Thus, initially designing the product with better reusability is required in future.

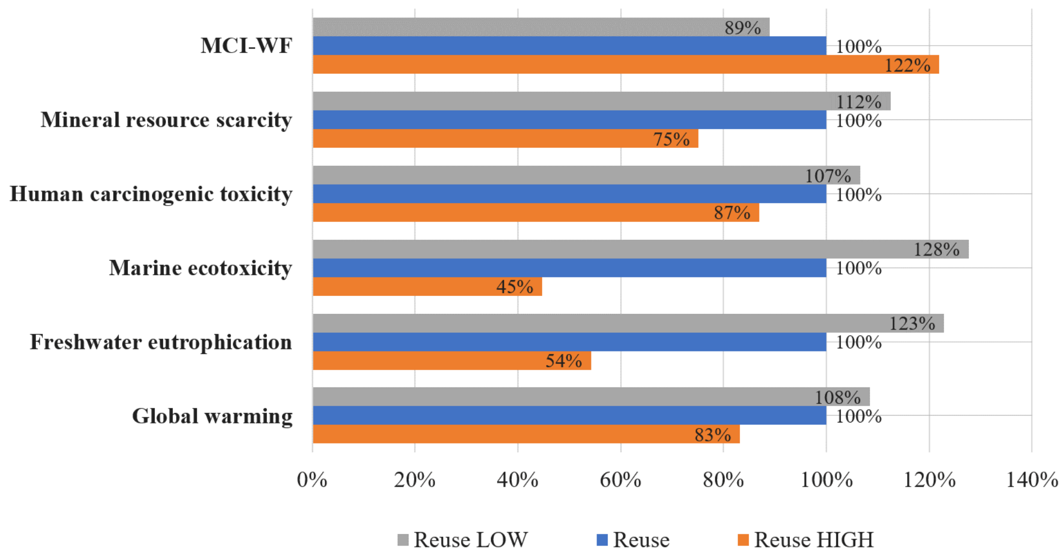


Figure 8.3: Comparison of the reuse cases (Reuse LOW and Reuse HIGH) with the reuse scenario. Impact indicators and MCI show that a higher reuse percentage is preferred.

The lifetime of the product has a big impact on the circularity and life cycle impacts. The figure A.5 in appendix shows the changes in the MCI value with a variation in the utility factor. The utility factor is calculated as shown in equation 5.8. Assuming a same intensity of use as an average product, changing the operational lifetime of the wind farm, has a big impact on the circularity. If the lifetime drops to 10 years the MCI drops to 0.14, and if the lifetime is doubled (40 years), it reaches 0.78. The MCI value has a steep variation with the utility factor close to 1, thus the wind farm owner should try to increase the operational lifetime of the OWF. Also, the environmental impacts of the OWF reduce with a change in the lifetime, this is because the emissions through the manufacturing of the wind turbine are negated with clean electricity generation of the wind turbine in its use phase. The $CO_2 - eq$ emissions of the modelled case study of the Utgrunden OWF for its 18 years of operations are 6.2 $kg\ CO_2 - eq/kWh$, if the OWF was decommissioned in 15 years instead the emissions would be 7.4 $kg\ CO_2 - eq/kWh$ and with 30 years of operation (no extra life time extension processes modelled) the emissions reduce to 3.7 $kg\ CO_2 - eq/kWh$. Thus, the wind farm owner should prolong the operation phase of the OWF mu taking corrective measures.

In order to improve the Circularity performance of the OWF the following changes should be implemented:

- Extend or optimize the turbine lifetime.
- Increase repairability and reusability of the components and design the components with a design for end-of-life perspective
- Increase the recycled-content of materials used in a wind farm
- Substitute the materials with higher recyclable materials if feasible
- Improve the efficiency of recycling processes

TheLCA results of the Utgrunden OWF converted in per kWh and per kg values for all the impact indicators are presented in the table A.3 in appendix. These values were calculated externally in the excel using the results from SimaPro. These values are commonly presented in the literature and thus offers a point of comparison. The results obtained are in a similar range as found in the literature. The $g\ CO_2 - eq/kWh$ for the modelled case study is 6.2 $g\ CO_2 - eq/kWh$ and the studies show a variation of 6.4 to 12.3 $g\ CO_2 - eq/kWh$ for the full life cycle of the offshore wind farm [119]. Also, the CO_2 emissions obtained per kg of material is 1.2 $kg\ CO_2 - eq/kg$. This means that using each kilogram of material emits 1.2 kg CO_2. This value obtained is also close to the value of 1.35 $kg\ CO_2 - eq/kg$ found in the literature [56]. The difference in the values could arise due to impact assessment method used and also these studies assess the full lifecycle of the OWF. The conducted study models the manufacturing and disposal phase of the OWF. Overall, the disposal phase has a huge potential in reducing the impact of the OWF. In the modelled case study, the disposal phase can reduce the impacts from manufacturing phase between 40% to 60%. The CO_2 emissions from manufacturing all the components reduced by 46% when benefits due to disposal (recycle and reuse) were considered. A LCA review paper by Davidsson indicates a reduction of 43% in CO_2 emissions when considering the disposal of materials [28]. Thus, the modelling done in this thesis focusing on the manufacturing and disposal phase of the OWF is fairly accurate and presents opportunities for further development.

8.2. RECOMMENDATIONS ON DECOMMISSIONING AND DISPOSING COMPONENTS

Based on the results obtained, approaches to decommission and dispose of the OWF are recommended by the author. Decommissioning of the structures depends on the size and quality of them, hence a standard procedure could not be used for all the OWF. The main structures to be decommissioned are wind turbine, foundations, cables and offshore substation. Before actual decommissioning of the components, an inspection of the structure to ensure the safety should be done. The decommissioning process then follows the prepared plan, approved by the authorities.

8.2.1. WIND TURBINE

Complete wind turbine needs to be removed from the site. The process starts with de-energising and isolating the turbine from the grid. The turbine components are dismantled onshore to reduce the risks of oil spillage and to reduce time and hence the costs of offshore operations. The offshore wind turbine can be removed with various steps, taking down individual blades, whole rotor or lifting the turbine as a single structure should be preferred if feasible. With advancements in the vessel's capabilities, older wind turbines (smaller) can be removed with a single heavy lift operation. After the removal of the turbine, it should be disassembled onshore. If the wind turbine can be made functional after replacing a few components, the whole turbine can be sold for second-hand use purpose. The advantage of buying a second-hand wind turbine is low cost and less waiting time. However, more research should be done on assessing the remaining lifetime of the turbine. The individual components are dismantled and can be disposed of as follows.

TOWER

The steel in the tower represents about 26% of the total mass in an OWF. The tower sections should be checked for any cracks and the sections can be used in remanufacturing a wind turbine tower or can be used as a supporting structure for other applications. If not, being made from steel, they can be easily recycled. Also, substituting the steel with other sustainable materials is also gaining traction. Recently in May 2020, Modvion a Swedish company installed a 30m wooden tower [120].

NACELLE

The Nacelle of a wind turbine contains several materials, thus it is difficult to dismantle and segregate, The motor and gear oils should be carefully collected and can be incinerated for energy recovery. The electronic components include hazardous materials that need specialized disposal. The electronic components should be tested and if possible repaired or refurbished to use for other applications. If reuse of the components is not possible, the recycling of the electronic components according to the regulations should be carried out.

- **Magnets:** The neodymium-iron-boron magnets (NdFeB) contains the Rare Earth Elements (REE) like dysprosium and neodymium. As discussed before, these elements have a large environmental impact and are also considered as a critical resource thus special focus on recovering these REE should be given. The permanent magnets from the generator should be separated and the usable magnets can be reused after magnetization process. The recycling of the permanent magnets requires more research into developing a commercially scalable technology. Different treatment methods like demagnetization by thermal heating, hydrometallurgy involving dissolving magnets in solutions to recover REE or converting the magnets into powder and sintering. it into a magnet are in the research phase [121].

BLADES

The wind turbine blades still do not have a commercial mass scale solution and disposing of the blades are a top priority for the wind industry. The blade waste will represent only 10% of the total thermoset composite waste by 2025 [97]. However, the emphasis from the wind industry for better disposal is to maintain a clean image of wind turbines to make them a fully 'green alternative'. Reusing the blades for wind turbines is limited due to the deterioration in the quality after their lifetime. However, the blades present ways to remanufacture and re-purpose for other applications. The blades can be used to build bridges, public benches, house roofs, playgrounds, noise insulation barriers, precast concrete material and bike sheds. The figures 8.4a and 8.4b show examples of repurposing of wind turbine blades.

(a) Decommissioned blades used as bike sheds installed in Aalborg, Denmark. Source: [97]

(b) Decommissioned blades re-purposed for kids park. Source:[97]

The energy recovery process of burning in cement kilns which is mostly carried out at present lacks the ability to recover the fibres. More focus on commercial scale applications for pyrolysis and solvolysis process to recover the fibres in the blades is necessary. As the recycling of composite materials poses difficulties, a sustainable design approach in manufacturing blades should also be undertaken. Further research into making blades from other high-performance materials that are easily recyclable is required.

8.2.2. FOUNDATION

The monopile foundations can be either completely removed or are cut a few meters below the seabed and the rest part is left in-situ. Fully removing the foundations has shown the potential environmental benefits by recovering the metals. However, currently the process of cutting the foundations up to the seabed is preferred, as it reduces the risks and does not harm the marine environment. However, leaving the foundations in the seabed results in permanent loss of materials, also the area turns unfit for installation of any other OWF in the same location. The foundations can be fully removed by vibrating the foundation column and lifting at the same time. Measure should be taken to not harm the marine environment by means of isolating the removal process. Thus, more research is required to implement sustainable removal processes. After the removal of the foundations, the hole needs to be landfilled. The whole foundation if feasible can also be reused as a base for upcoming technologies like Airborne Wind energy systems. These systems harness the wind at high altitudes with the help of kites. They are lighter in weight compared to wind turbines thus the reuse of foundations could be feasible for these technologies.

8.2.3. CABLES

The cables include both the array and export cables, they are generally buried into depths of more than 1 meter below the seabed. If repowering is considered, the same cables might be used due to their long lifetime. However, it depends on the technology and capacity of the wind turbines. The cable ratings also depend on the wind turbine capacity. The full removal of the cables causes damage to the environment, however, the benefits from recycling the cables are also evident, thus the cables should be excavated from the seabed by implementing sustainable measures. Further increase in the recycling efficiency of the cables due to plastic content needs to be researched.

8.2.4. OFFSHORE SUBSTATION

The offshore substation can be divided into two parts, the topside consisting of all the electrical equipments, and the foundation. The topside should be decommissioned as a single structure and should be disassembled onshore. The components then can be checked for possible repair and reuse. Foundations can be removed similar to the method of removing the foundations of the wind turbine.

As the decommissioning happens roughly 25 years after the OWF installation, there is inherent uncertainty in proper disposal of the OWF taking place. However, the regulations and environmental and monetary potential evident from this thesis should ensure that sustainable decommissioning of OWF occurs.

8.3. RECOMMENDATIONS ON MODELLING

The modeling to calculate the circularity potential by using MCI and assessment of environmental impacts by LCA study was carried out in this thesis. As extensive modelling focusing on decommissioning and disposal has not been thoroughly researched, the process posed certain challenges in this thesis. Recommendations on modelling based on author's experiences are given as follows:

<u>Circularity Modelling</u>

- Consider modelling for each material to increase the level of detail
- Model the reuse at a component level and recycling at material level

<u>Life Cycle Assessment Modelling</u>

- Choose the appropriate systems approach to take into account recycling (cut-off recycled content or allocation at point of substitution (APOS))
- Model empty processes and empty scenarios (without any impact) to represent certain materials not treated and satisfy the mass balance in SimaPro
- Run multiple scenarios and sensitivity analysis and to see the variation in different indicators and components and critically assess the results

9 CONCLUSION

With an expected surge in the installations of new Offshore Wind Farm (OWF) and due to the current ageing fleet, the decommissioning and disposing of the components in the OWF will soon increase dramatically. Currently, there is only limited practical experience in decommissioning the OWF. There is an urgent need to introduce improvements in handling the decommissioned OWF to further increase the sustainability of the wind farms. This offers opportunities for applying new concepts like Circular Economy (CE) for effective decommissioning and disposal. Further, assessment of the environmental impacts of the measures undertaken is essential to give insights into its sustainability.

A methodology to link the materials used in an OWF with the circularity and life cycle impacts of the OWF was developed in this thesis. This work fills the current research gap of a detailed circularity assessment with life cycle impacts in the decommissioning phase of an OWF. To fulfil the overall objective of this thesis, an interactive excel tool was developed that lists the materials used in a wind turbine, and the foundations and cables depending on the specifications of the wind farm selected by the user. The tool further calculates the circularity and recycling potential of the OWF and its environmental impacts, modelled through the Life Cycle Assessment (LCA). The tool allows the user (wind farm owner) to insert the specifications of the OWF into consideration and get the overview of recycling and circularity potential and environmental impacts of the OWF. The results obtained from the developed tool are discussed for a case study of Utgrunden OWF, consisting of 7 wind turbines (Enron Wind 70/1500) with 1.5 MW capacity, which were decommissioned in 2018. The following paragraphs reiterate some of the obtained results for Utgrunden OWF.

The first objective of this thesis of *Development of a tool to rank the materials in an offshore wind farm based on its mass, monetary value, criticality and climate impact*, was addressed by gathering the required data and modelling it in the tool. This process made evident the prominence of different materials under the assessed parameters. The steel is the most used material with 85% by weight of the whole OWF. Due to its quantity and high recyclability, steel can generate 215902 € by selling it as scrap. Also, cables (both array and export) pose a high potential of economic value around 226194 €, gained by recycling them. The NdFeB magnets used in generators of some wind turbines, due to the presence of Rare Earth Elements (REE), are the most critical material used in an OWF. The criticality signifies how a certain material is economically and strategically crucial for the European economy. Also, due to the manufacturing process of REE, the magnets pose high environmental impacts and emit 12.1 $kg\ CO_2/kg$.

The circularity potential of the OWF was calculated by Material Circularity Index (MCI) to fulfil the second objective of *Assessment of circularity indicators and calculating the circularity potential of the OWF*. A detailed circularity assessment based on individual material flows was conducted. The circularity potential for the Utgrunden OWF was **0.52**, indicating the material flows are 52% of a fully circular system. Different scenarios modelled portraying full removal of structures and reusing components found the MCI value increased to 0.65 and 0.64 respectively. Increasing the reuse, higher recycling of materials and extending the lifetime was found to be possible ways to improve the circularity of the OWF. Based on the recycling rates of the materials, the recycling potential of the wind turbine is **84%** indicating the fraction of materials that are currently recycled and that of the whole OWF is **67%**.

The Life Cycle Assessment (LCA) modelling in SimaPro focusing on disposal of OWF was conducted to meet the third objective, *Assessment of the environmental impacts of the OWF*. The results from the LCA study gave further insights into the material flows complementing the circularity indicator. The results obtained from SimaPro were then processed and linked to the developed tool. The net climate impact of **1.2** $kg\ CO_2 - eq/kg$ material or **6.2** $kg\ CO_2 - eq/kWh$ of the OWF was obtained. Comparable environmental impact from full removal and reuse scenario was obtained.

The final objective of *Recommendation of practices and measures while decommissioning and disposing the OWF* was based on the results obtained through this thesis. The scenarios performed gave insights into the potential of reusing the components. This objective shows the OWF owner a scope for improvement in the decommissioning phase to recover monetary and environmental benefits. The components can be reused in other wind turbines or repurposed for other applications. The components should be designed for better repairability and reusability keeping the end-of-life phase in mind. A special focus on blades, cables, steel and magnets should be given as they are prominent materials based on different parameters. Waste should be handled effectively to improve the image of wind turbines to be a fully 'green' alternative.

9.1. FUTURE WORKS

The thesis successfully establishes a methodology to link together the topics of decommissioning, circular economy and life cycle assessment. This thesis work can be further expanded to consider the complexities of these topics. The data used for the mass of materials corresponded to wind turbines up to 5MW, thus to be able to model the larger turbines that will be decommissioned in future, updating the data to include larger turbines is required. Further, a split between the wind turbine technology as either geared and direct drive should be taken into account for more accuracy in the mass of the materials. The offshore substation should be considered for full representation of the OWF.

Further research into complexities in the multiple use of components and a clear distinction between downcycling and upcycling should be done for calculating the circularity. Also, research to capture a more holistic view of CE with refurbishment and repurposing of the component and the environmental impacts of the processes and economic value should be conducted. LCA of the decommissioning processes with lifting and cutting of the structures should be modelled for accurate comparison of different disposal scenarios. Also, defining the disposal processes into global LCA databases should be done to prevent misinterpretations. Particularly the recycling processes for the blades needs to be developed in the databases. Also, updating the licence of SimaPro to facilitate linking with excel tool and making the process more dynamic should be considered in future.

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A

APPENDIX

A.1. HISTORICAL SCRAP PRICES OF MATERIALS

The scrap market prices varies depending on the supply and demand of the material and other factors. The graphs below show the historical prices in USD/ton for 3 years from June 2017 to June 2020.

Figure A.1: Historical scrap market prices from June 2017- May 2020 of Steel from London Metal Exchange

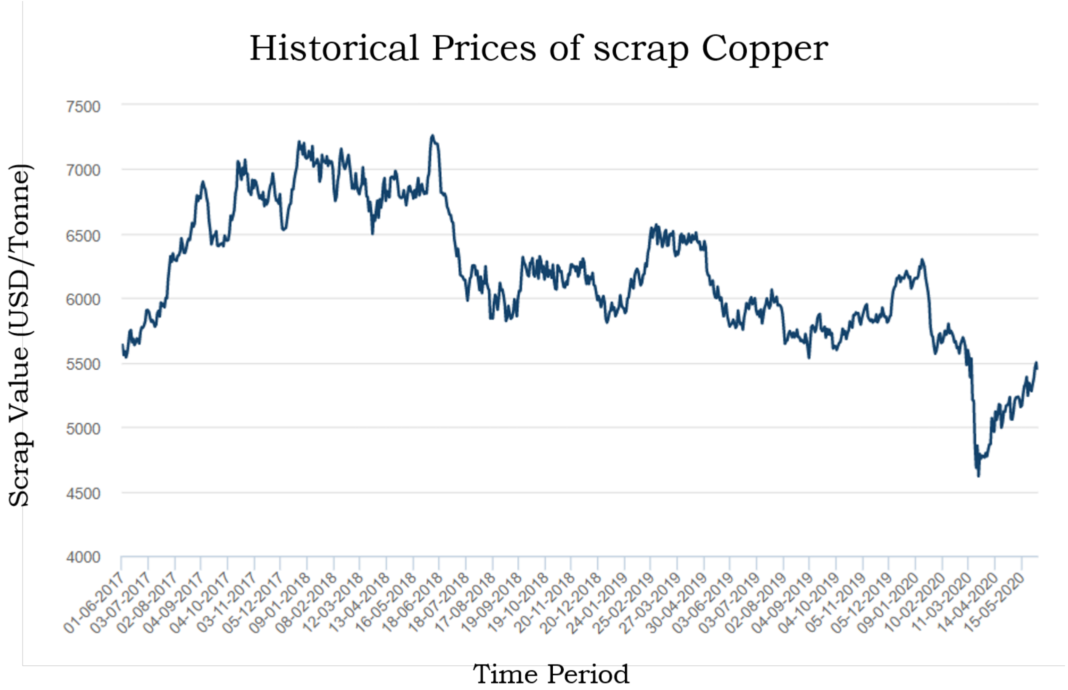


Figure A.2: Historical scrap market prices from June 2017- May 2020 of Copper from London Metal Exchange

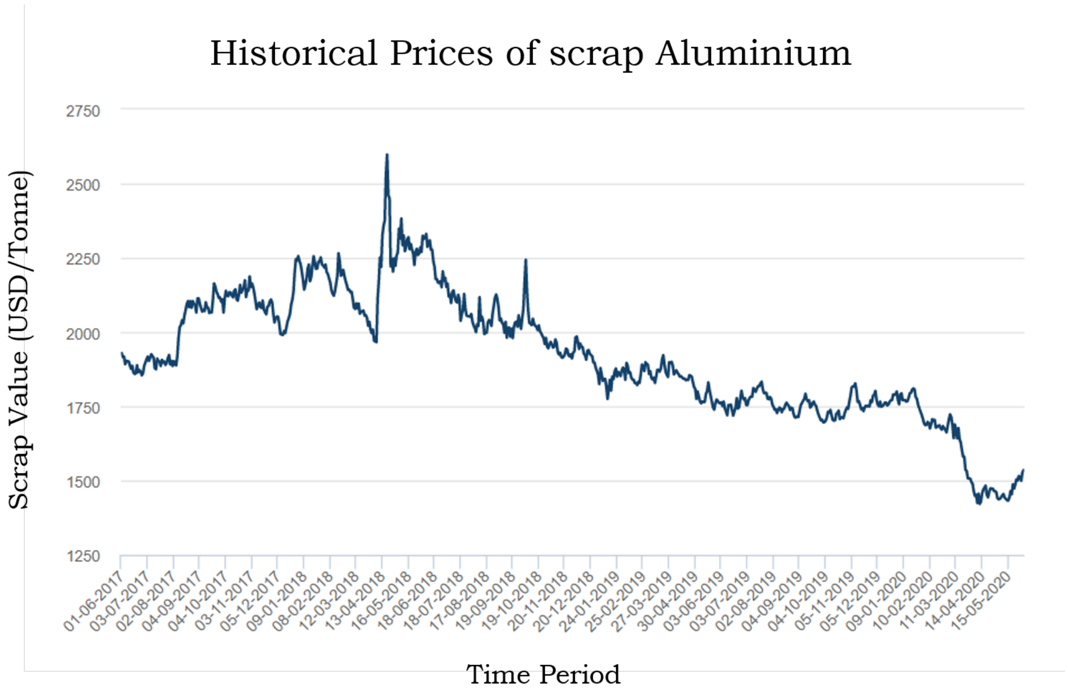


Figure A.3: Historical scrap market prices from June 2017- May 2020 of Aluminium from London Metal Exchange

A.2. CIRCULARITY

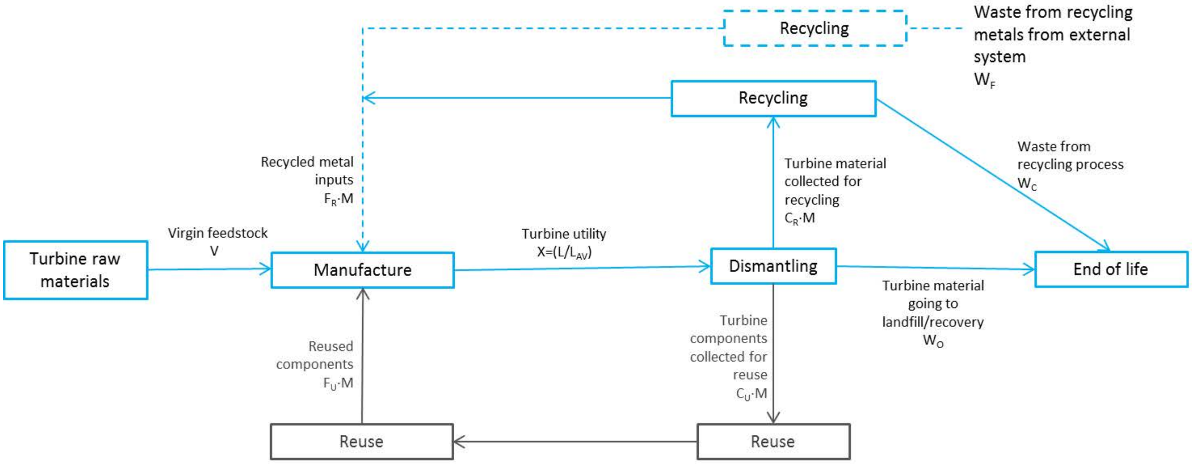


Figure A.4: Diagrammatic representation of the flow of materials in a wind farm construction and disposal as depicted in Vestas published LCA studies [35]

The figure A.4 shows the material flow in a system and mentions the formulae to calculate the circularity potential according to the Material Circularity Index (MCI).

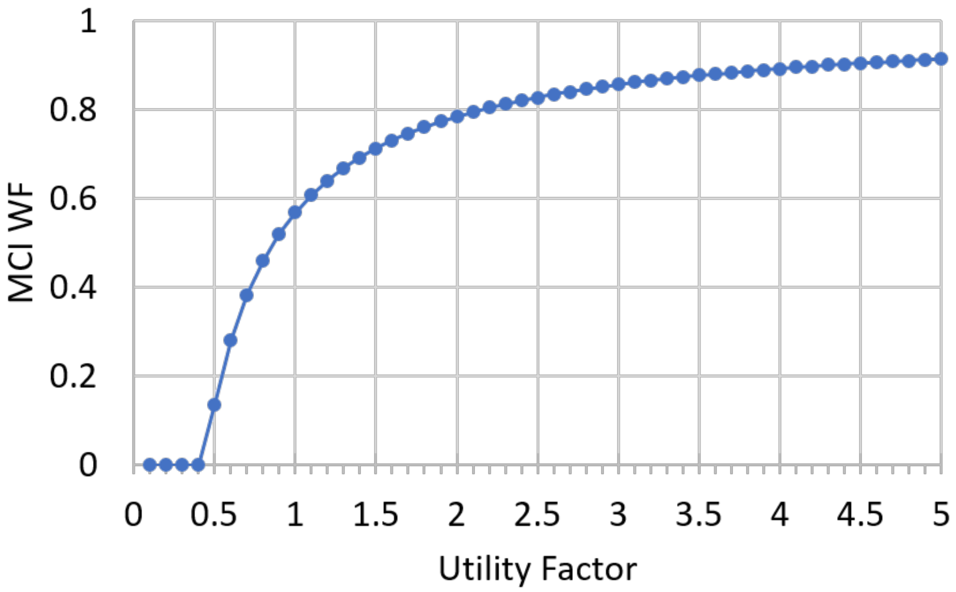


Figure A.5: Variation of the MCI with changes in the product lifetime or the utility factor. Note that minor change around average product life has a big impact on circularity.

The figure A.5 shows the results of varying lifetime of the OWF from 10 years to 100 years. Increasing the lifetime increases the circularity of the OWF and effort should be taken to keep the OWF in operational phase for longer.

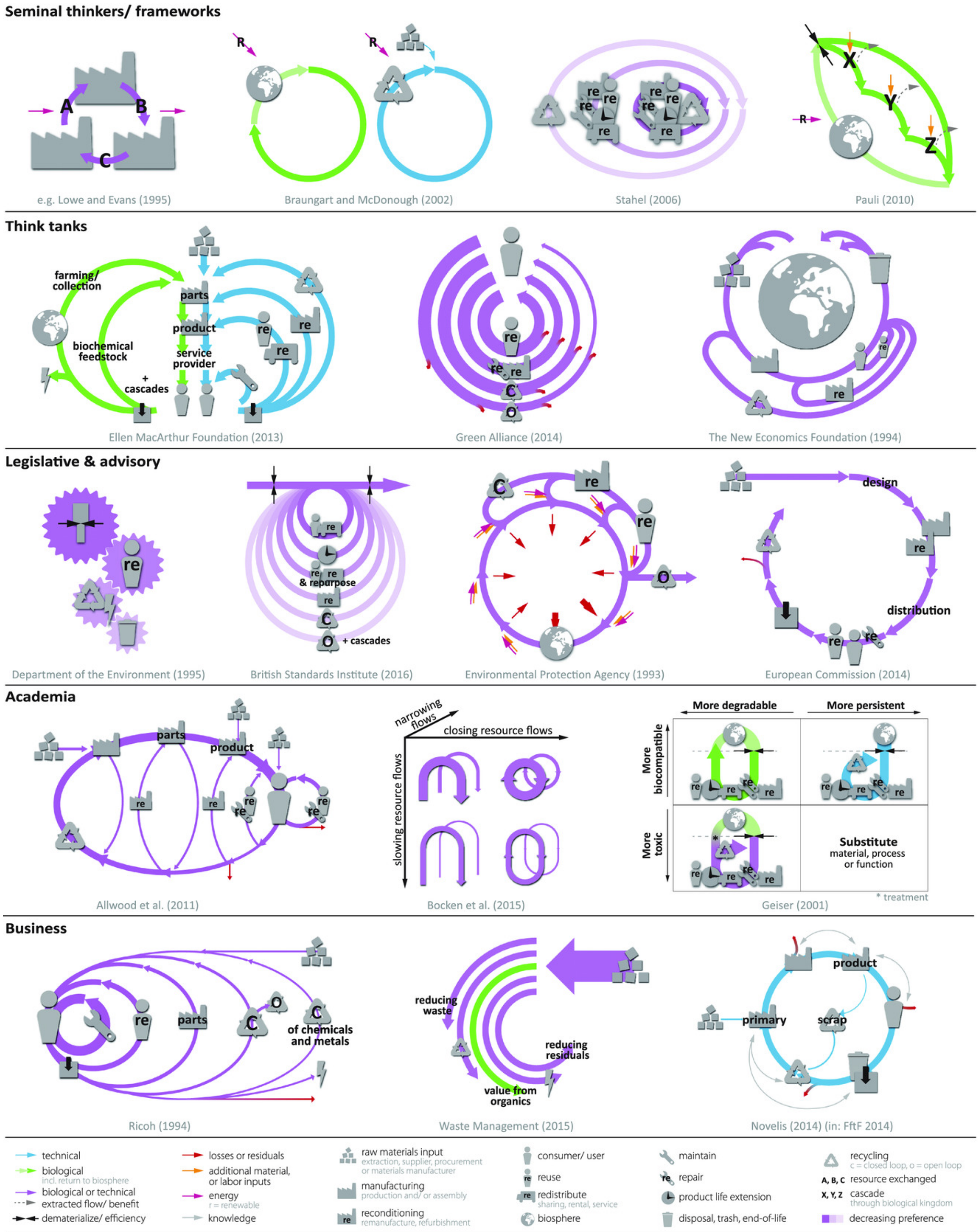


Figure A.6: Overview of interpretations of the Circular Economy concept [122]

Figure A.6 shows the different representations of the Circular Economy (CE) principles as interpreted by businesses, academics, think tanks, frameworkers. This signifies there are differences in considering the paradigm of CE.

A.3. LIFE CYCLE ASSESSMENT MODELLING

Table A.1: Default processes in the ecoinvent v3 library in SimaPro used for various operations of manufacturing, recycling and transporting materials.

Operations	ecoinvent processes
Steel Production	Steel, low-alloyed {GLO}| market for | Cut-off, S
Cast Iron Production	Cast iron {GLO}| market for | Cut-off, S
Fibre glass Production	GERP, polyamide, injection moulded {GLO}| market | Cut-off, S
Epoxy Production	Epoxy resin, liquid {RER}| market for epoxy resin, liquid | Cut-off, S
Aluminium Production	Aluminium, primary, ingot {IAI Area, EU27 EFTA}| market for | Cut-off, S
Copper Production	Copper {GLO}| market for | Cut-off, S
Magnet Production	Permanent magnet, for electric motor {GLO}| market | Cut-off, S
Transport OWF - port	Transport, freight, sea, transoceanic ship {GLO}| market for | Cut-off, S
Transport OWF - port	Transport, freight, inland waterways, barge {RER}| market for | Cut-off, S
Transport port - recycling	Transport, freight, lorry 32 metric ton, euro5 {RER}| market for | Cut-off, S
Steel recycling	steel scrap, sorted, pressed {RER}| sorting and pressing | Cut-off, U
Cast Iron recycling	Iron scrap, sorted, pressed {RER}| sorting and pressing | Cut-off, U
Aluminium recycling	Aluminium scrap, new {RER}| treatment of, at refiner | APOS, U
Copper recycling	Copper {RER}| treatment of scrap by electrolytic refining | Cut-off, S
Cable recycling	Used cable {GLO}| market for | Cut-off, S
Incineration	Municipal solid waste {DK}| treatment of, incineration | Cut-off, S

The table A.1 shows the processes from the ecoinvent database used to conduct the LCA study in SimaPro. The processes include the manufacturing of materials, recycling of the specific materials, transportation by ship and truck from OWF site to onshore recycling facility and incineration of the non recyclable material and wastes. 'GLO' represents the the values based on global averages. 'RER' represents European average values. 'market for' signifies a process similar to buying a material from a market with different technology mix in production and average transportation to the manufacturer. 'Cut-off' indicates the cut-off approach used, while 'APOS' approach process in case of aluminium recycling was used as the 'Cut-off' processes were empty in the database. 'S' denotes the system process.

The figure A.7 shows the network of the system modelled in SimaPro. The network tree diagram shows the full life cycles of the OWF considered in this analysis. The processes under the 'Full Wind Turbine' on the left show the building of the whole wind turbine by using components as sub-assemblies. Each component is then linked with the quantity of material used, obtained from the tool developed. The processes on the right hand side under the 'Disposal Full Wind Turbine' show the way each separate component being disassembled. It also portrays the transportation form the OWF site to the nearby port by ships and from the port to the onshore recycling facilities by truck. The disposal of each OWF component are lnked with recycling scenario where the materials with different recycling rates are recycled or they are reused directly reducing the material required for manufacturing. The green lines indicate the benefits either from recycling or reusing the components.

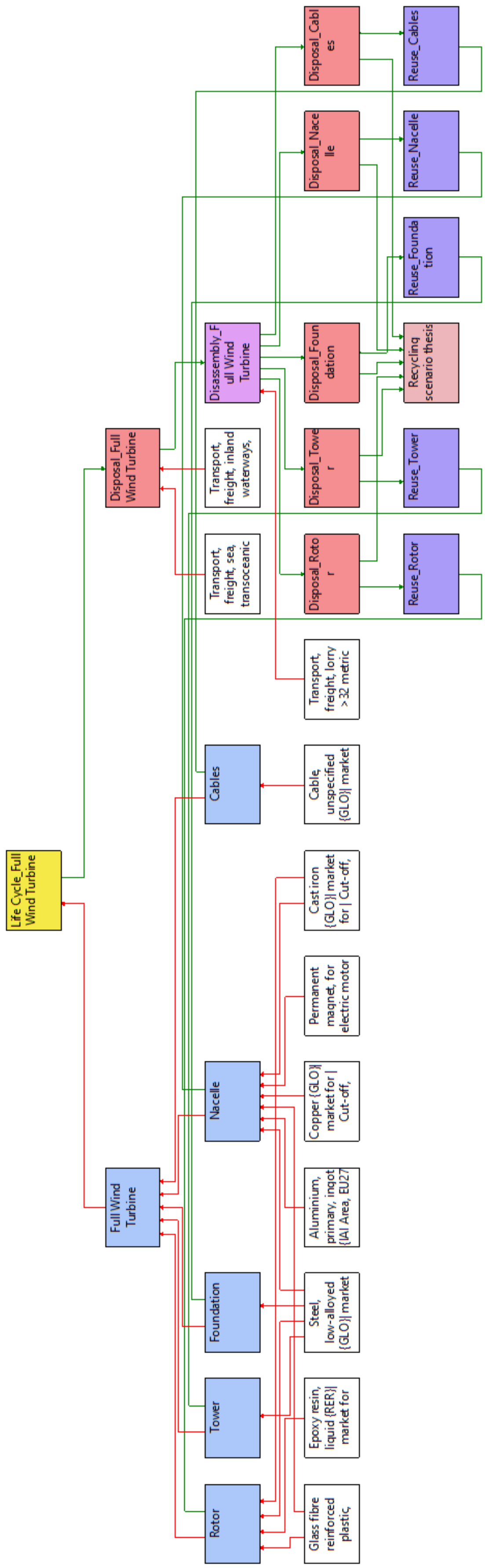


Figure A.7: Network tree diagram obtained by modelling of the LCA study in SimaPro. This shows the full life cycle model of the OWF with the defined processes. Full wind turbine models the wind turbine and disposal models how end of life.

Table A.2: List of the parameters used in the SimaPro software. This ensures changing the inputs at a single place while running the software. The highlighted values in the scenarios are changed compared to the baseline scenario

SimaPro Parameter	Baseline Scenario	Full Removal Scenario	Reuse focused Scenario
Rotor_Cast_Iron	7.98	7.98	7.98
Rotor_Steel	4.76	4.76	4.76
Rotor_GFRP	11.11	11.11	11.11
Rotor_Epoxy	5.43	5.43	5.43
Tower_Steel	110.37	110.37	110.37
Nacelle_Aluminium	1.27	1.27	1.27
Nacelle_Copper	1.71	1.71	1.71
Nacelle_Magnet	0.90	0.90	0.90
Nacelle_Steel	28.86	28.86	28.86
Nacelle_Cast_Iron	17.51	17.51	17.51
Nacelle_GFRP	2.89	2.89	2.89
Foundation_Steel	216.80	216.80	216.80
Cables	14.55	14.55	14.55
Mass_WF	424.00	424.00	424.00
RR_Cast_Iron	98.00	98.00	98.00
RR_Steel	92.00	92.00	92.00
RR_GFRP	30.00	30.00	30.00
RR_Epoxy	30.00	30.00	30.00
RR_Aluminium	95.00	95.00	95.00
RR_Copper	98.00	98.00	98.00
RR_Magnet	0.00	0.00	0.00
RR_Foundation	50.00	100.00	50.00
RR_Cables	90.00	100.00	90.00
RC_Eff_Cast_Iron	0.90	0.90	0.90
RC_Eff_Steel	0.90	0.90	0.90
RC_Eff_GFRP	0.20	0.20	0.20
RC_Eff_Epoxy	0.20	0.20	0.20
RC_Eff_Aluminium	0.70	0.70	0.70
RC_Eff_Copper	0.70	0.70	0.70
RC_Eff_Magnet	0.00	0.00	0.00
RC_Eff_Cables	0.55	0.55	0.55
Reuse_Rotor	3.00	3.00	15.00
Reuse_Nacelle	3.00	3.00	15.00
Reuse_Tower	5.00	5.00	30.00
Reuse_Foundation	5.00	5.00	30.00
Reuse_Cables	3.00	3.00	50.00
Dist_recycling	100.00	100.00	100.00
Dist_from_shore	5.00	5.00	5.00

The table A.2 lists the input parameters used in the LCA modelling in SimaPro for all the scenarios considered. The first section in the parameters indicate the mass of materials in tons in each component. The 'RR' indicates the recycling rates of the materials. 'RC'_{Eff} indicates the recycling efficiencies. The 'Reuse' states the fraction of the component being reused and at the end the distances from the OWF to show and to the recycling facilities are considered.

A.4. SUPPORTING RESULTS

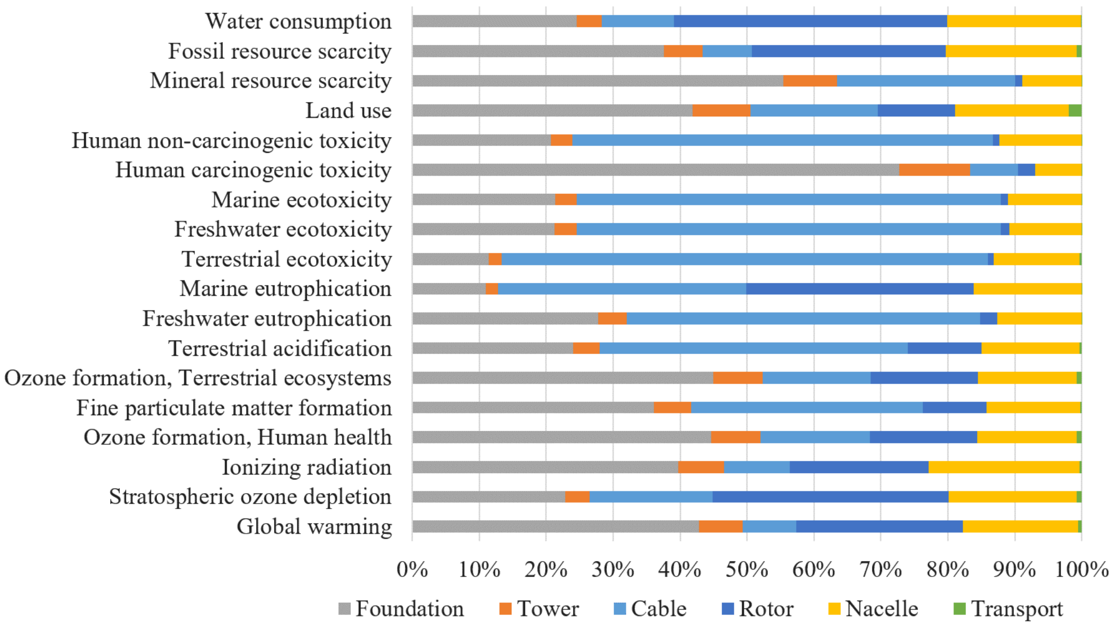


Figure A.8: Environmental impacts of baseline, reuse and full removal scenarios for the Utgrunden OWF. Results of all the impact indicators of ReCiPe 2016 Midpoint (H) method obtained from SimaPro.

The figure A.8 shows the environmental impacts of the OWF obtained from the LCA modelling in SimaPro. The impacts are shows for all the 18 midpoint indicators of the ReCiPe Midpoint.

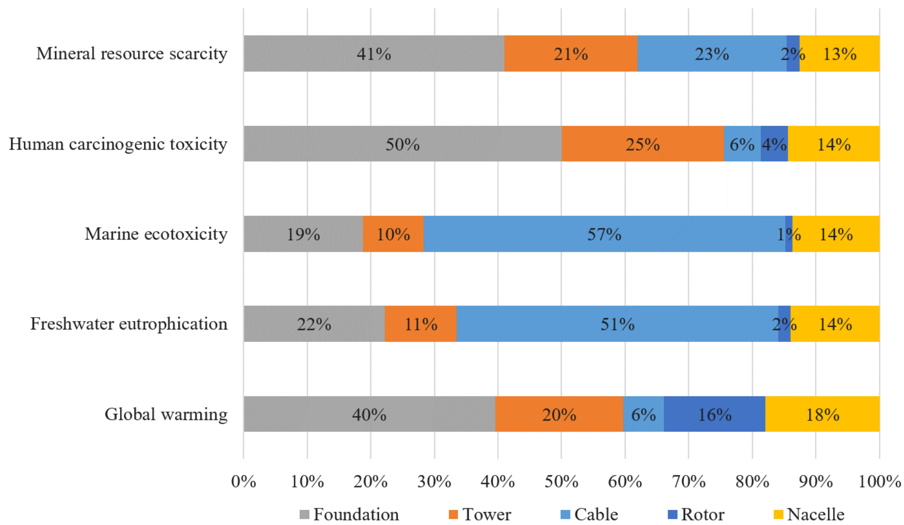


Figure A.9: Environmental impacts of **manufacturing phase** for the different components of the Utgrunden OWF for baseline scenario. Results of the impact indicators calculated by using ReCiPe 2016 Midpoint (H) from SimaPro.

The figure A.9 shows the impacts from the selected impact indicators only considering the manufacturing of materials. No benefits after recycling or reusing the components are considered.

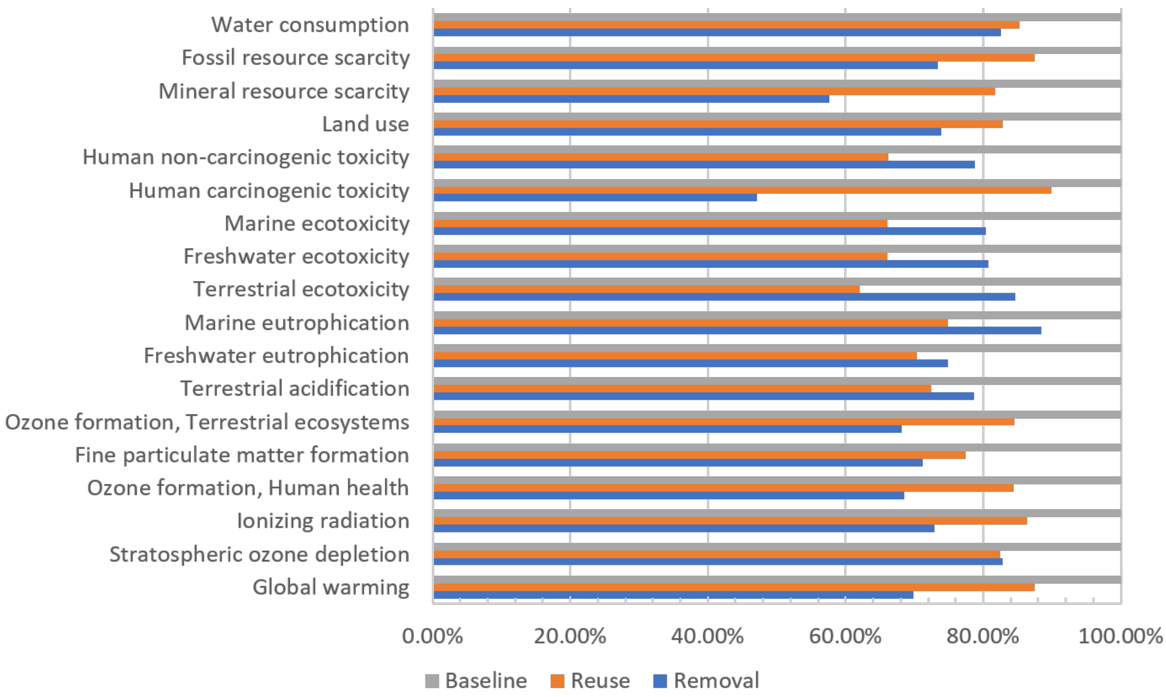


Figure A.10: Environmental impacts of the different components of the Utgrunden OWF for baseline scenario. Results of all the impact indicators of ReCiPe 2016 Midpoint (H) method obtained from SimaPro.

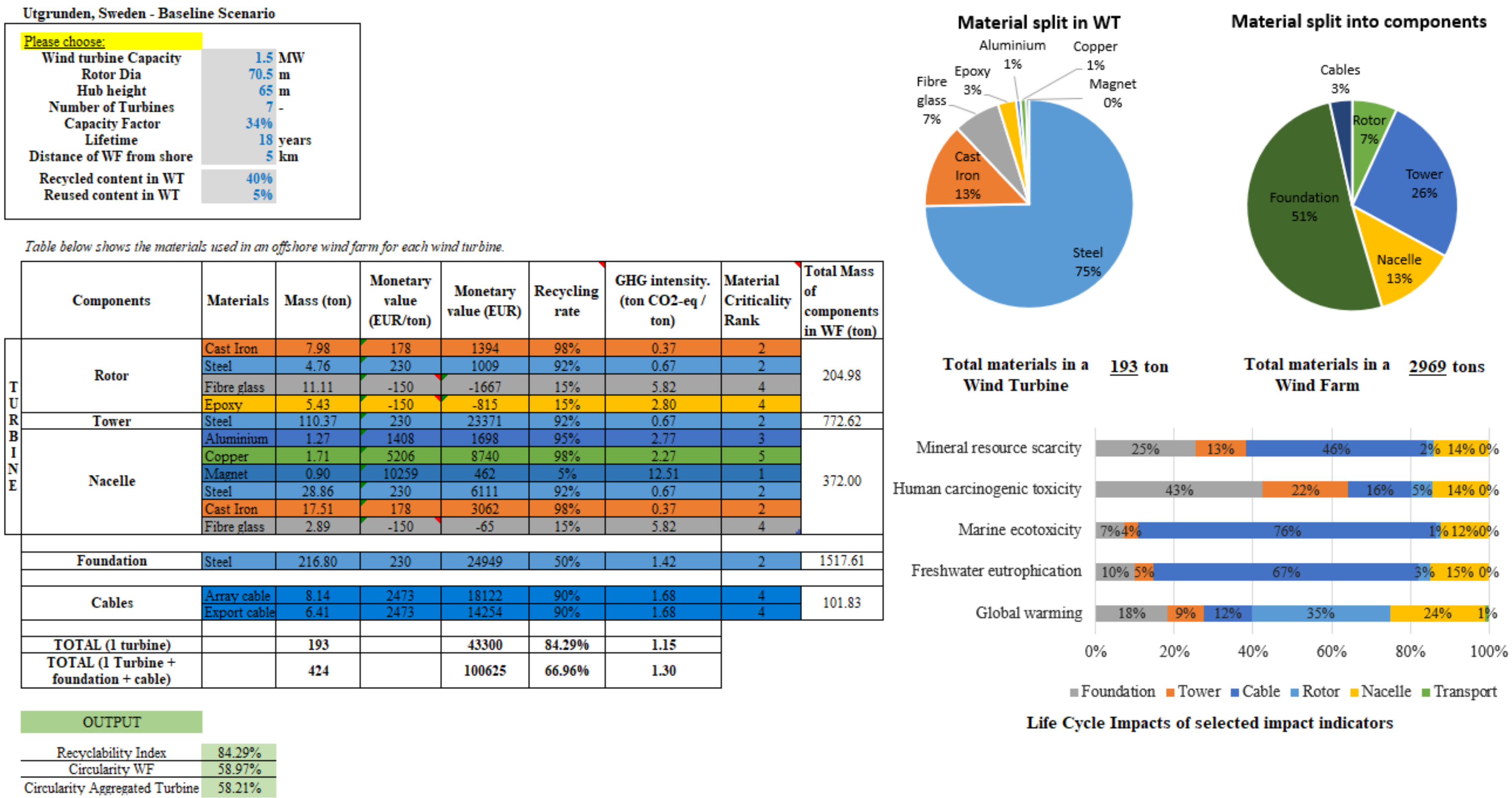
The figure A.10 shows the environmental impacts of all the impact indicators in the baseline, full removal and reuse scenario. Reuse scenario has a lower impact in a few categories.

The table A.3 lists the environmental impacts for all the indicators calculated into per kWh and per kg of material values externally in excel for better comparision.

Table A.3: Results of the LCA modelling for Utgrunden OWF, converted into per kWh and per kg values externally.

Impact category	**impact**	**Unit**	**impact**	**Unit**
Global warming	6.20064624	kg CO2 eq/ kWh	1175.633	g CO2 eq/ kg
Stratospheric ozone depletion	3.45513E-06	kg CFC11 eq / kWh	0.000655	g CFC11 eq / kg
Ionizing radiation	0.253043216	kBq Co-60 eq/ kWh	47.97658	mBq Co-60 eq/ kg
Ozone formation, Human health	0.017602863	kg NOx eq/ kWh	3.337474	g NOx eq/ kg
Fine particulate matter formation	0.019019022	kg PM2.5 eq/ kWh	3.605976	g PM2.5 eq/ kg
Ozone formation, Terrestrial ecosystems	0.0183493	kg NOx eq/ kWh	3.478998	g NOx eq/ kg
Terrestrial acidification	0.041451488	kg SO2 eq/ kWh	7.859135	g SO2 eq/ kg
Freshwater eutrophication	0.009534092	kg P eq/ kWh	1.807648	g P eq/ kg
Marine eutrophication	0.000763574	kg N eq/ kWh	0.144772	g N eq/ kg
Terrestrial ecotoxicity	174.3360911	kg 1,4-DCB/ kWh	33053.84	g 1,4-DCB/ kg
Freshwater ecotoxicity	1.724815373	kg 1,4-DCB/ kWh	327.0222	g 1,4-DCB/ kg
Marine ecotoxicity	2.429925801	kg 1,4-DCB/ kWh	460.71	g 1,4-DCB/ kg
Human carcinogenic toxicity	2.922538396	kg 1,4-DCB/ kWh	554.1086	g 1,4-DCB/ kg
Human non-carcinogenic toxicity	53.33551482	kg 1,4-DCB/ kWh	10112.33	g 1,4-DCB/ kg
Land use	0.139244351	m2a crop eq/ kWh	26.4005	dm2a crop eq/ kg
Mineral resource scarcity	0.266386999	kg Cu eq/ kWh	50.50654	g Cu eq/ kg
Fossil resource scarcity	1.703278526	kg oil eq/ kWh	322.9389	g oil eq/ kg
Water consumption	0.077673645	m3/ kWh	14.7268	dm3/ kg

A.5. TOOL INTERFACE



Utgrunden, Sweden - Baseline Scenario

Please choose:		
Wind turbine Capacity	1.5	MW
Rotor Dia	70.5	m
Hub height	65	m
Number of Turbines	7	-
Capacity Factor	34%	
Lifetime	18	years
Distance of WF from shore	5	km
Recycled content in WT	40%	
Reused content in WT	5%	

Table below shows the materials used in an offshore wind farm for each wind turbine.

	Components	Materials	Mass (ton)	Monetary value (EUR/ton)	Monetary value (EUR)	Recycling rate	GHG intensity. (ton CO2-eq / ton)	Material Criticality Rank	Total Mass of components in WF (ton)
TURBINE	Rotor	Cast Iron	7.98	178	1394	98%	0.37	2	204.98
		Steel	4.76	230	1009	92%	0.67	2	
		Fibre glass	11.11	-150	-1667	15%	5.82	4	
		Epoxy	5.43	-150	-815	15%	2.80	4	
	Tower	Steel	110.37	230	23371	92%	0.67	2	772.62
	Nacelle	Aluminium	1.27	1408	1698	95%	2.77	3	372.00
		Copper	1.71	5206	8740	98%	2.27	5	
		Magnet	0.90	10259	462	5%	12.51	1	
		Steel	28.86	230	6111	92%	0.67	2	
		Cast Iron	17.51	178	3062	98%	0.37	2	
		Fibre glass	2.89	-150	-65	15%	5.82	4	
	Foundation	Steel	216.80	230	24949	50%	1.42	2	1517.61
	Cables	Array cable	8.14	2473	18122	90%	1.68	4	101.83
		Export cable	6.41	2473	14254	90%	1.68	4	
	TOTAL (1 turbine)		193		43300	84.29%	1.15		
	TOTAL (1 Turbine + foundation + cable)		424		100625	66.96%	1.30		

OUTPUT	
Recyclability Index	84.29%
Circularity WF	58.97%
Circularity Aggregated Turbine	58.21%

Figure A.11: Main page of the tool developed showing different parameters of each material (mass, monetary value, GHG intensity, criticality, recycling rate). Circularity potential of the Wind farm and life cycle impacts. The dialogue box on top left allows the user to choose specification of the OWF being considered.

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