An assessment of circular economy measures in the construction value chain for offshore wind turbines

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Abstract

The construction sector is responsible for high energy consumption and large emissions of carbon dioxide, which is strongly linked to building materials. Within the European Union, the construction sector generates more than a third of all waste and circular economy is considered as a suitable approach to tackle these challenges. Furthermore, the need for renewable energy sources has increased, with wind turbines being an important source. However, there have long been difficulties in recycling the massive rotor blades from wind turbines, but recently the world's first recyclable rotor blades have been installed at an offshore wind farm in Germany which has been in operation since the end of 2022. With regard to this background, the purpose of the study has been to evaluate whether circular economy can be applied to offshore wind turbines. This has been assessed by making a case study of a wind developer who develops, builds, operates and decommissions wind farms and who, among other things, has developed the wind farm in Germany with recyclable rotor blades. Various circular measures within the construction value chain for offshore wind turbines applied by the developer have been evaluated. Data were collected through interviews and a document study. The result showed that circular economy can be applied to wind turbines to a certain extent. This conclusion is based on difficulties in completely excluding waste generation, for example large offshore foundations are planned to be left in the seabed after decommissioning wind farms. The study also showed that there are several challenges in the transition to a circular economy such as permitting processes, stakeholder involvement, financial obstacles and challenges associated with the rapid technical development of wind turbines. However, the study showed that the developer applies several circular measures within the framework of their operations, especially in maintenance.

Sammanfattning

Byggsektorn är ansvarig för hög energiförbrukning och stora utsläpp av koldioxid, vilket är starkt kopplat till byggmaterial. Inom Europeiska unionen genererar byggsektorn mer än en tredjedel av allt avfall och dessa utmaningar anses kunna lösas med applicering av cirkulär ekonomi. Vidare har behovet av förnyelsebara energikällor ökat, där vindkraftverken utgör en betydelsefull källa. Det har dock länge funnits svårigheter att återvinna de massiva rotorbladen från vindkraftverk, dock har världens första återvinningsbara rotorblad installerats på en vindkraftspark i Tyskland som är i drift sedan slutet av år 2022. Med hänsyn till denna bakgrund har studiens syfte varit att utvärdera huruvida cirkulär ekonomi kan tillämpas på havsbaserade vindkraftverk. Detta har undersökts genom att göra en fallstudie av en exploatör som utvecklar, bygger, driver och avvecklar vindkraftsparker samt som bland annat har utvecklat vindkraftsparken i Tyskland med återvinningsbara rotorblad. Olika cirkulära åtgärder inom byggvärdekedjan för havsbaserade vindkraftverk hos exploatören har utvärderats. Data insamlades genom intervjuer och en dokumentstudie. Resultatet visade att cirkulär ekonomi till en viss del kan appliceras på vindkraftverk. Denna slutsats grundar sig i att det finns svårigheter med att fullständigt utesluta avfallsgenerering exempelvis då stora fundament planeras att lämnas kvar i havsbotten vid avveckling av vindkraftsparker. Studien visade även att det finns flera utmaningar i övergången till en cirkulär ekonomi såsom tillståndsprocesser, intressentinvolvering, ekonomiska hinder och utmaningar förknippade med den snabba tekniska utvecklingen av vindkraftverk. Dock så visade studien att exploatören tillämpar flera cirkulära åtgärder inom ramen för deras verksamhet, särskilt inom underhåll.

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Table of Content

Chapter 1 Introduction

1.1 Background

Ever since industrialization, society's way of living and working has resulted in a significant impact on the climate. Compared to pre-industrial times, the carbon dioxide concentration in the atmosphere has increased by approximately 50 % and, in addition, the levels of other greenhouse gasses have also increased. The increased levels of greenhouse gasses intensify the greenhouse effect and leads to global warming. Even though climate change most often is described as a future concern, research shows that there already exist changes in the climate as a result of mankind's imprint (Naturvårdsverket 2023). In order to limit global warming and mitigate climate change, the Paris Agreement was adopted in 2015, by 196 parties. The aim of the international legally binding settlement is to keep global warming well beneath 2 degrees Celsius, preferably 1.5 degrees Celsius, in comparison to levels from the pre-industrial times. To accomplish this goal, the participating parties have to implement *long-term low greenhouse gas emission development strategies* that will reduce the greenhouse gas emissions in order to attain climate neutrality around mid-century (United Nations 2023).

A contributing factor to climate change is the construction sector. The construction sector is responsible for a large share of carbon dioxide emissions and for severe energy consumption. A significant amount of the negative side effects can be related to the building materials that are used in buildings and infrastructure. The construction sector is characterized as one of the main consumers of material and producers of waste, which contributes to resource scarcity (UKGBC 2023) and climate change. In fact, in the European Union the construction sector generates more than a third of all the generated waste. The European Union refers to this as *construction and demolition waste* and it includes different types of materials commonly used in buildings and infrastructure such as wood, glass, concrete, plastic and metals (European Commission 2023). To tackle the issues related to this waste, the European Union has implemented rules and guidelines with the aim to reach two goals considering the waste stream. The first goal is to assure that the waste is handled in an environmentally sound way. The second goal is to make use of the valuable components in the waste to contribute to the transition to a circular economy (European Commission 2023). In comparison to the linear processes from industrialization where raw materials are used in the manufacturing of new products and waste ends up in landfills, circular economy means that waste should be considered as an asset and something to be used in the creation of new products. Circular economy is considered to be able to mitigate climate change as a large part of all emissions can be related to the manufacture and waste of products (Ellen MacArthur Foundation 2023a). Circular economy can be applied to all kinds of products, systems and industries such as the construction industry and certain construction projects. Within the construction sector it is considered important to integrate the circular economy throughout the entire value chain to support sustainable development (Dewagoda et al. 2022).

To completely separate waste from landfill within the construction sector can be challenging as some materials are difficult to recycle. In addition, it can be difficult to replace those materials if there do not exist alternative materials that meet the same requirements. Furthermore, there are certain types of infrastructure that society depends on, which may contain materials that cannot be recycled. One type of infrastructure that society depends on is energy facilities. Due to the current energy crisis and the dependency on finite energy sources, there is a great demand for the expansion of renewable energy (Energi 2023). The construction of wind turbines represents an important part of this development. Wind energy is classified as a circular system because it relies on wind, which is unlimited in comparison to coal and nuclear material, which represents finite energy sources. However, for a long time there has been a waste management problem regarding wind turbines. The rotor blades from wind turbines have ended up in landfills since they are made of a composite material that has been difficult to recycle. However, the trend appears to be reversing as the world's first recyclable rotor blades have been installed in a German wind farm (RWE 2021a). Consequently, it is of interest to investigate whether circular economy can be applied to wind turbines by studying various processes associated with the construction, operation and decommissioning of wind turbines.

1.2 Purpose and research aims

The main purpose of this thesis is to examine whether circular economy can be applied to offshore wind turbines. This will be assessed by analyzing different circular measures in the construction value chain of wind turbines, such as installation and operation and maintenance. The objective is also to evaluate the possibility to adopt circular measures from experience with current wind farms to future wind farms. The research is expected to highlight challenges and opportunities with circular economy in the construction sector. In addition, the aim is to raise awareness regarding the connection between climate change and traditional linear economics. Furthermore, the research study will hopefully contribute with knowledge about how wind turbines can be built and developed in sustainable ways to enable circularity and contribute to a more sustainable business development.

1.3 Research questions

- Which circular measures are applied in the construction value chain by a wind developer?
- What are the main challenges within the wind energy industry regarding the transition to a circular economy?
- How can circularity increase in wind power projects?

1.4 Focus and delimitations

The focus of the research study is to examine whether circular economy can be applied to offshore wind turbines. The reason why offshore wind turbines should be studied alone is that there are important differences between onshore and offshore wind turbines. For instance, there are structural differences in the construction of offshore and onshore wind turbines. Different types of foundations are used depending on whether wind turbines are located onshore or offshore. Furthermore, offshore wind turbines often mean larger wind turbines, which means a greater need for material which represents a problem connected to resource scarcity.

The purpose of the study is to get an idea of how the entire construction value chain of wind turbines can become more circular. Instead of focusing on the environmental impacts that the wind turbines have, the focus will rather be on methods and business strategies that will increase the circularity. Moreover, there will be a focus on the larger structural components which are the foundation, tower and blades as these require large amounts of material, which represents a challenge in the circular economy. Furthermore, these components are more connected to the construction industry in comparison to the electrical components of the turbines.

1.5 Thesis outline

In the opening chapters, chapter 1 introduction and 2 method, the study's research topic and its research approach are presented. In chapters 3 to 5, relevant theoretical background linked to the research topic is presented. The empirical results from the study are presented in chapter 6. In chapters 7 and 8, the results are analyzed in relation to the theoretical background and conclusions are presented. Finally, the thesis concludes with some suggestions regarding continued research on the subject in chapter 9.

Chapter 2 Method

In this chapter the chosen research method is described. Moreover, different theories about methodology are presented as well as considerations regarding the choice of different techniques within the research process.

2.1 Literature review

When conducting a research study, it is necessary to carry out a literature review in order to gain a profound understanding of the existing theory within the research topic. The literature review represents the identification of relevant and up to date literature, as well as the compiled information from it (Merriam 1994). In the beginning of a research study the literature review can serve as a support when formulating the research questions and in the end of the study the literature review works as a theoretical framework for the evaluation of the obtained data and for the answering of the research question (Säfsten & Gustavsson 2019).

In this research study, most of the literature has been retrieved from the database LUBsearch through Lund University and the result is presented in three chapters. The first chapter describes circular economy, the second chapter focuses on circular economy in the construction sector and the third chapter describes wind turbines. In the first chapter definitions, commitments and regulations regarding circular economy are presented. The theoretical framework is mainly based on the definition of circular economy by the Ellen MacArthur Foundation, where the butterfly diagram represents a key model for the study. In addition, the theoretical framework is supplemented with theories regarding circular business models from scientific articles. Furthermore, regulations and commitments by the European Union and the Swedish government are presented. The literature in the second chapter is mainly based on scientific articles that describe circular measures in the construction value chain, such as *Revamping construction supply chain processes with circular economy strategies: A systematic literature review* by Chen, Feng and Garcia de Soto and *Driving systematic circular economy implementation in the construction industry: A construction value chain perspective* by Kaveesha Dewagoda, Thomas and Chen. In the last chapter the larger wind turbine components, permits for offshore wind turbines in Germany and in Sweden and end of life options are described. The literature in this chapter is mainly based on academic literature.

The theory was selected with regard to the purpose and questions of the research study. By looking at the general concept of circular economy as well as sector wise application within construction a deeper understanding of circularity and suitable measures within the construction sector was developed. The chapter about wind turbines constitutes a key chapter for the case study since it provides meaningful information about the materials that are used in the structural components of offshore wind turbines, differences in the permitting process and end of life options that specifically applies for wind turbines.

2.2 Research method

Depending on the purpose and questions of a research study, an appropriate method must be selected. There are different approaches to investigating a phenomenon. A common description is whether the approach of the research study should be qualitative or quantitative. Qualitative research refers to characteristics of the investigated phenomenon and focuses on the bigger picture of the investigated phenomenon. Something that characterizes qualitative studies is that the knowledge requested in the study cannot be described using a numerical value. However, quantitative studies refer to number, size and quantity, something that can be measured. Quantitative studies are characterized by high standardization with limited scope for flexibility. Furthermore, the difference between qualitative and quantitative studies can be found in the nature of the data, which usually consists of numerical values for quantitative studies and respectively words or images for qualitative studies (Säfsten & Gustavsson 2019).

Another common description of the approach in a research method is whether it is inductive or deductive. These principles describe working methods that result in different layouts of the study. In an inductive study, the study begins with observations that give a result and then theoretical rules can be based on the result. In a deductive study, on the other hand, the theoretical rules form the base of the study and the theoretical foundation is then examined through observations, which leads to a result. In other words, there are already assumptions and hypotheses about a phenomenon in a deductive study that are examined more closely, while the purpose of an inductive study is rather to find new theories about the assessed phenomenon (Säfsten & Gustavsson 2019).

2.2.1 A qualitative and inductive study

In this research study, a qualitative and inductive approach was considered suitable with regard to the purpose of the study and the character of the research questions of the study. Since the purpose of the study is to investigate how circular measures can be applied in the construction value chain, it was considered that the only suitable way to investigate this was through a qualitative investigation, where words are the focus of the data collection. This would have been difficult to describe with numbers and thus a quantitative study is not a suitable alternative. Furthermore, the study was considered to be able to contribute to theoretical assumptions about the assessed phenomenon in comparison to answering quantitative hypotheses and thus an inductive approach was considered to be most appropriate for the study.

2.3 Case study

A case study is appropriate in those studies where the purpose is to examine a defined system within a research topic. A case study can, for example, be described as interpretation in context, with a focus on insight, interpretation and discovery of phenomena. Most case studies are of a qualitative nature and suitable to use when the variables are connected to the surrounding situation. Furthermore, a case study can be described as particularistic, descriptive, heuristic and inductive. This means that case studies focus on a specific phenomenon or situation, provide insights into the investigated phenomenon and focus on interpretation, process and understanding of the studied phenomenon (Merriam 1994).

In this research study, the case study was considered as a suitable method to investigate which circular measures can be applied to wind turbines by studying a wind farm developer’s processes and evaluating how they apply circular economy measures. By focusing on studying one wind farm developer, better insight and understanding is considered to arise in comparison to studying the industry as a whole.

The study was carried out in collaboration with the company RWE Renewables, which is a developer of offshore and onshore wind farms. With regard to the research topic, it was decided to look at circular measures that the company applies in their construction value chain as well as studying a specific project. The project that was selected is called Kaskasi and is located offshore in the German exclusive economic zone. The project was selected because the world's first recyclable rotor blades are used in the project. Since the waste management of rotor blades has long been a challenge within this kind of infrastructure project, the Kaskasi project was considered a suitable project for this study. Furthermore, new installation techniques have also been applied in the project which makes it even more interesting for the study.

2.3.1 Empirical data

Empirical data consists of the observations collected in a study (Säfsten & Gustavsson 2019). In this study, it was chosen to collect the empirical data via interviews and through a document study. During the study, weekly meetings were also held with a supervisor at RWE Renewables, who later will be referred to as respondent 7. The supervisor from RWE Renewables works as a business development manager and has offered guidance and help in carrying out the study, for example by finding suitable interviewees within the company. Furthermore, the supervisor has contributed with helpful information about the wind energy industry and its processes. Consequently, a greater understanding and insight into the industry was achieved thanks to the supervisor, as a result the collection of relevant empirical data for the study was improved.

2.3.2 Interviews

When investigating a phenomenon where personal perceptions and experiences are of interest, an interview is a suitable technique for the data collection. The purpose of interviews is for the researcher to create an understanding of actual conditions based on the descriptions from the respondents. In an interview, the researcher leads the conversation and the interview has a certain structure. There are three kinds of structures that describe an interview; structured, semi-structured and unstructured. The structured interview follows a specific template with fixed questions and answer options, which can be similar to an oral questionnaire. The unstructured interview contains some themes that are freely discussed. The semi-structured interview represents something in between and it is the most common option in engineering science. Most often, an interview guide is used for the semi-structured interview (Säfsten & Gustavsson 2019).

An interview guide consists of several questions and themes that are linked to the purpose and questions of the study. When creating an interview guide, it can be helpful to start writing down the themes that should be covered in the interview and then formulate questions linked to each theme. The nature of the questions can vary in an interview guide, for example they can be factual questions, questions about experiences, values and opinions. If the respondent does not give satisfactory answers, there are several techniques that can be applied. For example, the researcher can ask different kinds of follow-up questions to the respondent to find out more about certain topics (Säfsten & Gustavsson 2019).

There are several factors to consider before and during an interview. For instance, the location of the interview. An interview can, for example, be conducted at the workplace where the respondent works. The important thing is to find a quiet place where no outsiders can hear the conversation (Bryman 2018; Säfsten & Gustavsson 2019). Furthermore, an interview can be conducted with one or more respondents. Most often, interviews are conducted with one respondent, but sometimes it may also be appropriate with two respondents. The benefit of interviewing several respondents at the same time is that a lot of data can be collected in a short time, which is advantageous when a phenomenon has limited information. On the other hand, there is a risk that the respondents take control over the interview. Moreover, an interview can be conducted face-to-face or over the phone. There are studies that claim that face-to-face is the preferred method as it can create trust between researcher and respondent. However, there are also studies that suggest that telephone interviews work just as well. It is the situation that must determine which method is applied. In addition, there are different techniques for obtaining the respondent's answer. It can be recorded or written down. There are pros and cons to both techniques. When writing down the answers, there is a risk that important information will not be included, however when recording there is a risk of limiting the respondent's answers (Säfsten & Gustavsson 2019).

Using interviews as a data collection method has its advantages and disadvantages. The benefits are that there is a flexibility during the course of the interview that enables adaptation of answers and follow-up of questions, that in-depth and detailed information is obtained, there is a high response participation in interviews and high validity is obtained in the answers. However, interviews are time-consuming and resource intensive. If the selection of respondents is poor, it can contribute to misleading results and the respondent can be influenced by the researcher or the situation which can give low reliability (Säfsten & Gustavsson 2019).

Interview method and interviewee selection

In this research study, the interviewees were selected by their positions within RWE Renewables in Sweden and in Germany. The selection was made so that the interviewees mainly represent a certain area within the construction value chain. However, the respondents' answers sometimes overlapped several areas of the construction value chain. Moreover, several of the interviewees were asked questions about the end of life phase, since there was limited information about this phase.

Five interviews were conducted in study, the number of interviews were considered appropriate since quality should be prioritized over quantity in a qualitative study. Moreover, it was adapted to the study’s limitations. The interviews were conducted in a semi-structured manner. This was considered the most appropriate approach since the study is qualitative and the different experiences and opinions of the respondents were sought. In addition, this option was considered suitable for asking spontaneous follow-up questions about certain topics. An interview guide was drawn up for each interview, which is shown in appendices 1-5. The various interview guides were created with regard to each respondent's profession, which could be related to one or several areas within the construction value chain. Questions were formulated regarding sustainable measures in the different areas.

RWE Renewables has limited power in the design and manufacturing stage since they purchase wind turbines from manufacturers. However, the design stage was assessed by interviewing the head of sustainability at the company and a respondent from the procurement department was interviewed to obtain an understanding of the company's connection to manufacturers and sustainable procurement. The construction stage was studied by interviewing a senior project manager for the Kaskasi project in Germany. The interviewee was selected both due to his experience within planning and construction of wind farms, as well as his involvement in the Kaskasi wind farm project. The operation and maintenance stage were assessed by interviewing a general manager for the Kårehamn wind farm in Sweden, in order to obtain relevant and experiential information about sustainable measures in actual conditions. When it comes to the end of life stage, there is limited experience in this field, especially for offshore wind turbines. Therefore, this interview was carried out with two respondents from the onshore team at the company. One was joining the interview in person and the other on video call.

The location of each interview was determined based on the respondent’s workplace. Two interviews were conducted with employees in Sweden, one at RWE Renewables' office in Malmö and one via video call due to the long distance to the respondent's office. Furthermore, three interviews were carried out with respondents who work in Germany. Two of these interviews were video calls and one was a telephone meeting, to accommodate the respondent's availability. The answers from the respondents were written down during the interviews.

2.3.3 Document study

A document study represents secondary data, consisting of documents. In scientific studies, it is common to collect both primary and secondary data. Based on secondary data, a different point of view about a phenomenon can be obtained. In addition, it may sometimes be difficult or impossible to collect the information through primary data. Documents include digital, written, visual and physical material and thus there exists several different types of documents. Examples of documents are protocols, pictures, statistics, annual reports, organizational descriptions, news and archive material. When it comes to documents from companies, not everything is available and public. Documents from companies can include advertising, internal newsletters, meeting protocols, reports, technical documentation, quality reports, deviation reports and more. Furthermore, websites, e-mail and social networking sites also constitute documents (Säfsten & Gustavsson 2019).

When carrying out a document study, it is important to be critical of the sources and assess criterias such as authenticity, independence, time distance, competence and tendency. For example, it may be important to investigate whether the source is a primary source who witnessed the phenomenon, which belongs to the criterion of independence. Furthermore, it is interesting to know if the source has a tendency to be biased and for what purpose the document is published. In addition, it is important that the person who created the document is an expert and has sufficient competence for the case. The benefit of a document study is that the data cannot be influenced by the researcher, it is usually readily available data and a cost-effective way of collecting data. However, there is a need to check the credibility of the sources when studying documents and it is secondary data that is observed (Säfsten & Gustavsson 2019).

In this study, documents have been obtained from various parts of the company's value chain and sustainability work. Furthermore, documents have also been obtained from the Kaskasi project in Germany, as this represents an important area of the study. The document study is based on several different types of documents from RWE Renewables such as policies, internal reports and website information. The documents were selected with regard to the purpose of the study. Documents were studied on the website rwe.com, that described RWE's business model, where they operate, their circular economy policy as well as documents regarding sustainable measures and investments in their wind farm projects. Relevant documents were found by searching for circular economy, circularity and sustainability on RWE's website as well as searching for specific projects mentioned in interviews and at meetings.

The internal documents were collected by asking the respondents if they could share any documents within the subject that could be of interest for the study. This was followed by a review and selection of the collected internal documents to determine which documents were relevant for the study and could provide more information in addition to the information from the interviews.

2.4 Validity and reliability

2.4.1 Validity

Validity is a concept that describes the credibility of the results achieved in a study. In other words, validity says something about how much the performed measurements correspond to the factors that are intended to be measured. For example, it can be abstract to measure the concept of quality and therefore validity corresponds to an important concept in research studies to achieve credible and reliable research. Validity is often divided into the categories internal and external validity (Säfsten & Gustavsson 2019).

Internal validity concerns whether the results actually answer the research questions. In order to draw a conclusion, alternative explanations for the result must be excluded as much as possible (Säfsten & Gustavsson 2019). There have been different interpretations and definitions of the internal validity over the years and there is research that suggests that studies should not follow a certain definition of validity as it risks limiting the possibilities of the study. Within qualitative case studies, it is important to consider that the results often depict the reality perceived by those in it. Within these studies the perspective is in focus in comparison to reality itself. In case studies, it is thus the researcher's obligation to honestly present the informants' perspective, which represents a kind of internal validity (Merriam 1994).

External validity describes whether the result is valid in a broader sense, for example whether it is possible to apply the result to other situations. It thus describes the possibility of generalization. This possibility is associated with the design of the study. For example, the design can be to study many research units based on a few variables, which leads to statistical generalization, or a few research units can be studied with respect to several variables, which can give the opportunity to apply the results to other contexts (Säfsten & Gustavsson 2019).

There are various techniques to strengthen the validity of a study. For example, triangulation can be applied, which means that more than one researcher, data source or method is used. Having several researchers perform a study can increase validity by reducing the risk of errors during the course of the study. By using multiple data sources, which means using more than one data collection technique, the validity is strengthened. Furthermore, several research methods can be used in the study (Säfsten & Gustavsson 2019).

The validity of this research study is considered to be at a medium level. To strengthen the internal validity, the results from the interviews have been presented with a focus on the respondents' perspectives and how they perceive circular measures within the company. Furthermore, triangulation of data sources has been applied, as both interviews and document study have been used in the collection of data. Regarding the external validity, it is considered possible to apply the results to other contexts to a certain extent, since a few research units have been studied with respect to several variables.

2.4.2 Reliability

The concept of reliability refers to the possibility of repeating the study and obtaining the same results. It could, for example, be that another researcher carries out the study or that the study is carried out at other times. If the study has a high reliability, the result will be the same. There are various factors that can cause random error in a survey such as the researcher, the respondents, the measurement instruments and the survey situation. For example, how the researcher interacts with respondents can affect the results and the researcher can also analyze and interpret the results incorrectly. Furthermore, respondents can influence the result based on their knowledge and interest in the subject. Moreover, the results can be affected if respondents answer questions the way they think they should answer instead of answering based on their real opinion. Measurement instruments with incorrectly worded questions in a survey can also contribute to incorrect data. In addition, the survey situation can affect the result and thus it should be taken into account if the environment can affect or disturb the study (Säfsten & Gustavsson 2019).

The reliability of the study is considered to be at a medium level since it is possible that the respondents' opinions may vary depending on the researcher or on which occasion, they answer the questions. Furthermore, it is important to consider the situation of the study and bear in mind that all interviews and documents originate from the case study company, which is likely to provide biased information. For instance, some documents are taken from RWE Renewables' website, which means that some information regarding sustainability and circularity may be presented with a desired image in mind and that less sustainable measures are not presented as openly. Furthermore, there is a risk that the respondents' answers are not transparent enough to identify relevant challenges. However, the method is considered to be sufficiently accurately described for a similar study to provide very similar results. However, the result could possibly have been different if a study is carried out after a few years, because new measures can be implemented over time and new laws can come into force, which can have a significant impact on circularity.

Chapter 3 Theoretical framework: Circular economy

Circular economy can be described as a production and consumption model. When it comes to the origin of the concept, there is a lack of evidence to a single source or date. However, the discussion of practical applications of circular economy to modern industrial and economic systems is relatively new and can be traced back to the late 1970s. During the following decades of the 20th century the concept was raised by the U.S. professor John Lyle and his student William McDonough, the German chemist Michael Braungart as well as the architect and economist Walter Stahe who have all been referred to as contributors to the concept (Ellen MacArthur Foundation 2013a). The focus of the concept is to prolong the life cycle of products and materials by practicing the following methods; sharing, leasing, reusing, repairing, refurbishing and recycling for as long as possible (European Parliament 2022a).

Circular economy can be described as the opposite to linear economy. Our current economy is a linear system as the manufactured products are made by raw materials that are taken from the Earth and these products are eventually considered as waste and are disposed. On the contrary, the principle of a circular economy is to prevent the creation of waste and reduce the use of raw materials. The aim of circular economy is to tackle severe challenges such as climate change, pollution, biodiversity loss, resource scarcity and waste (Ellen MacArthur Foundation 2023a).

Circular economy has gained increasing attention within academia, businesses and governments in the last decade as a way of creating sustainable business (Lazarevic, D. & Valve, H. 2017; Tunn, V.S.C. et al. 2019). A foundation that has been meaningful to the development of the concept as a policy agenda in Europe, is the Ellen MacArthur Foundation. The Ellen MacArthur Foundation released the report Towards *the Circular Economy: Economic and Business Rationale for an Accelerated Transition* in 2013. The report was unique in its way to consider economic and business opportunites within the circular economy. For example, the report includes case studies, financial analyses and identifies methods and new business models to facilitate the transition to a circular economy. Moreover, The Ellen MacArthur Foundation has also contributed with a coherent framework and models for the concept of circular economy (Kovacic et al. 2020).

3.1 Definition

There exist several definitions of circular economy. For instance, the definition can differ between organizations and foundations. According to the European Parliament (2022a para. 2) "Circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended". The Ellen MacArthur Foundation (2023a) describes that the concept will reduce pollution and waste as well as mitigate climate change and biodiversity loss. In addition, the foundation claims that the circular economy is based on three principles, which is the circulation of products and materials, the regeneration of nature and the elimination of waste and pollution.

In a study conducted by Julian Kirchherr, Denise Reike and Marko Hekkert (2017) 114 different definitions of circular economy were studied. By analyzing the different definitions, the authors concluded a general definition of circular economy as 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 (Kirchherr et al. 2017 p. 229).

3.2 The Butterfly Diagram

The concept of a circular economy can be explained and visualized by models, for example the butterfly diagram. The butterfly diagram was introduced by the Ellen MacArthur Foundation and it is a circular economy system diagram that describes the continuous material flows in a circular economy. The butterfly diagram consists of two cycles, one technical and one biological (Ellen MacArthur Foundation 2023b). The biological cycle can be seen to the left in figure 1 and it shows the different stages of biological material from harvest to regeneration of nature. The biological cycle primarily focuses on products that are consumed, such as food. Nevertheless, other biobased materials such as wood and cotton can eventually be integrated in the biological cycle once they have reached a condition where they are useless in the making of new products (Ellen MacArthur Foundation 2023c).

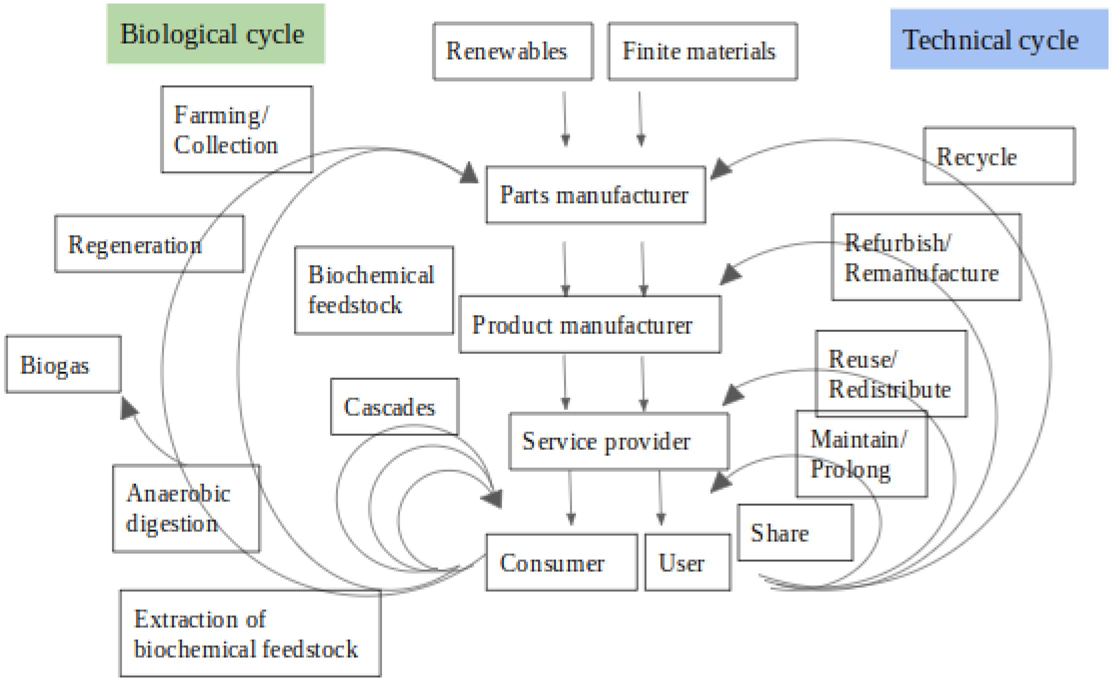

Figure 1: The butterfly diagram, source Ellen MacArthur Foundation.

The technical cycle is represented by the blue lines to the right in figure 1. It shows different kinds of circulations of materials and products depending on which process that is used. The processes in the technical cycle are share, maintain/prolong, reuse/redistribute, refurbish/remanufacture and recycle (Ellen MacArthur Foundation 2023b). The different processes can be related to different loops in the figure. The smaller inner loops are preferred in a circular economy in comparison to the larger outer loops. This can be explained by retaining the embedded value of keeping products whole compared with the value of the sum of its different components. Hence, the inner loops should be prioritized. Furthermore, the inner loops result in cost savings for businesses and customers since it circulates already existing products and materials instead of manufacturing new ones. The largest loop is represented by the process recycling which is the least desired process in a circular economy due to loss of the embedded value (Ellen MacArthur Foundation 2023d).

The different processes in the technical cycle are described below. Each process will work ultimately if the products are manufactured and designed with the specific process in mind. For example, products that have a modular design or are designed to be durable or easily repaired or a combination of these will be suitable for sharing and reuse, while designing products so that the different materials easily can be separated will help in the recycling process. Moreover, designing for several processes is also crucial (Ellen MacArthur Foundation 2023d). The processes below are arranged starting with the smallest, most preferred loop to the largest, least desired loop.

Sharing

By sharing items, the utilization of products has the potential to be significantly increased. However, the process of sharing is not suitable for all products in the technical cycle. Some examples of products that are suitable for sharing are tools, clothes, cars and habitations. There already exist platforms where these types of products are being shared such as community tool libraries, platforms for clothes renting, carpools and home-renting platforms (Ellen MacArthur Foundation 2023d).

Maintaining

By continuously maintaining products, their usable lifetime can be prolonged. Hence, the value of the products is increased. Moreover, maintenance represents a process that keeps products in good condition and also reduces the risk of defects and weakening. Maintenance is suitable for all products that are exposed to wear and tear (Ellen MacArthur Foundation 2023d).

Reusing

Reusing is a way of keeping products as they were produced in their original form and for their intended purpose. Business models for reusing concepts are increasing. For example, reusable packaging is a rising concept that is noted amongst different industries. Furthermore, resale platforms for clothing have become increasingly popular. This way of reuse covers the customers' need for new items at a considerably lower price compared to completely new products. Simultaneously, reuse platforms help to prevent unwanted items from becoming waste (Ellen MacArthur Foundation 2023d).

Redistributing

Redistribution is a process where products are diverted from one market to another as a way of finding interested customers. This process is an intention to ensure that the products are used as well as preventing waste (Ellen MacArthur Foundation 2023d).

Refurbishing

Refurbishing describes the process where products are repaired, components are replaced, aesthetic improvements are performed, or specifications are updated. This process restores the value of products and keeps them in good condition. Both individuals and specialists can perform refurbishing. An example of refurbishing is companies that refurbish old mobile phones and sell them at low price compared to completely new phones (Ellen MacArthur Foundation 2023d).

Remanufacturing

When products do not function any longer and need extensive work in order to be usable, remanufacturing is a suitable process. In this process products or components are re-engineered to match the condition of new products. The level of performance is either the same or higher in comparison with a new manufactured product. Remanufactured products often have a warranty that is either the same or longer than the one of new products. Remanufacturing prevents products or components from becoming waste. While this process is more expensive compared to the previously mentioned processes it represents an option for cost savings for businesses and customers in comparison to newly manufactured products (Ellen MacArthur Foundation 2023d).

Recycling

Recycling is the process that is suitable when the products can no longer be used, and the options of refurbishing or remanufacturing is not appropriate. In this case recycling is the only way to make sure that the materials within the products do not become waste. In the recycling process products or components are transformed to basic substances or materials and reprocessed into new materials. This method results in lost embedded value, since the time and energy that was spent in the making of a product is forever lost. However, the materials within the product keep their value. For those products that do not suit any of the other processes of the technical cycle, it is crucial to design them for recycling. Nevertheless, all products should be designed for recycling the technical cycle (Ellen MacArthur Foundation 2023d).

3.3 The aim of circular economy

Circular economy is a concept that aims to tackle several global challenges. The root of these challenges can be explained by the pattern of raw material usage. Raw materials have a limited supply, but the linear economy does not take that into account. Moreover, increased levels of

CO_2 emissions, energy consumption and negative environmental impacts are all related to raw materials extraction and usage. For example, 45% of the CO_2 emissions are related to the manufacturing of every-day products. As the world's population is growing the need for raw materials increases, which implies a need for a circular economy (European Parliament 2022a).

Adopting a circular economy would be beneficial for the environment, people and business. It would tackle climate change and biodiversity loss by reducing waste, pollution and greenhouse gas emissions while also regenerating nature (Ellen MacArthur Foundation 2023a). Furthermore, the circular economy will benefit consumers by offering durable and innovative products that will last longer, which benefits personal finances (European Parliament 2022a). In addition, a circular economy could bring several benefits for companies such as enhanced competitiveness, cost savings connected to waste prevention, reuse and eco design and increased innovation. Moreover, it is estimated that 700,000 jobs could be created in the European Union by 2030 and the economic growth could be boosted with 0.5% of gross domestic product by adapting the circular economy (European Parliament 2022a).

3.4 Circular business models and strategic management

In order to implement and create practical applications of the circular economy, the concept of circular business models have been developed. According to Bocken et al. (2016), this concept describes business models that are adapted to the circular economy through methods that slow, narrow and close resource loops which results in reduced resource input and minimized waste and emission leakage. *Slowing resource loops* means extending the utilization period of products through methods such as designing long-life products as well as repairing and remanufacturing products. *Closing resource loops* refers to circular resource flows enabled by recycling which closes the loop between post-use and production. *Narrowing resource flows* refers to resource efficiency with the aim of using fewer resources per product (Bocken et al. 2016). Geissdoerfer et al. (2018) argues that the definition by Bocken et al. should be complemented with the elements *intensifying* and *dematerialising* that refers to a more intense use of products as well as substitution of product utility by software solutions and service. Moreover, they argue that in order to reach sustainable development it is more tangible to apply the concept of circular economy to organize economy and society rather than the concept of sustainable development, since sustainable development is a more broad and therefore vague concept (Geissdoerfer et al. 2018).

A similar explanation of closed loops described by Bocken et al. (2016) can be found in the butterfly diagram by the Ellen MacArthur Foundation, which provides a general understanding of how these loops work (Ellen MacArthur Foundation 2013b). Furthermore, Ferguson and Souza (2010) have also drawn attention to the concept of closed loop systems, claiming that it is the only sustainable business practice. However, in order to implement sustainable business models on an organizational level there should also be a long-term perspective, a focus on sustainable value creation and stakeholder management should be more proactive as the stakeholders increase in number. Then the sustainable business model's strategic, analytical and communicational potential can be fully utilized (Geissdoerfer et al. 2016; Geissdoerfer et al. 2017).

Case studies where companies have introduced circular business models have shown some patterns as well as challenges. For instance, patterns such as designing and producing goods out of waste, promoting reverse logistics from partnership building, communication and collaboration efforts for system change have been observed (Geissdoerfer et al. 2018). Moreover, the observed challenges included the transition from linear to circular processes. This was mainly noted in the supply chains and in purchasing processes of customers. In addition, the customers' product quality perception was reduced after the companies had adopted remanufacturing and recycling in their business models despite the companies' high requirements of product quality and relatively small cost structure advantages in comparison to before. This resulted in lower realizable prices (Geissdoerfer et al. 2018). According to Rashid et al. (2013) active participation of all stakeholders are necessary in the implementation of circular business models. However, the customers represent a particularly important stakeholder, since they have to help solve issues regarding product returns. These issues include uncertainties within quantity, quality and delivery timing and by increasing the user involvement in the supply chain the issues can partly be resolved. Nevertheless, the issues are connected to the dependence on end-of-life products that determines the appropriate sustainable strategy, reusing, remanufacturing or recycling, within closed loops (Rashid et al. 2013).

According to Atasu et al. (2021) the success of implementing circular business models depends on many factors. However, the authors emphasize the importance of finding a strategy that addresses areas within the scope of the business and is consistent with the company's resources and capabilities. The finding of a suitable circular business model is also supported by Rashid et al. (2013), claiming that product systems have an enormous diversity, which indicates that there is a need for substantial research and engagement in the development of different and unique circular business models that can be applied to particular product systems.

3.5 Circular economy within governments and policy

The concept circular economy has been adopted by several governments and organizations in the last decades. For example, China, the UK and the US have made commitments and policies regarding circular economy (Bleischwitz et al. 2022). Furthermore, the European Union and the Swedish government have made commitments that are described in this subchapter.

Circular economy commitments by the European Union

The European Union has made several commitments towards the transition to a circular economy. For instance, the European Commission presented their circular economy action plan in March 2020 and two years later in March 2022, the first measures connected to the circular economy action plan were released by the Commission (European Parliament 2022a). The measures released by the European Commission includes proposals within the areas; textile industry, construction products, production of sustainable products as well as new rules that empower customers in the sustainable transition. The proposal regarding sustainable products regulates eco-design and focuses on the product design stage, where 80% of products' environmental impact are determined. The new proposals include requirements that will prolong the use of products through eco-design. For example, products should be designed to be more durable, reusable and reparable. Furthermore, the products should easily be maintained, refurbished and recycled as well as energy and resource efficient. Other measures that are proposed are product-specific information, Digital Product Passports, increasing green public procurement and introducing incitements for sustainable products. The product-specific information will be a helpful tool for customers to understand products' environmental impacts and the Digital Product Passport will enable tracing of substances of concern as well as facilitate repair and recycling of products (European Parliament 2022b).

The Construction Products Regulation is one of the regulations presented in the measures released by the European Commission. The Construction Products Regulation represents one of two targeted sectoral initiatives, which is prioritized due to the product group's significant impacts. In the European Union, around 50% of resource extraction and consumption and over

30% of the total annual waste is related to buildings. Moreover, 36% of energy-related greenhouse gas emissions and 40% of the total energy consumption in the European Union originates from buildings. The Construction Products Regulation is a revision of former rules that has been in force since 2011 and the new revision aims to combat the challenges within construction by modernizing the regulatory framework. The new framework will enable information about environmental and climate performance of construction products as well as facilitating the development of common European standards. In addition, the design and production phase will make construction products more durable, repairable, recyclable and possible to re-manufacture after the introduction of new requirements. Moreover, the free movement of construction products on the internal market will be strengthened by updated rules for economic operators in the supply chain and increased market surveillance. Furthermore, digital services such as a construction database and Digital Products Passport will be introduced to reduce administration (European Parliament 2022b).

Circular economy commitments by the Swedish government

The development of a circular economy within the European Union and globally is one of the reasons that the Swedish government has developed a strategy and a national action plan for the transition to a circular economy with the aim of reaching the environmental and climate goals, as well as the global goals in Agenda 2030. In the Swedish national strategy for circular economy different business and consumption models and material cycles are described (Regeringskansliet 2023). In the action plan different policy instruments and measures are presented, some of them are already adopted while others are proposals. The action plan is described as a step towards a circular economy (Regeringskansliet 2021a).

In the Swedish strategy plan for circular economy, four focus areas are presented as particularly crucial in reaching a circular economy (Regeringskansliet 2020). The focus areas are:

1. Circular economy through sustainable production and product design.
2. Circular economy through sustainable ways of consuming and using materials, products and services.
3. Circular economy through non-toxic and circular cycles.
4. Circular economy as a driving force for business and other actors through measures that promote innovation and circular business models.

In table 1 below, proposals for the four focus areas presented in the Swedish government's strategy plan for the transition to a circular economy are shown. The proposals indicate the overall direction of future policy instruments and measures (Regeringskansliet 2020).

Table 1. Focus areas with proposals from the Swedish government's strategy plan for circular economy.

Focus area	1. Sustainable production and product design	2. Sustainable consumption of materials, products and services	3. Non-toxic and circular cycles	4. Promote innovation and circular business models
Initiatives to promote the focus area	- Design products for a long service life, by enabling reuse and repair, and finally recycling. - Promote the development of production processes that are resource- and energy-efficient. - Promote product information regarding content, origin, environmental impact and methods after consumption. - Introduce policy instruments such as quota obligations to enhance the use of non-toxic recycled materials in new products. - Introduce financial instruments for pollution payments regarding materials and products. - Implement standards which supports product design that is resource-efficient circular and non-toxic. - Promote bio-based, renewable and sustainably produced raw materials in production processes rather than fossil-based raw materials.	- Develop useful consumer information that enables sustainable and circular decision making in everyday life. - Enable and make it financially benefiting for businesses and consumers to choose sustainable methods as sharing, repairing and reusing products. - Look into how a sharing economy can be implemented while meeting the consumers' interests. - Use public procurement to promote efficiency, recycling and circular business models. - Increase the supply and demand for services offering reuse, repair and sharing.	- Increase the use of renewable and bio-based raw materials rather than fossil raw materials, without disturbing biological diversity and the ecosystem. - Make sure that it will be possible to recycle more of the waste. - Promote reuse of products before recycling. - Improve the ways households and businesses get rid of their waste. - Implement high requirements on non-toxicity in recycled and raw materials. - Increase the understanding of the society's material flows. -Prohibit particularly toxic substances in products. - Improve dangerous content information, to promote safe recycling. - Expand the capacity for recycling. - Handle waste in non-toxic and resource-efficient cycles.	- Promote circular business models and resource circularity through investments in research, innovation and technology development within digitization, recycling, and traceability. - Implement policy instruments that will help to increase the supply and demand for circular services, products and materials. - Implement policy instruments that will increase the profitability of circular business models. - Increase the business and innovation climate in order to support circular companies to grow nationally and internationally. - Promote and speed up the development and establishment of sustainable production of new circulars innovations and technology by making the environmental permit review more efficient, while maintaining environmental protection.

In the Swedish action plan for the transition towards a circular economy several measures are presented, some of them are already established while others are proposals. Each measure is connected to one of the four focus areas, presented in the strategy plan. Within focus area *1. Circular economy through sustainable production and product design,* measures such as climate declarations for new buildings, a new construction product regulation in the European Union and Sweden's support in the European Union's product policy framework for the circular economy are presented. The climate declarations for new buildings will facilitate circular and bio-based construction by the requirement that a new building's climate impact must be reported (Regeringskansliet 2021b). This rule has been applied since January 1st, 2022 and it only covers new buildings. Hence, other facilities such as tunnels, sports fields and wind turbines are not covered by this rule (Boverket 2021).

Within the new construction product regulation in the European Union measures such as reporting of information about construction product content as well as digitalization would promote the transition to a circular economy in the construction sector. Furthermore, Sweden will work to support the regulations by the European Union concerning product design, the increased use of recycled materials in new products as well as circular business models that will support reuse, re-make and recycling (Regeringskansliet 2021b).

In focus area *2. Circular economy through sustainable ways to consume and use materials, products and services,* public procurements are presented as a measure to promote circular economy, reuse, recycling and circular business models. For instance, the National Agency for Public Procurement had a mission in 2020 on behalf of the government to look into how strategic procurement can promote a circular economy in the purchasing process. Moreover, in 2020 and 2021 the National Agency for Public Procurement and the Swedish National Board of Housing, Building and Planning was given the task to develop and modify the National Agency for Public Procurement's support in public procurements in order to reduce climate impact through the entire life cycle in the construction and real estate sector in public procurements in a cost-effective way (Regeringskansliet 2021b).

The measures presented in the third focus area*, Circular economy through non-toxic and circular cycles* refer to methods that will promote reuse and reduce waste. For instance, the government has tried to improve the regulation (2009:907) on environmental management in government agencies by commissioning the Swedish Environmental Protection Agency to review it. The aim of this measure was to steer the market towards sustainable services and business models as well as reduce waste and toxic products. Moreover, the government has commissioned the Swedish National Board of Housing, Building and Planning to identify systematic errors in construction since it represents a great waste of material and energy. The aim is to enhance the resource efficiency of these materials. Furthermore, the government has the aim to promote the expansion of the current material recycling facilities and in order to handle source-sorted waste it might be necessary to implement new innovative treatment methods. The third focus area also includes rules and aims within the construction sector. For example, new requirements regarding waste sorting from construction and demolition, waste prevention requirements as well as updated rules on control plans regarding construction waste, demolition waste and construction products that can be reused. In addition, the government has a goal to increase the management of non-hazardous waste from construction and demolition, by preparing construction materials for reuse and material recycling. Furthermore, the government wants to find new solutions to handle excavated material in a circular manner (Regeringskansliet 2021b).

In the fourth focus area, *Circular economy as a driving force for business and other actors through measures that promote innovation and circular business models,* environmental permits and promotion of research are some of the presented measures. Regarding the environmental permits, the government wants to modernize and make the environmental permit review more efficient in order to promote the establishment and development of sustainable production by new circular innovations and technologies. For instance, the government has started a review of the current system of environmental testing with the purpose to identify measures to develop a more modern and efficient environmental assessment while maintaining environmental protection. In addition, the government wants to make testing for environmental permits, supervision and environmental monitoring reinforced and more efficient (Regeringskansliet 2021b).

Considering research in the fourth focus area, the government intends to promote research, innovation and technology development within areas such as material recycling and digitalization. The goal is to improve circular business models and develop industrial processes to be more resource and cost efficient. The measures within this area includes Swedish participation in projects of common European interest (IPCEI) with the aim to develop fossil-free solutions within industrial ecosystems and sustainable technologies. It also includes the establishment of national research programs and investments in strategic innovation areas. Furthermore, the government wants more research that addresses different matters in society based on Agenda 2030, with a focus on a fossil-free and non-toxic circular economy and strengthened cooperation within the European Union and globally (Regeringskansliet 2021b).

Chapter 4 Theoretical framework: Circular economy in the construction sector

4.1 An important sector for the transition towards a circular economy

The construction sector is a prioritized sector in the transition towards a circular economy as it represents a sector with a great impact on the global environment. For instance, this sector is responsible for 33% of emissions and 40% of waste generation as well as the consumption of 40% of the natural resources in the world (van Stijn and Gruis 2020). In the European Union, 15% of the carbon emissions are derived from cement, plastics, steel and aluminium within the construction sector and buildings account for 40% of the total energy consumption (European Union 2022). In addition, around 40% of the total extracted mass from building demolitions is waste (United Nations 2020). Consequently, the construction sector receives a lot of attention within circular economy policies due to its resource consumption and waste production (Mansuy et al. 2022).

When applying the circular economy to the construction sector, different scales within the sector are often studied separately. According to Pomponi and Moncaster (2017) the different scales can be described by a framework, consisting of the following three levels:

- Macro level
- Meso level
- Micro level

The definition of the scales differs somewhat in the literature. Pomponi and Moncaster (2017) argue that the macro-level covers cities and neighbourhoods, the meso-level refers to whole buildings and the micro-level describes assemblies and components. This framework is supported by Benachio et al. (2020), except from the macro-level that they claim represents an industry scale. The research of circular economy in the construction industry can be divided into the three scales. For instance, the macro-level includes research of reuse of construction materials (Nußholz et al. 2019; Nordby 2019) and construction and demolition waste management (Niu et al. 2021; Cai and Waldmann 2019). Research regarding whole buildings belongs at the meso-level such as research about buildings with reused construction materials (Manelius et al. 2019). At the micro-level research about the reuse of specific construction materials are included such as wood (Foster 2020) and concrete (Yu et al 2021) as well as research on new reuse methods (Sanchez & Haas 2018a).

4.2 The complexity within the construction sector

The construction sector is characterized by great complexity, which makes the implementation of a circular economy challenging. For instance, there is a complex system of logistics, stakeholders and courses of action (Hart et al. 2019). All sorts of construction projects can also be divided into two categories, infrastructure and buildings. Moreover, every construction project is unique. For example, the location, the stakeholders involved, and the construction methods differ between projects. Furthermore, the set of materials and components used in a construction project are also unique and the way these are placed together can also vary. In addition, there are several different phases within construction such as the design, construction, maintenance, operation, modification, renovation, deconstruction and demolition. Hence, the transition to a circular economy within the construction sector needs to be applied to multiple aspects and areas within the sector and thereby several courses of action will be necessary (Mansuy et al. 2022).

4.3 Circular measures in the construction value chain

Within the construction sector value chains represent a kind of business model, which consists of all the activities and functions that are necessary in the project (Letsbuild 2019; Huan et al. 2004). The aim of the value chain is to make sure that the project is successful and reach maximum profit (Letsbuild 2019). The value chain includes the areas; design, manufacturing or production, construction or installation, maintenance and operation, and end of life which includes deconstruction or demolition (Huan et al. 2004). To integrate circular economy throughout the entire value chain is considered as a step towards sustainable development in the construction sector (Dewagoda et al. 2022). Looking at the entire value chain, several circular actions can be implemented in different fields, some of them are presented below.

Design

Of all the stages in the value chain, the design stage is considered to be specifically crucial in the implementation of circular economy. The reason for this is that several aspects are determined in this stage such as the way the construction is built, how it is used and how it will be handled in the end-of-life stage (Foster 2020). In the design stage there are several different strategies on how to implement circular economy. For instance, the construction can be designed with a life cycle assessment (LCA) in order to find ways to reduce the climate impact of the construction. In the life cycle assessment different objectives can be assessed such as CO_2 emissions, greenhouse gas emissions or global warming potential (De Wolf et al. 2020; Malabi Eberhardt et al. 2021; Oh et al. 2016).

Moreover, strategies such as off-site construction and designing for disassembly can be chosen. The off-site construction leads to material efficiency and waste reduction (Benachio et al. 2021), while designing for disassembly means that the construction contains of components that can be disassembled which enables the practical disassembly of the construction (Cai and Waldmann 2019; Munaro et al. 2019). Furthermore, designing with reused or recycled materials is another effective strategy to implement a circular economy by reducing waste generation and prolong the utilization of materials. The reuse opportunities can be evaluated by using different tools such as BIM model simulations to assess the reuse potential of different designs (Akanbi 2018; Akanbi 2019), life cycle analysis to compare the use of different reused materials (Eberhardt et al. 2019; Hossain & Ng 2018) as well as material stock data in order to promote reuse of materials (Oezdemir et al. 2017; Heinrich and Lang 2019; Manelius et al. 2019).

Manufacturing

The manufacturing phase is the phase where manufacturers and suppliers manufacture the products for the construction project. There exist several circular economy principles regarding the manufacturing phase. For instance, the building material agreement can be revised so that the manufacturers retain the ownership and can reuse the building materials after the construction’s end of life (Leising et al. 2018). Moreover, the manufacturers of building materials can introduce a circular economy by reusing secondary materials in the production (Nußholz et al. 2019). Furthermore, industrial symbiosis can be established, which describes a cooperation between the construction sector and other sectors in order to develop products together which covers both parties' demand and supply (Chen et al. 2022). In addition, material passports can be introduced to keep track of materials and their residual value and to enable take back management (Leising et al. 2018).

Another aspect of interest in the manufacturing phase is to choose local manufacturers and suppliers in order to reduce the energy and emissions connected to transportation distances

(Schmidt et al. 2021). Moreover, construction firms should prioritize choosing secondary building materials that are durable, recyclable, repairable and of high quality (Cai & Waldmann 2019; Munaro 2019; Kelly et al. 2019). Therefore, it is important with market competitiveness when it comes to characteristics and cost of secondary building materials (Liu et al. 2021; Migliore 2019).

Construction

Within the construction phase, a method that has several positive outcomes that correlates with circular economy principles is Lean construction (Benachio et al. 2021). Lean construction has been developed from the concept Lean production. Lean production is a production system that originates from the automotive industry with the aim of improving production by making it more flexible and efficient (Ohno 1988). The principles from Lean production have later been applied in the construction process under the name Lean construction and within the construction industry the concept was introduced by Koskela (1992). A principle within Lean construction that has a significant connection to the circular economy is off-site construction (Benachio et al. 2021). Off-site construction is also known as industrialized construction, modular construction or prefabrication (Chen et al. 2022). Off-site construction means that components for the construction project are manufactured off-site and in comparison, to the construction site the environment is more controlled in an off-site construction (Kyrö et al. 2019). Since the off-site construction is more similar to the manufacturing industry in comparison to the construction industry, it makes it easier to apply the principles of Lean production when this concept is used (Minunno et al. 2018). Some of the benefits with off-site construction is improved resource efficiency, quality control and less interference in the process (Jaillon & Poon 2010). By introducing off-site construction objectives such as waste reduction, reduced resource needs and less rework can be achieved (Serena & Altamura 2018; Benachio et al. 2021).

Operation and maintenance

Performing proactive and regular maintenance principles is an important phase in the construction value chain. By doing this the inner loops within the circular economy are prioritized and it is easier to determine the construction’s longevity (Dewagoda 2022). Moreover, according to Bourke and Kyle (2019) service life planning should be performed in order to ensure that the service life is as long or longer than the design life and the material choices should be adjusted to an eventual extended longevity. In order to monitor the performance of constructions and modernize maintenance plans during the service life of a building, a tool made by Akanbi et al. (2019) can be used. This tool evaluates the state of building materials over time. Moreover, another circular economy practice is to invest in preventive maintenance rather than recuperative maintenance (Benachio et al. 2020).

End of life

At the end of life phase, the building materials should be diverted from landfills to support circular waste management. The possibility to recover used building materials is connected to the design phase regarding designing with reused or recycled materials. However, it is impossible to divert all the construction wastes from landfills (Chen et al. 2022). In order to evaluate which materials can be recovered, resource assessments such as a pre-demolition review (Condotta & Zatta 2021) or a waste inventory (Bougrain 2020) can be performed.

When it comes to the choice between deconstruction or demolition, deconstruction is considered as the better option since it diverts building materials from landfills (Gálvez-Martos et al. 2018). Moreover, the deconstruction method helps retain homogeneous fractions after the disassembly (De Gregorio et al. 2020). However, the disassembly can be so complex that the economic and environmental costs connected to the disassembly exceeds the costs of investing in new components. Hence, a cost-benefit analysis is necessary in end of life planning (Sanchez and Haas 2018b).

After deconstruction circular logistics principles such as take-back schemes can be implemented, which means that the components or materials are returned to the manufacturers or suppliers (Kelly et al. 2019). Other circular ideas of logistics principles include industrial symbiosis and material banks. The concept of industrial symbiosis describes resource transferences between different industries of resources that are not fully utilized (Marinelli et al. 2021), while material banks are independent agents that store material and resources between utilizations (Cai & Waldmann 2019).

4.4 Challenges in the transition towards a circular economy

There exist several challenges within the implementation of circular economy in the construction sector. For instance, the objectives of implementing circular economy should cohere with many other business objectives. This means that other project objectives such as risk, cost, quality, health and safety should not be compromised in the sustainable development (Osobajo Oluyomi et al. 2020; Gálvez-Martos et al. 2018). Regarding the economic dimension, there might be a need for different business models in order to find profitability such as new ownership models, collaborative models with more transparency in data sharing to enable sustainable development as well as new business models between contractors instead of choosing the cheapest tenderer (Leising et al. 2018; Pomponi & Moncaster 2017).

Another factor that affects the implementation of circular economy is the complex system of stakeholders involved in every project (Hart et al. 2019). To successfully implement circular economy, stakeholders with great power should introduce policies that promote sustainable choices within the construction sector. For instance, circular procurement models can facilitate the transition to a circular economy by promoting circular materials, innovations and technologies (Alhola et al. 2019). Moreover, the behavioural dimension of stakeholders also matters. According to Pomponi and Moncaster (2017) attitudes towards recycling, energy and carbon reductions and reused materials can be a challenge when implementing circular economy.

Chapter 5 Theoretical framework: Wind turbines

Wind energy is renewable energy which is obtained through wind turbines. Wind turbines are used in many parts of the world to reinforce the power grid and mitigate climate change (Kaya 2022). There exist different types of wind turbines regarding application and design. For instance, wind turbines can be divided into different groups depending on the axis direction. A wind turbine can have a vertical axis direction or a horizontal axis direction. Moreover, larger wind turbines have the capacity to produce more power than smaller ones. However, there are operative disadvantages in larger wind turbines with vertical axis direction and therefore wind turbines with horizontal axis directions are the ones that have been established in larger sizes. Wind turbines with horizontal axis directions use the aerodynamic lift principle in order to rotate. What characterizes wind turbines with lift driven rotors is the rotor shafts orientation. The orientation can either be upwind or downwind. Regardless of the type of wind turbine, they all convert kinetic energy from wind into mechanical energy of rotation (Gasch & Twele 2012).

Since the energy system of wind turbines is dependent on wind, seasonal differences as well as geographical location affects the efficiency of the wind turbines. Some of the benefits of wind turbines are that they can generate power day and night compared to solar power that also is a renewable energy source, the pollution from wind turbines are almost non-existent in terms of emissions and the installation of wind turbines is flexible in the way that they can be installed in inaccessible and hilly areas (Kaya 2022). However, when installing wind turbines, it is essential to find a location where the mean wind speed is advantageous (Thomsen 2014).

When several wind turbines are installed together, they represent a wind farm. A wind farm can be installed onshore or offshore. Offshore wind farms are located in areas rather close to the coastline where the water is relatively shallow (Thomsen 2014). In comparison to onshore wind farms, offshore wind farms do not risk being hindered by limited space due to densely populated areas and the wind resource conditions are more beneficial offshore with dense winds and plenteous space. However, any kind of offshore work is often way more expensive compared to working onshore, as much as five to ten times more expensive. Therefore, offshore wind farms need to be larger systems with integrated sub-systems in order to be economically feasible (Gasch & Twele 2012).

5.1 The components of offshore wind turbines

Offshore wind turbines consist of several components. However, seen from the outside it can be described by three main components which are the nacelle, the tower and the rotor. The nacelle is placed on top of the tower and it contains several electrical components such as a generator and a gearbox. The electrical components inside the nacelle convert the kinetic energy into electricity. The rotor both consists of the blades as well as a central hub, which the blades are connected to. Another important component of an offshore wind turbine is the foundation. There exist different types of foundations for offshore wind turbines, but the most common ones are called jacket, tripod, monopile and gravity base (Thomsen 2014).

When designing an offshore wind farm, several factors need to be considered. The conditions offshore differ from the one onshore resulting in challenges and opportunities. For instance, the wind is more advantageous offshore with a higher average wind speed and the ambient turbulence is lower. However, the offshore environment generates loads from sea ice, currents and waves and the sea level varies over time. Moreover, corrosion is more aggressive offshore due to salinity and high humidity. The offshore wind turbines should function for many years, up to 20 years, at locations that are hard to access for maintenance. All these factors result in high requirements regarding the design (Gasch & Twele 2012). In the following sections, the larger structural parts of an offshore wind turbine are further described.

Tower

The tower's function is to support the structure of the turbine which is the mass of the rotor and the nacelle (Nyserda 2023). The tower is made of two or more sections of tubular steel (Thomsen 2014). These sections are mounted on site. The taller the tower, the more electricity can be generated by the wind turbine, since the wind speed increases with height. Moreover, a high tower also results in less turbulent wind since the wind turbulence changes above 30 meters above ground level (Energy Efficiency & Renewable Energy 2023).

There exists a significant construction complexity when it comes to the tower of a horizontal axis wind turbine. Together with the foundation the tower shall provide a static stability of the whole wind turbine structure, which is a decisive criterion for obtaining a construction permission. In addition, it is also very important that the tower and foundation should provide a dynamic stability of a wind turbine (Gasch & Twele 2012).

The design of the tower has several connections to the economic efficiency of a wind turbine. For instance, the design of the tower affects transport and installation costs. In addition, the cost for the tower itself represents a significant part of the initial costs of the wind turbine, around 15-20 %. Moreover, the profit of a wind turbine depends on optimum height of the hub which is directly related to the height of the tower. As mentioned earlier, the wind speed increases with height and the increase can be described with a logarithmic pattern. If the hub is positioned at elevations above the atmospheric surface boundary layer it leads to a constantly higher energy yield. Consequently, the optimum height position of the hub and therefore the height of the tower is adapted to every unique site (Gasch & Twele 2012).

Tubular towers represent a common tower design which means that the tower has a round or polygonal section. In tubular towers the size of the section area increases from the top to the bottom. The tower can be manufactured from different materials such as steel, concrete or a hybrid of steel and concrete (Gasch & Twele 2012). However, for offshore wind turbines steel is mainly used (Zee et al. 2017). The tubular design enables secondary steel also called internals inside the tower. Secondary steel is also part of the design of the tower and it consists of several parts that are crucial for the operation and maintenance of the wind turbine such as electrical conduits, access staircase, internal ladder, lifts, platforms, light panels and cable trays. Regarding offshore wind turbines, secondary steel can also include helipads, boat landing, crane pedestals and anodes (Ng & Ran 2016).

Another factor that must be considered in the design of offshore wind turbine towers is the risk of corrosion caused by sea water, changes in temperature, biological fouling and sea spray. Corrosion damages can reduce the life span of components since it removes the steel fatigue limit. Therefore, offshore wind turbine towers should be designed with a suitable corrosion protection system. When the corrosion system is designed, a balance should be made between the costs of the corrosion system and the costs of repairs (Ng & Ran 2016).

Foundation

The function of the foundation is to provide a steady base to the tower and to the other components that are above water (Nyserda 2023). In order to achieve that the foundation needs to create enough moment and holding force so that the bending moments and movements that originate from the wind's influence on the turbine can be resisted (Thomsen 2014). However, when designing a foundation to an offshore wind turbine there are more factors to take into consideration. The water depth, wave load, ground conditions and turbine induced frequencies have to be considered in the design. For instance, the load and bending moments created by the waves exceeds the loads from the turbine itself. Moreover, when the turbine acts and counteracts with the load from the waves this can result in higher loads for the foundation. Furthermore, the composition of the seabed will determine at what depth there is a bearing capacity from the ground. Other aspects that need to be considered regarding offshore foundations is the complex transport and installation due to the foundations' weight and size. Moreover, the installation of a foundation includes preparation with dredging and backfilling material in the seabed (Thomsen 2014). Taking the various conditions into account, a suitable foundation can be designed. In the following sections some of the most used offshore foundations will be further explained.

Monopile

The foundation monopile is made from steel and formed as a tube (Thomsen 2014). The tube consists of several sections and it has a diameter between 4-8 meters (Thomsen 2014; Ng & Ran 2016). Moreover, the wall thickness of the tube sections varies between 55-150 mm and the thickness depends on the loading conditions and the installation. The total weight of this type of foundation is up to 1000 tons. Monopiles are suitable to use in shallow water depths between 20 - 40 meters. However, this type of foundation can be too flexible in water depths between 30 - 40 meters and therefore special wires can be fitted together with the monopile in these kinds of water depths in order to ensure a stable construction (Ng & Ran 2016). When installing the monopile a large hydraulic hammer is used to install the foundation in the seabed. This foundation is often used in semi hard or hard seabed and due to the side friction of the seabed the monopile will stand upright (Thomsen 2014). During the installation different kinds of measures such as isolation casings and hydro sound dampers can be used to reduce the noise from the hydraulic hammer with regard to the environment (Ng & Ran 2016).

Tripod

A tripod is a foundation that is manufactured from steel and suitable to use in water depths between 25 - 50 meters (Ng & Ran 2016). The tripod is designed like a monopile with a large diameter at the top of the foundation in the wave zone area and at the bottom the construction is three-legged. This design results in significant stability to withstand bending moments. The tripod is installed by using anchor piles that go through pile sleeves at the end of each "leg" and are attached to the seabed. Due to the anchor piles the tripod can withstand strong vertical forces derived from the waves and the turbine, which is one of the benefits with the tripod. Moreover, because of the monopile design at the top of the foundation, the same calculations for loads deriving from waves can be used for monopiles and tripods (Thomsen 2014). However, the installation of a tripod foundation is rather complex, it requires special equipment and it takes two to three days to complete, in addition, to manufacture a tripod is expensive (Thomsen 2014; Ng & Ran 2016).

Jacket

A jacket foundation is a steel construction that consists of thin tubes in a lattice structure. The jacket foundation is fixed in the ground by anchor piles through corner pile sleeves (Thomsen 2014). The jacket foundation is the preferred foundation for offshore wind turbines placed on locations with large water depths between 50-80 meters (Empire engineering 2021). The benefits with jacket foundations are the low weight in relation to the size of the foundation and the possibility to increase the bending and force moments significantly by giving the foundation a larger footprint. However, this type of foundation is expensive to manufacture, and it is complicated to protect the foundation from ice loads, which increases the costs even more (Thomsen 2014).

Blades

The function of the blades is to convert energy from the wind into mechanical energy (Nyserda 2023). The reason why the rotor spins is because of differences in air pressure caused by the wind, since the air pressure on one side of the blade is reduced when wind is flowing on the blade. This results in both lift and drag forces, where the lift force exceeds the drag force which makes the rotor spin. The size of the blades varies. For onshore wind turbines the blade size is often over 52 meters, while the blades of offshore wind turbines can be twice as big (Energy Efficiency & Renewable Energy 2023). The blades represent a part of a structure that is highly loaded and lightweight, and it is important to find a balance between the load requirements and the manufacturing costs, operation and maintenance as well as deconstruction (Ng & Ran 2016).

When designing an offshore wind turbine, the conditions differ a lot from onshore and therefore the design can be different. For instance, the most common design of wind turbines has three blades (Energy Efficiency & Renewable Energy 2023) and the two-bladed turbine is not suitable to use onshore due to its noise and how it is visually perceived (Ng & Ran 2016). However, using the two-bladed turbine offshore would not have this impact and it would benefit the installation and transportation offshore. Moreover, the blades of offshore wind turbines can be designed to have a slenderer profile in comparison to the blades of onshore wind turbines. A slender profile of the blades results in a higher tip-speed ratio, which increases the noise. However, this is not a problem offshore. The benefits of a slender blade profile are potential reduction of material in the blades as well as a reduction of loads in several components such as the tower and foundation which results in material and cost savings. Furthermore, the offshore wind turbines can be designed with downwind rotors since the negative factors with this design, regarding noise and tower shadow, does not represent an issue offshore. This design can result in a reduced weight of the blades (Ng & Ran 2016).

The blades are often manufactured from fiber-reinforced plastics which is a polymer matrix reinforced with fibers (Ng & Ran 2016). This material has many benefits such as a low density and good quality regarding fatigue and stiffness. For the reinforcement material E-glass represents the most used one in wind turbine blades. The polymer can be thermosetting or thermoplastic and its function is to create a stable structure of the fibers. The thermosetting matrix is produced by an irreversible reaction, where a resin and a hardener react, and the resin creates crosslinking between the polymer chains. Since the reaction is irreversible, the recycling of the thermoset plastics is difficult. The matrix material can consist of epoxies, polyesters and vinyl esters. However, epoxy resins are most often used. The thermoplastic matrix materials are not as common to use as the thermosetting matrix materials due to difficulties in processing the materials. However, thermoplastic is easier to recycle and therefore research is carried out regarding this topic (Ng & Ran 2016).

5.2 Circular economy and wind turbines

As the demand for sustainable energy increases, wind turbines represent a renewable energy source that can reduce greenhouse gas emissions and mitigate climate change in comparison to energy sources that are not renewable. As a consequence, wind turbines have become a popular energy source and the waste volumes from wind turbines are expected to increase rapidly, both due to an increase of the number of turbines as well as an increase of the size. In order to prevent and reduce waste from wind turbines it is crucial to examine the entire life cycle of wind turbines and to implement circular business models (Woo & Whale 2022). The normal operation life for wind turbines is 20 years and when this point is reached there are three different options to apply; repowering, lifetime extension or decommissioning (Wind Europe 2022). Below these various methods and principles are explained further.

Repower

To repower a wind farm means replacing the old wind turbine or parts of it by new components or a new turbine (Wind Europe 2022; Woo & Whale 2022). The benefits with repowering are that the new turbine or components results in increased electricity output with a smaller number of wind turbines since the latest technology is more powerful and efficient. Moreover, a lot of the old existing wind turbines are located at optimal wind conditions and therefore it is beneficial to keep using these locations for wind turbines. For instance, an efficient example of repowering took place at a wind farm in Galicia in Spain as a result the electricity output was doubled while the number of wind turbines was reduced from 69 to 7. However, repowering requires a permit and the process of obtaining it can be slow and complex. The permitting process can be discouraging for the operators and less than 10 % of old wind turbines are repowered (Wind Europe 2022). In addition, partial repowering can be associated with risks since the original infrastructure needs to be compatible with the new possibly larger components and the maximum loads shall not be exceeded (Woo & Whale 2022).

Lifetime extension

Lifetime extension describes methods that extend the operation of the wind farm, making it exceed the design life. This is performed with minimal investments, necessary maintenance (Schumacher & Weber 2019) and it can include replacement or reconditioning of the generator and control systems (Wind Europe 2017). Moreover, it is often necessary to replace or repair the rotor blades' bolted connections, since these usually represent the element that reaches their design load limits first (Schumacher & Weber 2019). However, the overall design including the turbine size and the hub height remains the same (Woo & Whale 2022). Lifetime extension represents a common method that is often used when wind turbines have reached the end of their design life (Wind Europe 2022). A lifetime extension assessment needs to be carried out before considering this option. In the assessment the physical condition and the theoretically admissible lifetime of the wind turbine are determined. The results from the assessment both indicate the feasibility of the lifetime extension and when specific components should be replaced. Depending on the result of the assessment a decision can be made whether the lifetime extension method is a suitable option for the specific wind turbine or if another option should be considered (Schumacher & Weber 2019).

Decommissioning

The last option is decommissioning. Together with repowering this option often results in waste even if old turbines can be resold. The blades of a wind turbine are difficult to recycle due to the polymer composite materials and therefore the blades often are the focus of the challenges regarding wind turbine waste (Jensen & Skelton 2018). In the following sections different options after decommissioning are presented starting with the highest desired and ending with the least desired option according to the waste hierarchy.

Reuse

There exist several opportunities to reuse entire wind turbines or components of them. For instance, companies offer dismantling and resale services on this market. Moreover, there is a second-hand market within this area for wind turbine components. The pre used wind turbines and components play an important role for developing markets since it provides in-demand technology at lower costs (Woo & Whale 2022).

Repurpose

Repurpose means finding another function for a product or component than its original purpose while the product or component remains the same engineered structure. There are several examples of repurposing the blades of a wind turbine. For instance, wind turbine blades have been used as bus stops, museum pieces and signs, outdoor public seats, pedestrian bridges, powerline poles and house roofs (Woo & Whale 2022; Delaney et al. 2020).

Recycle

Around 94 % of the weight of a wind turbine excluding the foundation consists of recyclable metals. For example, the tower, generator, gearbox, nacelle and hub components contain metals like steel, copper and aluminium. The rest of the weight consists of polymer composites from the blades as well as rubber, plastic, power electronics, lubricant and cooling materials. These materials are complicated or not feasible to recycle (Beauson and Brøndsted 2016). Even if recycling of wind turbine blades is difficult to perform and not commercialized yet, there exists different techniques to recycle the blades. For instance, mechanically recycling by milling or grinding are suitable for glass fiber-reinforced composites, while chemical processes can be used for carbon fiber reinforced polymers. However, these methods can have disadvantages.

The mechanical recycling can be energy-intensive and the properties of the fibers can become deteriorated in the process (Woo & Whale 2022).

In the chemical recycling both glass and carbon fibers as well as matrices are recovered by using solvents to break down the composites' resins. This process affects the properties of the material components less than mechanical recycling. However, some solvents such as supercritical water as a green solvent are more suitable than others and the efficiency of this method is related to the matrix compounds, which poses a challenge (Woo & Whale 2022; Kalkanis et al. 2019).

Recover

Recover is another option in the waste hierarchy. For instance, wind turbine blades can be used for cement production as a fuel, which represents energy recovery. However, this option is considered problematic due to the emissions from the process, the low efficiency of incineration when using material that contains much glass fiber and its negative effects on the gas cleaning system (Woo & Whale 2022).

Dispose

To dispose components from wind turbines is the least preferred option after decommissioning. In most countries the wind turbine blades are often disposed of in landfills. However, in the European Union the majority of the member states supports a ban of composites in landfills (Krauklis et al. 2021) and as the influence of circular economy on regulations and laws are increasing, landfill of blades are most likely being avoided in the future (Woo & Whale 2022).

5.3 Permits for offshore wind turbines

In order to build an offshore wind farm, a permit is required and this requirement applies worldwide. However, the permitting process can have significant differences depending on the country in which the permit is applied for. For instance, one country can have a comprehensive permitting process with detailed regulations, while another only has a few regulations. As a consequence, the extent of plans for the wind farm and the regulatory process' consistency are affected depending on the national location of the wind farm. The permit for offshore wind farms represents a crucial challenge for technology development and there exists an aim to create a common European Union standard for the construction of offshore wind farms

(Thomsen 2014). In the following section the permitting processes for offshore wind farms in Germany and Sweden will be further explained.

Germany

Germany represents an important manufacturer of wind turbine components and installation equipment and has a large number of onshore wind turbines. Since the past two decades Germany has had ambitious aims regarding the offshore wind energy industry with plenty of planned projects. However, it was not until after the Fukushima nuclear plant catastrophe in 2011 that real change occurred, and the renewable energy industries were boosted due to the political plan to shut down all nuclear plants by 2022. As a result, the offshore wind farms have become popular and the potential along the German coastline is in favour for offshore wind farms (Thomsen 2014).

In the permitting process German laws and regulations concerning nature conservation, the environment, technology and sea ecology are included. There exist two different kinds of permissions, which depend on the region of the offshore wind farm. One of the regions is the territorial sea, also called the 12 nautical mile zone and the other is called the exclusive economic zone and represents the area ranging between 12 to 200 nautical miles from the coastline. It is the exclusive economic zone that is of importance regarding the offshore wind energy industry and the 12 nautical mile zone has less of a meaning to the industry with the exception of permission for underground electric cables (Thomsen 2014).

With the aim to accelerate the permitting process for offshore wind farms and to improve the spatial planning of grid infrastructure, the German government has increased the power of the Federal Maritime and Hydrographic Agency. In practice it means that the Federal Maritime and Hydrographic Agency should locate suitable areas for wind farms and maintain a plan for the offshore grid within the exclusive economic zone (Thomsen 2014).

When applying for a permit, the applicant needs to submit several documents that are required by the Federal Maritime and Hydrographic Agency. In addition, they need to hand in a time schedule, an action plan and an environmental impact assessment. Moreover, sometimes safety requirements surveys are also required. After all these required documents have been handed in, it is up to the public interest to ask questions and share their concerns. For instance, an authority or federal agency can have concerns regarding environmental or shipping factors.

The Federal Maritime and Hydrographic Agency then decides whether they need additional documentation from the applicant. After receiving additional documents, if requested, the federal agency again shares the documentation with relevant public interest parties, giving them another chance to express their concerns. Based on the concerns from the public interest and the documentation, the Federal Maritime and Hydrographic Agency then decides to approve or reject the proposal from the applicant. If the applicant receives a permit from the federal agency, this includes all the permissions from other public authorities. By letting the Federal Maritime and Hydrographic Agency collect permits from other relevant authorities the length of the permitting process is reduced (Thomsen 2014).

Sweden

The permitting process for offshore wind farms in Sweden has similarities with the process in Germany. In Sweden the permitting process also differs depending on which zone the wind farm plans to be constructed in. Just like in Germany the zones are separated by the territorial boundary which is located 12 nautical miles from the coastline. Within the territorial boundary there are internal waters and between the territorial boundary until 200 nautical miles from the coastline is the economic zone (Energimyndigheten 2022). However, the permitting process is significantly longer for offshore wind farms in Sweden compared to Germany and it usually takes about 9 years to receive the permit. In Sweden, wind developers apply for permits from several different authorities and courts. Furthermore, it is up to the developer to find a suitable area to build on and carry out their own investigations in this area, which also requires permits (Energi 2023). However, shortening the permitting process for Swedish offshore wind farms may become relevant. During the spring 2023 the Swedish government appointed an investigation to streamline the establishment of offshore wind power. The results of the investigation will be presented before the end of June 2024 (Regeringen 2023).

Chapter 6 Results

Chapter 6.1 and 6.2 are the result of the document study, while chapter 6.3 presents the results from the interviews. Documents from RWE Renewable's website as well as internal documents were used for the document study. The internal documents are presented below in table 2. Moreover, internal photographs from RWE Renewables were used in chapter 6.2 *Construction*.

Table 2: Internal documents that were used in the study.

Type of document	Document title	Author	Year	Used as a source in subchapter
Report	Emission study for the project OWF "KASKASI II"	BioConsult	2022	6.2 *Environmental effects*
White paper	Technology White Paper SGRE Wind Turbines RecyclableBlade Concept	Siemens Gamesa	2021	6.2 *Designing for recyclability - recyclable blades*
Report	Decommissioning Programme for Triton Knoll Offshore Wind Farm	RWE	2018	6.1 *End of life example*
Powerpoint presentation	Kaskasi OWF WTG SGRE "Recyclable Blades" O&M Team-update	RWE	2022	6.2 *Designing for recyclability - recyclable blades* and 6.2 *Construction*

6.1 RWE Renewables

Business model

RWE Renewables is a developer of sustainable energy solutions. The company is a part of RWE, which is a German international energy company. RWE Renewables has been active in the Nordics since 2018 where they develop, build and operate onshore and offshore wind farms (RWE 2023a). In the Nordics, Sweden represents the key market, but they are also expanding in Finland, Norway and Denmark. Currently they are operating wind farms in Sweden and Denmark. RWE Renewables is also active in Europe, Asia-Pacific and in North and South America (RWE 2023b).

RWE Renewables focuses solely on sustainable energy such as solar energy, wind power and energy storage and their goal are to accelerate the transition to a sustainable energy system. Outside of their main business area, RWE Renewables also focuses on supporting local organizations as part of their economic, environmental and social sustainability efforts. For instance, they support a research project at Lund University called Biopath, which aims to improve biodiversity work within the energy sector. Moreover, they are partners in the network *A sustainable tomorrow*, where they can contribute by sharing ideas and knowledge regarding renewable energy and collaborate with other partners in order to achieve the UN's global sustainability goals in Agenda 2030 as well as their own goal which is to reach zero net emissions by 2040 (RWE 2023b).

RWE Renewables represents the world's second largest operator of offshore wind farms. They have 18 offshore wind farms, which together have a capacity of 2.4 GW. The offshore wind farms are located in Europe along the coasts of Germany, the UK, Belgium, Sweden and Denmark. In Sweden they have one wind farm in operation and several in development. The Swedish wind farm in operation is called Kårehamn and it is located close to the Swedish island Öland in the Baltic Sea. The construction of the wind farm was finished in 2013 and it has 16 wind turbines from the supplier Vestas which each has a capacity of 3 MW. Some of the Swedish offshore wind parks in development are Södra Victoria and Neptuni. Södra Victoria is planned to be constructed southeast of Öland and the total capacity of the wind farm is estimated to be between 1,400 MW up to 2,000 MW. The wind farm is expected to reduce regional capacity shortages by strengthening the energy supply to southern Sweden. The other project in development, Neptuni, has an estimated capacity of 2,000 MW and would also strengthen the energy supply to southern Sweden (RWE 2023c).

Examples of circular economy measures

In some of their wind farm projects RWE Renewables has invested in solutions that support a circular economy. For instance, the company has used the world's first recyclable blades from the supplier Siemens Gamesa in the Kaskasi wind farm in Germany. The same kind of recyclable blades will also be used for 44 out of 100 turbines at the wind farm Sofia, which is in construction in the central North Sea, along the North East coast of the UK. There has never been such a large order of recyclable blades at any wind farm before. However, due to the current market capacity with a shortage of the new resin used in the blades, they could not order recyclable blades to all the wind turbines since it was not available. Moreover, they have a goal to produce 50 percent of the blades to the Sofia wind farm in the UK, which will support the local supply chain (RWE 2023d).

In another wind farm, Thor, which plans to be constructed in the Danish North Sea in 2026, greener steel will be used in the towers. The towers are called GreenerTowers and they will be provided by the supplier Siemens Gamesa. The GreenerTowers consist of greener steel, which results in at least 63 percent less CO_2 emissions related to the tower steel plates. In the production of green steel there is a higher percentage of scrap steel and the production is less energy-intensive and powered by green electricity. There will be a maximum of 0.7 tons of CO_2-equivalent emissions per tonne of steel in the new towers, which will be verified by third-party certification. The steel properties and quality of the towers will not be affected by the green steel production. RWE Renewables will be the first developer globally to use the GreenerTowers. Half of the 72 wind turbines at the Thor wind farm will be constructed with the new GreenerTowers (RWE 2023e).

Another measure that RWE Renewables has implemented to support a circular economy and reduce emissions is an agreement with Acta Marine for service operation vessels with green fuel for two wind farms in the North Sea. The agreement with Acta Marine includes to build and operate two green service operation vessels, which will be powered by methanol and batteries. The new vessels will reduce up to 10,000 tons of CO_2 emissions annually. The vessels are expected to be delivered by early 2025 and 2026 for the wind farms Sofia and another offshore wind farm in the North Sea called Triton Knoll. The new vessels will be used for long-term operation and maintenance of the wind farms. The initiative supports Operation Zero, which is an industry coalition with the aim of zero-emission from vessels and infrastructure used in the operation of offshore wind farms in the North Sea from 2025, launched by the Department for Transport and the ORE Catapult. Moreover, the initiative also supports the Carbon Trust programme, where RWE Renewables and other developers collaborated with the Carbon Trust in order to develop guidance on how to measure and address carbon emissions from the lifecycle of offshore wind farms (RWE 2023f).

End of life example

In RWE's offshore wind farm Triton Knoll which is located off the east coast of England and was commissioned in 2022, they plan to decommission the wind farm after about 25 years in operation. In a decommissioning plan for the wind farm they have made preliminary estimations of how the various components will be handled in connection to the decommissioning. During the decommissioning phase they will apply various principles with regard to the environment such as increasing the reuse of materials and promoting sustainable development. The blades and the towers plan to be disassembled and transported to the onshore processing area where they will be divided into manageable sizes for disposal or recycling. Regarding the towers, the value of steel is estimated to increase significantly and therefore they will prioritize selling scrap steel. When it comes to the blades consisting of glass reinforced plastic they are expected to be recycled, since disposal in landfills most likely will not be allowed.

The foundations, which in this case are monopiles, will be cut off below the seabed surface. The level of this cut will be decided with regard to safety aspects for vessels that will travel across the area in the future. Due to no available appropriate technology to remove the remaining parts of the monopiles, which probably also would be very expensive, those will be left in the seabed. However, by leaving the remaining parts in the seabed, the seabed will not be exposed to any more interference. The removed parts of the monopiles will most likely be sold as scrap. All the cables in the seabed will be left there. The waste management will be carried out in regard to the waste hierarchy and the legislation.

Circular economy policy

RWE has a circular economy policy that took effect from the 1st of March 2023. The circular economy policy is approved by the board of directors at RWE and applies to RWE AG including its direct subsidiaries. The principles are implemented in line with the regulations for respective country and business activity. The purpose of the policy is to approach RWE’s goal regarding full circularity by 2050. The ambition of the policy is to introduce circular principles in their business activities by reducing the consumption of natural resources, limit waste and design their assets to enable reuse or recycling of materials. The principles will be applied throughout the complete life cycle of assets, which includes development, construction, operation, decommissioning, demolition and re-cultivation. Since the majority of RWE’s assets have a lifespan over 25 years, the choice of components and material are crucial for the level of circularity by 2050. Their aim is to reduce the dependency on primary materials by procuring substantial components at competitive price levels. Moreover, RWE believes their circular economy policy will contribute to several sustainable development goals such as affordable and clean energy, economic growth, clean water and sanitation as well as responsible production and consumption (RWE 2023g).

In order to implement principles of circular economy in the different lifecycle phases, RWE has formulated a circularity framework to highlight the three main principles, which will be described in the following paragraphs.

1. The first principle is to *reduce consumption and increase inflow of circular material*. This principle will be implemented by finding ways to increase refurbished, reused and recycled materials in their material inflow. Moreover, they will prioritize suppliers which apply circular business models such as take back management. In addition, the principle also means taking responsibility for the supply chain by informing suppliers about their circularity requirements and choosing the more circular supplier and products if there is an equality in a relevant criterion such as price (RWE 2023g).

2. The second principle is to *enhance material (re)use and lifetime.* This principle will enable a more circular business model by encouraging lifetime extension and increasing the repair, refurbishment and reuse of components. These measures can be applied as long as they do not influence the required safety standards. By implementing these measures, the generation of waste is expected to be reduced as well as the need for new products. Aside from the circular aspect, principle 2 also benefits the economic aspects of the company (RWE 2023g).

3. The third principle is to *minimize end-of-life treatment*. In other words, the aim of this principle is to avoid undesirable options of waste management such as waste disposal in landfills as well as incineration of waste. Moreover, they have a target to minimize the outflow of materials. In addition, they will inform their direct downstream service providers of their circularity ambitions and request more circular waste management. Furthermore, they will choose the service providers with more circular business models in case relevant criteria such as price is equal (RWE 2023g).

In addition to the framework, RWE has also formulated three circular enablers that aim to support their circular goals. One of the enablers is to form long-term circular partnerships in order to increase circular inflow and outflow of their products and components. This will be implemented by maintaining and improving the partnerships with their direct suppliers such as original equipment manufacturers, industry peers and waste contractors. Together with their suppliers they hope to develop circular joint measures. In addition, they will support their partners to include circular measures during the design phase, such as increase the repairability and lifespan and produce recyclable products. Another circular enabler is to measure the circularity progress. This will be carried out by developing metrics and key performance indicators that are suitable for measuring the progress. For instance, they will develop data collection and reporting of waste. The aim of the measuring is to quantify important aspects, learn from and develop measures as well identifying where the circular measures can be improved. The last circular enabler is to design for circularity. This will be implemented by cooperation with partners and by encouraging them to design products that are recyclable, easy to repair and durable for a long period of time. This circular enabler aims to reduce future waste as well as greenhouse gas emission (RWE 2023g).

6.2 The Kaskasi wind farm

The Kaskasi wind farm is an offshore wind farm located in the German North Sea, 35 kilometres from Heligoland. The wind farm consists of 38 wind turbines from the supplier Siemens Gamesa. The construction of the wind farm was completed in 2022 and the wind farm has been in operation since the end of 2022. Each of the turbines has a capacity of 9 MW, with a total of 38 turbines and this results in a total capacity of 342 MW, which supports 400,000 households with renewable energy. The wind turbines at the Kaskasi wind farm have a hub height of 107.5 meters and a total height of 191 meters (RWE 2023h).

The Kaskasi wind farm is characterized by several innovations. A new kind of installation technique for the foundation has been tested as well as modified monopile foundations. In addition, the world's first recyclable wind turbine blades have been installed at the wind farm. With the new installation technique, the monopiles are installed by using a vibratory pile driving method instead of the established hammering technique. A research project called VISSKA is evaluating the efficiency of the new method, which aims to reduce the negative environmental effects of noise emissions. Moreover, the monopiles foundations have been supported by steel collars, which results in a higher load bearing capacity. The collars were installed at the seabed level, mounted around the monopiles. The design of the collars is an RWE patent, which is installed for the first time at the Kaskasi wind farm (RWE 2023h).

Designing for recyclability - recyclable blades

The Kaskasi wind farm is the first wind farm in the world to be installed with recyclable blades. The recyclable blades are manufactured by Siemens Gamesa with a new special resin whose chemical structure will enable separation of the components in the blade and the resin. The blades manufactured for the Kaskasi wind farm are 81-meter-long and constitute a step towards complete recyclability of wind turbines (RWE 2023h).

According to Siemens Gamesa the recyclable blades are a result of several factors. For instance, the increasing size and number of installations of wind turbines corresponds to a waste management challenge, which will escalate in the following years. Although the majority of wind turbine components can be recycled, it has never been cost-effective to recycle the blades due to difficulties in separating the resin system from the other materials in the blades. Moreover, there are options to reuse the blades for highway sound barriers or in the production of cement, but these options are relatively expensive. The cheapest waste management alternative at the moment is disposal in landfills of fiber-reinforced composites and approximately 10 % of the fiber-reinforced composite waste in Europe is related to wind turbines. However, this alternative has already been or is expected to be banished by several European countries. In addition, several countries plan to introduce a requirement for over 95 % recyclable material.

The new design means that the resin system can be effectively removed from the remaining materials, which often are glass and carbon fiber reinforced composites and a core material such as balsa or polyethylene terephthalate. Siemens Gamesa has validated the new resin system by multiple laboratory tests, which showed that the resin system meets their quality requirements. The new resin enables a more cost-effective recycling compared to previous recycling attempts. In the new recycling process, the properties of the materials are protected which allows them to be used in the production of new products (RWE 2021a). According to Siemens Gamesa the new recyclable blades will have the same quality, strength and service processes as their previous blades. Regarding the operation and maintenance there will not be a need for any special focus on the blades. However, RWE Renewables should regularly inspect the blades for mechanical changes such as delamination or cracks.

At the end of life stage, the wind turbines will be dismantled, and the blades will be transported to a facility where they will be recycled, and the material can be used in production of new products. The concept of the recycling process can be implemented in conventional production environments and when it is time to dismantle the wind turbines with the new blades Siemens expects there will be several suppliers for blade recycling on the market. The recovered materials from the recycling process are for instance expected to be used in the automotive industry, or in the production of flight cases and flatscreen casings or other consumer goods (RWE 2021a).

According to Siemens Gamesa there are several benefits with the new blades. For instance, the environmental footprint will be improved by increasing the circularity of wind turbines. For the developers of wind farms this will improve their chances in auctions and tenders, when there are environmental requirements. Moreover, RWE Renewables believes the recycling might enable selling the recycled materials which would possibly mean a shift from decommissioning cost to profits.

Construction

During the construction of the Kaskasi wind farm, the components were delivered to an area at an onshore port, which functioned as a storage location of material and components. Certain components could also be further assembled at this area before the offshore construction. The different components were later transported to the offshore construction site, where they were mounted. Respondent 7 described that this represents the normal case regarding logistics when constructing an offshore wind farm.

The monopile foundations used in the Kaskasi wind farm have a diameter of 6-6.5 meters and a maximum length of 64 meters (RWE 2023h). The monopiles were installed in water depths of 18 to 25 meters using a new vibratory piling technique and respondent 3 explained that they also used the conventional hammering technique. In figure 2 the monopiles are loaded on a vessel before construction.

Figure 2: Monopile foundations are lifted onto a vessel (RWE Renewables n.d.).

In the Kaskasi project the new vibratory pile driving method was carried out to install the monopiles with the objective to reduce underwater noise and installation times. In the method vertical vibrations are used to install the foundations into position. The project was carried out in cooperation with itap GmbH, BioConsult SH GmbH & Co. KG as well as the University of Stuttgart - Institute of Geotechnical Engineering and Technische Universität Berlin - Foundation Engineering and Soil Mechanics and funded by the German Federal Ministry of Economic Affairs and Energy. One of the aims with the new method was to find a more environmentally friendly alternative, which would take away the need for additional noise reducing measures to protect marine mammals (RWE 2021b) However, respondent 3 explained that they had to use their backup plan, the hammering technique, since there were difficulties with the vibratory pile driving method. The hammering technique is shown in figure 3.

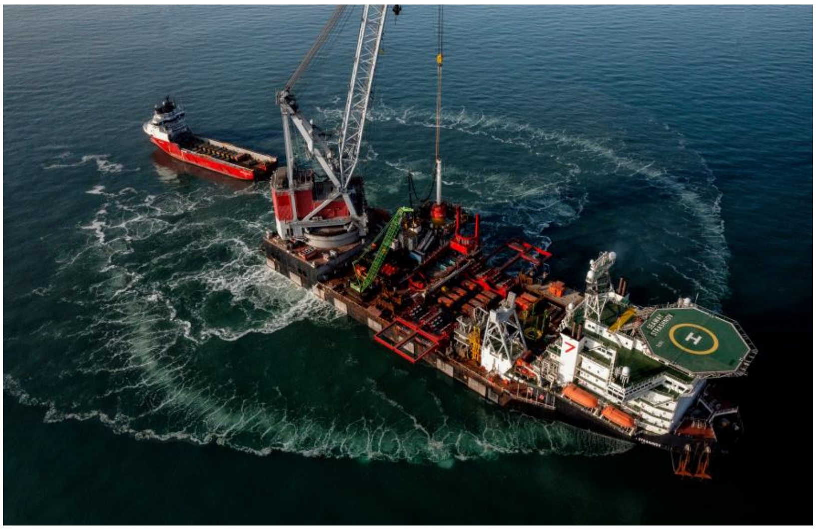

Figure 3: Installation of a monopile foundation carried out with the hammering technique (RWE Renewables n.d.).

Three of the monopile foundations in the Kaskasi wind farm were supported by special steel collars, which represents a design based on an RWE patent. The objectives of the new collar are to increase the bearing capacity and to improve the foundation's structural integrity as well as the support for lateral loading, which will be verified by tests. The collars were manufactured by Bladt Industries and the transportation and installation of the collars were carried out by DEME Offshore. The 7 meters high and 170 tons heavy collars were installed at the seabed level around the monopiles and grout material was used to fill the space between the components to form a stable connection (RWE 2022). The installation of one collar is shown in figure 4.

Figure 4: Installation of a steel collar, photo by DEME Group (RWE Renewables n.d.).

The towers were transported to the onshore port in sections, were they were mounted into one piece and later loaded on a vessel before construction. The construction of the towers is shown in figure 5.

Figure 5: Installation of a tower (RWE Renewables n.d.).

The blades were transported in one piece to the onshore port and three blades were installed to each wind turbine. The proportion and installation of the 81 meters long blades are shown in figure 6 respectively figure 7.

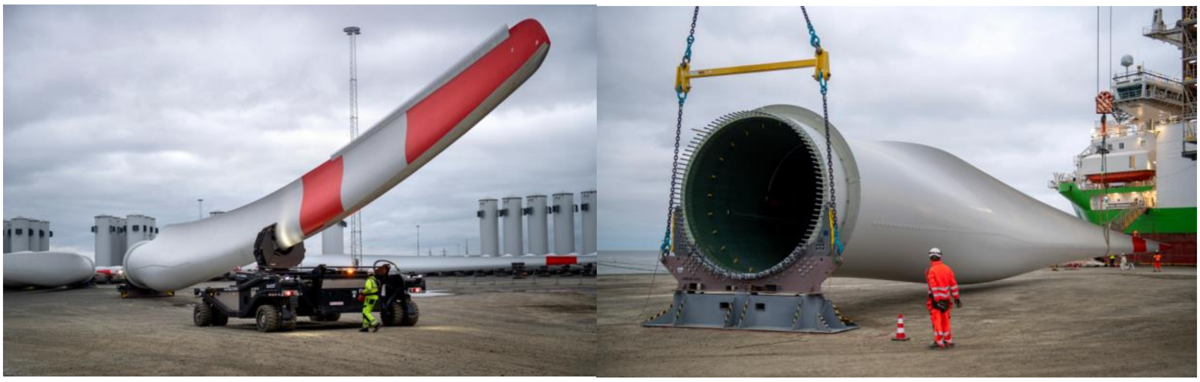

Figure 6: Handling of rotor blades at the construction site (RWE Renewables n.d.).

Figure 7: Installation of the blades (RWE Renewables n.d.).

Environmental effects

The environmental effects of the Kaskasi wind farm have been investigated in an emission study conducted by BioConsult SH on behalf of RWE Kaskasi GmbH. In the study emission paths and sources from the wind farm are described as well as the environmental effects on water, air, soil, fish, birds, macrozoobenthos and marine animals. The study identified several emission paths such as handling of all types of oils, diesel and lubricants, waste water, release of substances from coatings, air emissions from for example diesel generators, handling of the grouting material, underwater cleaning and noise emissions.

The emission study showed no indications of severe negative environmental effects regarding the assessed assets with regard to the specified amounts of emissions. The identified pollutants are either being properly disposed of or not used, which fulfil the requirement to minimize material emissions. Moreover, it is assumed that the technical systems are planned to minimize environmental effects, for instance by the usage of environmentally friendly operating resources. However, there exists a risk regarding bird strikes on the rotors and rest of the turbines. This mainly poses a risk for songbirds. However, the light emissions can be reduced to a minimum in line with the legal requirements, which would reduce the risk. The conclusion of the study was that the operation of the Kaskasi wind farm does not represent a threat to the marine environment in regard to the protective and precautionary measures.

6.3 Circular measures in the construction value chain

This subchapter presents the results of the conducted interviews. Information regarding the interviews and the respondents are shown in table 3.

Table 3: Interview respondents from RWE Renewables.

Profession	Respon-dent	Years of experience in the industry	Type of interview, date, duration	Topics	Interview questions
Head of sustainability offshore	1	16	Video call, 2023-04-17, 30 minutes	Design, end of life, circularity	Appendix 1
Procurement analyst (offshore)	2	20	Video call, 2023-04-20, 1 hour	Manufacturing (procurement), circularity	Appendix 2
Senior project manager (offshore)	3	14	Telephone meeting, 2023-04-19, 1 hour	Construction of Kaskasi, end of life, circularity	Appendix 3
General manager (offshore)	4	14	Video call, 2023-04-12, 2 hours	Operation and maintenance of Kårehamn, circularity	Appendix 4
Permit expert (onshore)	5	20	In person, 2023-04-13, 1 hour	End of life, circularity	Appendix 5
Project development manager (onshore)	6	9	Video call, 2023-04-13, 30 minutes	End of life, circularity	Appendix 5

Design

According to respondent 1 RWE Renewables has implemented a couple of overall policies and policy objectives as well as policies specifically for the offshore department that supports circular measures in the design stage. For instance, they have an aim to become 100 % circular by 2050. In order to reach this aim, they apply several principles. For example, they work with design by focusing on sustainable procurement of suppliers, recyclable blades and collaboration with suppliers towards circular solutions. Currently, they have not specified any specific objectives regarding the proportion of recycled material in new wind turbines. However, this is something that they will work on. When it comes to the tower and the foundation, there already exists a well functioned recycling market and respondent 1 believes that the foundation and the tower partially consists of recycled scrap steel. Regarding the blades, respondent 1 doubts that they consist of recycled material, however in the Kaskasi project the blades are designed to be recycled and they have an upcoming project in the UK where they will also use recyclable blades.

Regarding an extended use of wind turbines over 25 years, respondent 1 believes there are both advantages and disadvantages. Respondent 1 explains that the company would love to use the wind turbines for over 25 years, in order to maximize the utilization and it would be good for the economy as well. However, he acknowledge a limitation with the permit that is valid for 25 years and if they do not know if they are allowed to use them longer, he has difficulty justifying why they should design them for a longer period of time using more material in case they do not get the permit. Moreover, he explains that the components are prone to fatigue and may need repair, consequently new ones may be cheaper.

Respondent 1 explains that circularity in the end of life stage is taken into account in the design stage by fulfilling permit requirements regarding waste management in future decommissioning. However, it can be difficult to predict if components will be reused, repurposed or recycled since it is difficult to know which techniques will exist in 25 years due to the technical development, currently 80 % of the wind turbines consist of metal that is recyclable. However, the challenges are the composites and the electrical components such as the generator and the switchgear. In the future the company intends to use recyclable blades, but it does not matter if they are produced by Siemens Gamesa, such as in the Kaskasi project, or anyone else. The recyclable blades are currently more costly and there are limitations in the production which represent a current obstacle to producing these blades.

Manufacturing

In the selection of suppliers RWE Renewables applies internal sustainable policies.

Respondent 2 explains that during the last year they introduced a sustainability policy within procurements. The sustainability policy mainly focuses on the human rights aspect because there has been a change in law that applies to companies with more than 3000 employees, which is called the Supply Chain Due Diligence Act. There also exist other external sustainability requirements that affect the procurement process. For example, some countries within the European Union have requirements on the suppliers to participate in a tender or auction. To participate in a tender, the company should fulfil some qualities and show proof of sustainability measures etcetera.

Regarding take back management there exist some challenges according to respondent 2. The life cycles of wind turbines are 25 years or longer and the circular economy has not played a role in the past. For instance, there has happened a lot regarding suppliers and many of the old suppliers for onshore wind turbines do not exist any longer and cannot take back their components. However, regarding the new recyclable rotor blades respondent 2 would expect that the supplier describes the methods to how recycling can happen after 25 years. In the past, the steel scrap has been taken care of after decommissioning and reusable parts have been resold on the secondhand market. From onshore projects, either entire wind turbines or some spare parts components have been sold. Previously, already used turbines and components were most often sold outside of Europe. RWE Renewables has also reused wind turbines internally by moving wind turbines from a site in Germany to a site in Spain which occurred during 2022.

Respondent 2 describes that circular economy did just start in the renewables industry. Currently they do not have any requirements about the reuse of secondary materials in the production of the components. However, he believes that they will implement such requirements on recyclability, repairability and circularity. In addition, he expects there will be European Union regulations on material passports in the future. Respondent 2 believes that these passports could be very useful regarding carbon footprint in life cycles and for recyclability and therefore think it is necessary to approach these passports. When it comes to manufacturing RWE Renewables has limited opportunities for industrial symbiosis and to develop products together with other sectors, since they are not included in the manufacturing and therefore it is difficult to influence the design and how manufacturers cooperate.

Respondent 2 explains that the market for offshore wind farms is quite limited and that there only exist three main manufacturers worldwide. On the European Union market, bankability and track record limit the access of manufacturers. Offshore wind turbines are mostly assembled in Europe, there are some components from outside of Europe, but RWE

Renewables cannot change the assembly line. They would prefer limited energy and emissions connected to transportation distances. However, some of the components are manufactured in India and China such as great amounts of the electrical components. For the large steel components these are manufactured in Europe and only smaller parts consisting of steel are made outside of Europe.

When comparing manufacturers, the current main factors that they evaluate are pricing, availability and quality. Currently the level of ambition is limited regarding circularity and the reduction of greenhouse gasses. Right now, the priority is the price and the financial success of each turbine. Sustainability matters more when there are requirements from the governments in the permitting process/tender process. They do not have any circular parameters included in the selection of the suppliers. However, in the next few years those parameters will most likely become a part of the evaluated parameters.

Respondent 2 describes that circular products currently have a higher pricing, but that circular factors might become standard in a few years which could change the pricing. Most often the foundation and tower consist of recycled material, but limited parts of recycled materials are brought into the manufacturing process. The percentage depends on the company. However, this will probably increase by green steel. Green steel is an important topic in the wind energy industry right now. At the moment it only covers a limited part of the market due to the method. Green steel can be used in foundations and towers and it contains recycled materials and steel plates. Green steel is characterized by a higher amount of steel scrap in the manufacturing process as well as the avoiding of heating by gas or coal instead green energy will be used in the heating process. The production of green steel will probably increase in the following 3-5 years. For example, RWE Renewables plans to build a new wind farm in 2026-2027 and green steel will probably be more available when the steel components for that wind farm are manufactured around 2025-2026.

Construction

RWE Renewables has a sustainability group that for example looks for sustainable solutions to apply during the construction phase. Respondent 3 explains that several sustainable solutions were applied at RWE Renewables wind farm Kaskasi in Germany. At this project Siemens Gamesa was the main supplier. The foundation and offshore substation were from Bladt Industries, which is a Danish supplier. It represents the normal case that the turbine is from one supplier and everything below the tower is from another supplier. One of the sustainable solutions at the Kaskasi wind farm was a vibrating installation technique that was used instead of the usual hammering installation technique. The advantage of this technology was reduced negative impact on the surrounding environment and a research project called the VISKA project was carried out to assess the noise emissions and the environmental impacts. The new technique was used for 7 of the 39 monopiles. However, the technique did not work out as planned. They had carried out some testing prior to the project with monopiles onshore and that worked well but the installation depth onshore was not the same as the depths offshore, which made it difficult to predict the results from the installation technique. Therefore, they also had a backup plan with the hammering technique. In reality, the new vibrating installation technique made it difficult to force down the monopiles to the requested depths due to the dense layers of sand. Therefore, they completed the work by using the hammering technique. Respondent 3 does not think that the vibrating installation technique can be used in the future since it is challenging to use and because it did not work out as planned. It is also expensive and not ideal to have two kinds of installation techniques available at a site, in case there is a need for a backup technique.

The main circular measure that stands out in the Kaskasi project is that the world's first recyclable blades were installed at this wind farm. The recyclable blades are made by Siemens Gamesa. Respondent 3 explains that the blades were not part of the original plan but during the project they were contacted by Siemens Gamesa and offered to try this new solution. The blades consist of a new resin that will enable recycling. However, this should not affect the typical functions of the blades. Respondent 3 describes that the recycling of blades has long been a critical area. Regarding the maintenance of the new blades respondent 3 explains that there is no difference. The only difference is the resin in the new blades, otherwise it consists of the same components. Respondent 3 is hesitant if Siemens knows what kind of products that will be manufactured from the blades at this moment, since it is many years until the decommissioning. Respondent 3 explains that the glass fibers are not suitable for new blades because of the quality requirements, perhaps they can be used in the production of new boats.

The turbines at the Kaskasi wind farm are planned to be in operation for 25 years and they have a normal warranty time, that is project specific. Primarily for the Kaskasi project, Siemens Gamesa who is the main supplier are responsible for the maintenance and after that they will do the maintenance inhouse with the help of some contractors for special components.

Regarding the foundation and tower as well as other components of the wind turbines, recycling of steel, copper, aluminium, is possible and often carried out. Respondent 3 is not entirely sure about if there exists any circularity between the waste from old wind turbines to the production of new ones. In RWE's business case they assume that someone else will take care of the metals and pay for them after decommissioning due to the existing recycling market of metals. When it comes to insulation and plastics respondent 3 does not know if they are partially or fully recycled. Moreover, Respondent 3 is not fully aware of which components contain recycled material in the Kaskasi project. However, the steel materials in the tower and foundation may be a combination of recycled and new steel. The monopiles consist of more than 99 % steel as well as coating and cables.

Operation and maintenance

RWE Renewables is responsible for the operation and maintenance of several of their wind farms, one of which is called Kårehamn and located offshore, outside the coastline of Öland, Sweden. Respondent 4 explains that the Kårehamn wind farm is located within the territorial border and the nearest wind turbine is 3.5 kilometres from the coastline. The wind farm consists of 16 turbines of 3 MW each. The wind turbines have concrete foundations, so called gravity foundations. The weight of the turbines is 4000-6000 tons each. The wind farms produce a total of 200 GWh annually, which covers the majority of Öland's electricity needs which is 300-350 GWh annually. The wind farm is located on the eastern side of Öland and the cable goes into Öland.

Respondent 4 describes that maintenance of a wind turbine is required once a year, but it is spread over the year. They have designed an excel sheet covering 25 years with different intervals on different components. Some maintenance measures are carried out every year, some in fixed intervals such as every fourth, fifth, seventh or tenth year. For example, a replacement of all bolted connections in the turbine, which includes the entire tower with tower sections, blades and between the foundation and the tower, is carried out every fourth year. Another component that is replaced continuously are backup batteries in the turbine, which come in handy in the event of a power cut so that the turbine does not need to be restarted. According to the turbine manufacturer Vestas, the batteries need to be changed every fifth year but sometimes it is yearly and sometimes more rarely. Another component that they change is hoses for oil every ten years due to the risk that dry cracks may form and for preventive purposes.

There are different methods of maintenance and they differ on land and at sea. For example, offshore there can be a focus on repairing turbines in different areas spread over the year. Normally 2 technicians work for a week on a wind turbine, but the company has boats where the technicians can stay overnight, which enables several technicians going out together and working on the turbines, which make the maintenance more effective. This represents a kind of strategy to make the maintenance more efficient, because the size of wind turbines increases the further out to sea the wind farm is located. As a result, they do not want to shut down the turbines for a week and they want to finish the maintenance quickly and efficiently.

Another difference between offshore and onshore maintenance is that there are more employees per wind turbine offshore in order to boost with people when the weather is good enough to go offshore. According to respondent 4 there are about 0.4 technicians for an offshore wind turbine and 0.1-0.2 technicians for an onshore wind turbine. At Kårehamn, there are six employees from RWE Renewables of which five are employed technicians. Moreover, there are two persons working on the boat that should be available 12 hours every day, but in reality, they do not work that much. Furthermore, there are about 12,000-13,000 hours of maintenance carried out by external companies per year, but the hours vary every year. In England, there are slightly different routines and rules regarding who is allowed to carry out the work and there is a need for permission from managers etcetera. Therefore, there are approximately 0.6 technicians per turbine in England as well as external staffing.

In Kårehamn, they are working offshore about 140-180 days per year, depending on the year. Respondent 4 explains that the majority of maintenance takes place between May and September due to several factors such as better weather and lower waves in the summer. Moreover, the electricity price, electricity consumption and production are also lower in the summer. Furthermore, the turbines should be in operation between September and April. Between May and September, they work offshore about three quarters to four quarters of the month for about 20 days. During wintertime they work offshore half or less time, about a third of the month. During winter there is not so much maintenance, instead they focus on troubleshooting, visual checks and checking of measurement values.

Respondent 4 describes the wear and maintenance of the structural components. The tower basically does not have a need of maintenance, aside from changing bolt connections at regular intervals. The blades offshore are mainly suffering from erosion damage. They consist of fiberglass with gelcoat on the outside and even if there does not exist a lot of contamination at the location, the surface or paint wears away. The biggest damage occurs over time in the form of pure wear, mainly on the leading edge, which is the most exposed part of the blades at high wind loads. They are repaired by persons who are sitting on ropes, sanding, painting and mending the blades. Another thing that can happen to the blades, is a lightning strike and therefore they have lightning conductors at the blades. However, it can become burn marks around the lightning conductor attachment and then it may have to be replaced and the damage needs to be repaired. Their strategy for the maintenance of the blades is to perform annual visual checks with cameras from the foundation and boats as well as drone inspections.

Regarding the foundation there is little maintenance and very little wear. It is examined with underwater drones, where erosion protection made of stones around the foundation is checked to make sure it looks okay and that the stones are still there. Moreover, they check the cable and sacrificial anodes for the reinforcing mesh inside the concrete. They do not check all foundations but a certain percentage of foundations annually. There exist schemes for the replacement of sacrificial anodes since they become thinner over time. However, replacements are bad for the environment and expensive so therefore their strategy is to measure the sacrificial anodes over time to assess when there is a need to replace. That is their strategy with most components instead of just following the given replacement intervals. Furthermore, growth of algae and mussels can occur on the foundation and there is a lot of this in Kårehamn, but it does not pose a danger so therefore they let them grow. Respondent 4 also mentions that the gearbox and the generator in the wind turbine sometimes need to be changed, however they can be very difficult to replace.

Respondent 4 describes his previous experience from onshore projects at another company where there was a lot of maintenance carried out. Those turbines were old with gearboxes and they changed the gearbox oil regardless of whether it was okay or not, they just followed instructions. At RWE Renewables they take oil samples at least once a year and try to recognize a trend when it should be replaced. When carrying out maintenance at sea, there is a lack of regulations in Sweden and it is more regulated in the other countries that RWE Renewables is active in. There are few rules in machinery directives such as that maintenance should be carried out and third-party inspection of lifts and elevators. However, they are far behind on the marine side.

Respondent 4 explains that the design lifespan of the wind turbines at Kårehamn is 25 years and that the warranty period depends on the contract with the suppliers. They got a guarantee of 5 years for the turbines, foundations and cables, but it can be shorter or longer warranty. It is also possible to write a service agreement with the supplier and then the warranty can be longer, but there is no standard, it depends on the strategy for the contract. Many companies use the turbine suppliers to do the maintenance, but they have chosen a different path at RWE Renewables. Respondent 4 explains that they are thinking of using the wind turbines at Kårehamn for more than 25 years and are already doing a mid-life assessment to check the condition of the turbines. At the moment, they only have permits and turbine certificates for 25 years, so they need to investigate the process for longer permits. RWE Renewables has a goal to keep the turbines in operation for as long as possible. Therefore, they must carry out a risk assessment to evaluate if this is possible. For instance, it is expensive to change blades and gearboxes. It is also possible to check the error history. If there is a need to replace too many components, it will be cheaper to take down the turbines earlier and resell them on the second-hand market due to the size of the components and difficulties in finding spare parts.

Respondent 4 describes that the wind energy industry is becoming a more mature industry. For instance, there are repair companies that can repair gearboxes and the gearbox often needs to be replaced once during the lifetime of a wind turbine. It is possible to apply the repair cycle as a strategy and keep spare parts in stock for preventive purposes. Moreover, it is also an option to buy or replace the gearbox with a new variant if they have stopped making the same type, there are often three different types of gearboxes that are compatible with the turbine. Respondent 4 does not think that towers and foundations are currently used to the maximum extent when they are taken down after 25 years. However, there are risks of using towers and foundations that were designed 25 years ago. Wind turbines are constantly being developed, when a new wind farm is constructed it is already dated. There are risks of using the old components if there have not been any regular checks or continuity and if trends and developments have not been followed during the maintenance. Respondent 4 has heard from colleagues that there is also more maintenance with foundations in steel regarding corrosion, which can affect the opportunity to use those foundation over 25 years.

Respondent 4 explains that they received a maintenance manual from the turbine supplier Vestas at the time of the deliverance of the turbines, concerning every component that Vestas had bought in from various sub-suppliers. However, they have discovered that what is written in the manual may differ from the sub-suppliers' recommendations. Respondent 4 thinks there are potential to improve the maintenance, which could possibly extend the lifespan of the wind turbines. For instance, by continuous monitoring, checking trends, more sensors and measuring points and basically by evolving a better maintenance system. It is impossible to know when components will break so therefore it is important to check trends in order to predict patterns and adjust the maintenance.

Respondent 4 explains that there is a well-functioning collaboration between groups in the company to promote circular measures in operation and maintenance. They have a sustainability department and an engineering department who offers support by finding different ways to optimize the maintenance. They also have a purchasing department that targets the secondary market and has several companies that they can send price requests to and compare lead times and quality. There is shared experience and lessons learned from other projects, weekly, monthly and annually. For example, the employees in Kårehamn have collaborated with some colleagues that are working on a wind farm in England with the same type of turbine. The turbines in England are two years younger so the employees at Kårehamn have shared their experience regarding the turbines and discussed what they noticed as correct information and not correct information in the manual from Vestas. Respondent 4 explains that it is all about to get to know the turbines and components.

When it comes to challenges to extend the lifespan of wind turbines, respondent 4 claims that it is mainly the authorities that represents the greatest uncertainty. To receive a permit for extended use of the turbines is similar to the process of building a new wind farm. Permissions are needed from several parties such as the Swedish Armed Forces, the County Administrative Board, the municipality and the Land and Environmental Court. Offshore wind turbines are not old in Sweden, so not much is known about this. It takes at least ten years to be allowed to build offshore and the oldest offshore wind farm in Sweden is 14 years. Respondent 4 does not believe that there is resistance from stakeholders in the municipality since the local response to the wind farm has been positive, local people have been involved in the project and acceptance has been reached through dialogue.

End of life

The experience of decommissioning offshore wind turbines is limited within the company. Respondent 1 has only been involved in two tests of wind turbines decommissioning offshore. Respondents 5 and 6 work within the onshore department, where there is some more experience in comparison to offshore. However, respondent 5 also has limited practical experience of decommissioning and explains that there have been consulting assignments regarding this subject in connection with permits for new wind farms. For example, concerning the estimated price of the demolition and how to handle the components. Respondent 5 explains that rotor blades are a future matter, the goal is to recycle them in the future since landfill is not an option because it is not sustainable, and it is expensive. Respondent 5 and 6 describes a few Swedish projects where entire turbines or larger components have been dismantled. For instance, there were wind turbines in the city Malmö that were taken down due to flaws and because they were designed as prototypes. Moreover, there was a turbine in Småland that had broken down due to a problem with the rotor blades. However, respondent 5 and 6 are unsure about the extent of the dismantling, maybe it was only the blades that were replaced. In addition, respondent 6 explains that they plan to take down two wind turbines in Landskrona due to difficulties in finding spare parts of gearboxes and because it is more profitable to take them down.

There are different options after decommissioning a wind farm. Respondent 1 describes that from onshore decommissioning, components have for instance been sold on the secondhand market, which is an option they prefer in comparison to recycling. However, to buy on the secondhand market has risks regarding safety, quality and capacity. And the age of secondhand wind turbines are old, some are 50 years old. Also, the capacity is very small compared with new turbines. Furthermore, it is mainstream that limestone and silica from the fiberglass from the blades are used in cement production as a substitute, however it does not represent the best option since it is a form of downcycling. There are also cases where repurposing has been used for instance to build bridges out of old blades, but it is not mainstream, and it probably will not become mainstream according to respondent 1. Moreover, the metal recycling industry is very developed so it is easy to recycle metal components and from onshore turbines the concrete can be used in for example new street constructions. Around 15 % of the turbines are composites and electronics. As mentioned there is a demand from the cement industry for the blades however it is very difficult to promise a certain quantity on a regular basis and perhaps there is not an industry for this within the adjacent 400 km area and the industry needs to have a constant quantity feed in order to develop industries that can take care of this. There is a need for several sectors to go together and deliver enough quantities to create a capacity that would deliver constant feed to the industry. Furthermore, it is currently not profitable for an industry to recycle blades only from RWE Renewables since there is not enough waste and therefore, they have to cooperate with other companies. Another challenge is that these recycling industries need to be located relatively close to the location of the wind farm so that the deliveries of waste are not too long, which would be negative for the environment.

Respondents 5 and 6 express an uncertainty about what happened to the components from the Swedish projects. Regarding the wind turbine in Småland they believe that the supplier might have been interested in taking a closer look at the blades, since there was a concern regarding the blades therefore it is somewhat unclear what happened. Respondent 5 believes that old towers have been recycled, expensive metals such as copper and cables also have been recycled and the rotor blades have probably ended up in landfill. In addition, the respondents describe that special vehicles are used for deliveries of components to the wind farm area in connection to the construction, while normal trucks are used after decommissioning wind farms. Consequently, some components are divided after decommissioning to enable transportation with normal trucks. For instance, respondent 6 has heard that the blades can be divided into four parts and later crushed into small pieces in connection with the decommissioning. Moreover, respondents 5 and 6 mention a test project in Finland, where rotor blades from old wind turbines are to be sent to be recycled. In addition, respondent 6 describes that there is hope that the industry will solve the problem regarding the recycling of blades, The Swedish Wind Energy Association has an ongoing project about recycling blades and the wind turbine supplier Vestas has a project on how to recycle old blades.

Respondent 1 explains that at the end of life stage the option that is preferred amongst lifetime extension, repowering or decommissioning is lifetime extension. Lifetime extension is preferred since it is more economic, however no one has done this offshore. Respondent 3 also thinks that lifetime extension is a big topic and explains that they carry out structural health monitoring at the end of life which measures several factors such as forces, elongation and compression of steel, frequencies and stress. As a result of the structural health monitoring it is possible to calculate how many extra years the wind turbine can be in operation.

Repowering is also an option at the end of life stage. According to respondent 6, the choice of a suitable option depends on what the company profits from, whether it is lifetime extension, repowering or decommissioning. Respondent 1 explains that the technical development in the industry is fast and when they have been repowering onshore there has been a need for new bigger foundations, towers etcetera. Therefore, repowering often implies replacement of all the components. This means that there is a need for a new plan regarding the exact placement of new turbines as well as a need for new permits. Respondent 5 and 6 explains that in a few years, a lot will happen, when the technical lifespan of several wind farms expires. Right now, it is difficult to find places to build on and they will probably want to use the existing areas for repowering. However, it is difficult to build new wind farms in the south of Sweden, because they are often built on arable land near buildings and since the wind turbines have increased in size, it becomes more complicated to build new wind farms there. In the north of Sweden there are better conditions for repowering regarding this aspect. Moreover, they explain that cables may need to be updated in connection with repowering but repowering often results in fewer turbines so it may vary, but most likely there will be a need for replacement of the cables. Respondent 3 has the same perception of repowering and does not believe in repowering by changing only some of the components. He compares the capacity of each turbine at the Kaskasi project, 9 MW, to his new project in the Netherlands where it is 50 MW. Since the turbines grow in size this means a dramatic increase of loads and there is also a need for new cables and sections of re-cabling. After 20 years in operation 80 % of the physical properties of foundations are affected. Therefore, he thinks that repowering only works by changing all the components and to exchange them with larger sizes. According to respondent 6, the company will apply for repowering of the wind farm in Landskrona, since the turbines do not work as they should and therefore, they can be taken down prematurely. They plan to replace all parts except the foundations, the wind farm consists of 4 turbines, half of them were installed in 2007 and the other half in 2002.

The respondents have different ideas about how long wind turbines can be used. Respondent 5 believes that wind farms can be used over 25 years and explains that some wind farms in Skåne in Sweden have been in operation for 30 years, which is much longer than planned. They have started to count on a longer lifespan of 30, 35, 40 years and then it is all the larger components, the blades, towers and foundations, which are expected to be used for this long. Respondent 6 explains that it is the mechanics such as the gearbox that usually breaks, but a new gearbox gives new life to a wind turbine. Respondent 3 also thinks that wind turbines can be used for a longer time and explains that there is a safety margin and it is difficult to say how much longer they can be in operation around 5, 6 or 7 years. It is difficult to say exactly how much longer but definitely longer than 25 years. It might be possible to extend the lifetime of the foundation by making it a bit stiffer, but they should not do this more than needed, therefore they should assess this to find the optimal solution. However, respondent 1 believes that it might be problematic to use offshore wind turbines over 25 years due to the technological development. Respondent 1 explains that the capacity of wind turbines has increased dramatically so there is a need for new components and also after 25 years offshore in the water the components show signs of fatigue. Moreover, respondent 1 believes that it is difficult to design components with a longer lifetime. However, according to respondent 3 there is a change in the market. In the Netherlands they plan to extend the permit of offshore wind turbines up to 35 years with the possibility to extend up to 40 years and the turbine suppliers believe that it will be possible to keep the wind turbines in operation for 35 years. This is also discussed in Denmark for the project Thor. Respondent 3 does not know if this is discussed in other countries, but he believes that it will be possible to implement this in Germany as well as in many other countries.

Circular economy

The respondents share their thoughts about the circular measures that the company applies. Respondent 1 describes that they have different terms in the contracts with their contractors and suppliers to reduce waste volumes and they also chose suppliers in consideration of sustainability. According to respondent 3 they support circularity by applying waste sorting. For example, they clearly separate plastic, metals, oil contained parts, batteries, liquids and washing water. The waste is collected and contained offshore and then it is transported to onshore where it is taken care of. Furthermore, respondent 3 describes that they will use hydrogen turbines, hydrogen electrolyzed units and solar power at his new project in the Netherlands and it is the world's first project that this is used in combination with offshore turbines. According to respondent 5, it is more sustainable at RWE Renewables compared to the sustainability department that he previously worked at, which was state-owned. At RWE Renewables they for instance focus on sustainable traveling and waste sorting. Moreover, they work a lot with sustainable development, biological diversity and resource use. For example, they carry out various investigations regarding bats and birds. Partly before they build wind farms, but also afterwards as follow-ups. They adapt their projects to the animals. For example, they avoid building in areas where there are birds and bats that can be negatively affected. In addition, they shut down some wind turbines at night-time during certain months in the summer and early fall to prevent the animals from colliding with the wind turbines. As a developer of wind farms, they have a certain responsibility for nature. However, there are currently no demands regarding these investigations, but RWE Renewables believes that there will be demands for this in the future. Moreover, there are good opportunities for inspiration between different projects within the company. According to respondent 3, the trigger to use recyclable blades will be a part of the company's agenda no matter where they build.

Several of the respondents believe there is room for improvements regarding the circularity. According to respondent 4, the circularity can get better and explains that they were quite late with the circular measures, however it now represents an important part of the company. Previously, coal was a big part of the company and that is how the business started, but now they are trying to change that and stop producing energy from coal. Moreover, respondent 4 thinks that the company's waste management can improve and that it is better in Sweden than in England. It represents one of the company's environmental goals to improve waste management regarding waste that arises in daily work, in the office and during maintenance of the turbines. At the Kårehamn project they sort waste and receive a waste report specified with, for example, hazardous waste, oil etcetera but they are behind in the other countries. However, respondent 4 thinks that the focus on sustainability has improved and that there was no focus when the wind farm belonged to E.ON. For example, respondent 4 wanted to build artificial reefs of seaweed, algae, mussels when the wind farm still belonged to E.ON. and there was no interest in that. However, RWE Renewables is very supportive regarding this project.

According to respondent 1, the company can increase circularity by focusing on reuse or refurbishment of components, but most important is the design and manufacturing phase to prevent waste. Within construction soil and gravel are important as well as packaging, deliverances and packaging waste. Respondent 2 believes that the level of ambition can improve. For instance, by improving greenhouse gas targets. The CO_2 emissions primarily come from the manufacturing of steel, aluminium and copper. Due to the CO_2 footprint there should be a green steel target or focus regarding all steel components. Moreover, respondent 2 explains that all vessel operators and vessel services declare their emission targets, but the major challenge is the manufacturing stage. Furthermore, respondent 2 explains that in the floating offshore market, concrete is used, and it is more difficult to recycle in comparison to steel.

There is also research and initiatives within the industry to find new materials for the components. According to respondent 5, the opportunity to build the tower out of wood is being investigated and this is tested with a prototype wind turbine. However, this probably only applies onshore. Respondent 5 thinks that wood is an exciting material to apply in wind turbines because it is a domestic material that is recyclable and it can also be reused, maybe in construction. Moreover, wooden towers are more durable than steel since they can be transported as discs and then glued together at the construction site. As a result, this can simplify the transportation since it is not necessary to ship the entire diameter, instead it can be delivered in half sections.

According to the respondents there exist several challenges in the transition towards a circular economy. Respondent 1 wonders how circular they can become in the long term and if 100 % circularity is profitable and feasible. Moreover, respondent 1 claims that there is a need for price incentives and collaboration and thinks that it cannot be solved without regulators. Furthermore, respondent 1 describes the transition towards a circular economy as a philosophical challenge and describes that circular economy represents a big leader for reducing carbon, however it is also important to respect biodiversity. For instance, there is a question how they should handle the huge metal piles in the water from the wind turbines after 25 years when an artificial biodiversity has grown around the monopile. Should they leave it there and not disturb the biodiversity or should they remove it and follow the circular economy principles. According to respondent 3 it is standard to cut off monopiles 2-3 meters below the seabed and in this process, it is also possible to use a vibrating technique to extract the pile a bit more, but it can cause damage to the monopile. It is still not possible to remove them totally from the seabed.

Respondent 1 explains that another challenge is the lack of material because the need to build new wind turbines exceeds the amount of recycled material. Thus, it is not certain that all recycled material ends up in wind turbines, it can also end up in construction sites, which is just as good according to respondent 1. Respondent 3 also recognize a challenge with material scarcity especially in Europe, since there is an increased demand of more Gigawatt produced, which requires bigger turbines, which results in more material being used. Therefore, he thinks that there will be a resource topic the following years considering copper and steel. The scarcity in Europe is related to increased transport distances which is negative for the environment and if the European Union does not increase their capacity, they will be highly relying on other countries such as China. When it comes to onshore wind turbines respondent 3 explains that there exist concrete towers, which can be complicated to recycle, compared to offshore metals which are easier to recycle. According to respondent 2, there are currently only a few steel manufacturers who support offshore wind turbine production with a great part of commodity steel and a limited part of green steel.

Respondent 4 describes challenges regarding the choice of durable wind turbines and explains that when a new wind farm is built, it is already outdated since the technical development offshore is very fast. There is a constant flow of new turbines on the market and they do not have time to evaluate new models before they are in operation. According to respondent 4 they need to ask themselves if they dare to take a chance on a new model with a higher capacity or if they should take an older model that they know is safe and will last for a long time. However, the company has a due diligence department where they collect information from the sites and compare the quality of different components. As a result, they have knowledge about which components last for a long time for future projects, for example the history of gearboxes.

Several of the respondents believe that there is a need for support and cooperation between stakeholders in order to increase the circularity of wind turbines. According to respondent 1, there is a need for extended producer responsibility, and they should implement take back measures for the key components, since there is a need for a transition in the end of life with take back schemes. Respondent 3 also thinks that circularity depends on the suppliers and how they can use recyclability. According to respondent 3, RWE Renewables would always choose sustainable products if they had the choice. Moreover, respondent 3 believes there is a need to include sustainable requirements in the tender phase if possible. Respondent 2 explains that RWE Renewables is a member of Wind Europe, he thinks that the sector can have higher ambitions and explains that RWE represents a global player that influences others.

Permitting process

Respondent 5 explains that the government is responsible for the permitting process for offshore wind farms in Sweden and that they must apply for permits from several different parties. When applying for a permit, the approximate size of the wind turbines should be specified in the application and then they have to make an estimate. Often, they specify extra-large turbines to consider the development of technology. However, if they later use smaller turbines, they could have placed them closer together because then they take up less space and therefore there would be enough space for more turbines. Respondent 5 explains that the optimization of space represents a challenge within the application of permits. Moreover, they have to place wind turbines with regard to natural and cultural values.

Respondent 5 explains that there is also a permitting process for repowering, which takes about three years for onshore wind farms. However, it depends on how preventive they are with carrying out surveys, for example they often do the survey about birds before they submit the application for a permit. When they build onshore wind farms at a new location, it also takes about three years from when they submit the application until they are allowed to build if there is an appeal, in normal cases it is usually appealed. If it does not go to the highest instance, the permission process takes about two and a half years.

In case of demolition of Swedish onshore wind farms, they have to restore the area within the permit period, and it is the supervisory authority that can decide how it should be done and to what extent. Usually they remove the upper part of the foundation and cultivate on forest land and cropland. The soil depth is according to the Swedish Energy Agency's investigation from 2016/2017.

According to respondent 5 the Swedish permitting process can definitely be improved timewise. Respondent 5 believes it would be better with one entry to the permit, that someone looks at everything once, instead of many authorities having to review it. It can come to a halt in some cases, for example one authority might give permission to build a wind farm, while another does not allow an electricity cable to be laid in the area.

According to respondent 3 the German permitting process can also be improved. When they applied for a permit for the Kaskasi project, which is located in the exclusive economic zone, it took three-four years to receive the permit. Furthermore, respondent 3 explains that right now they have to carry out investigations of all the environmental impacts from the construction. This includes surveys about fish and birds and an environmental assessment. When this is done, the application is open for opinions from other stakeholders and after that the permit can be given. However, there is a change in the permitting process with pre-investigations by the government which could reduce the permitting process by three years.

Chapter 7 Analysis

7.1 Applying the Butterfly Diagram on wind turbines

One way to evaluate whether circular economy can be applied to wind turbines is by analyzing wind turbines based on Ellen MacArthur Foundation's model, the butterfly diagram. Wind turbines belong to the technical cycle in the butterfly diagram, in figure 8.

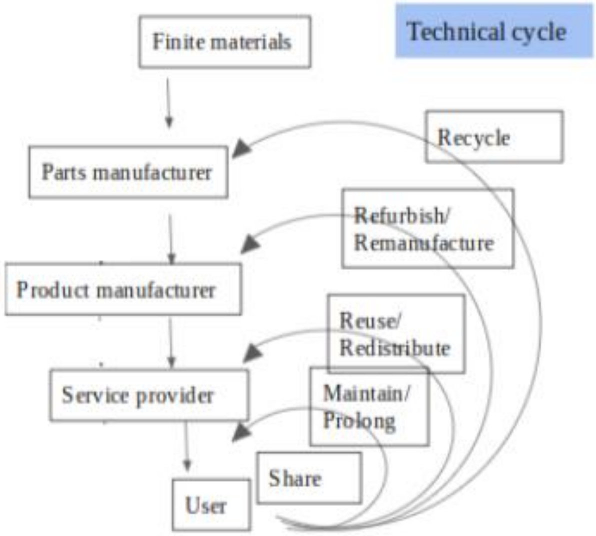

Figure 8: The technical cycle in the butterfly diagram, source Ellen MacArthur Foundation.

All loops in the diagram cannot be applied to wind turbines. Starting with the innermost loop, sharing, it is clear that this is not a feasible option for wind turbines. However, the underlying purpose of sharing, maximum utilization of products, is fulfilled as wind turbines are constantly in operation during their lifetime, which also fulfils the criterion of Geissdoerfer et al. (2018) regarding an intensive use of products. The next loop, maintaining, is definitely a necessary element in the operation of wind turbines. The result showed that maintenance of wind turbines is something that is a high priority for the company, and they have local offices in connection to their offshore wind farms that are staffed all year round. Both preventive maintenance and recuperative maintenance are carried out. Furthermore, planning, follow-up and feedback from other projects is something that distinguishes the maintenance processes at RWE Renewables. This shows that the company very well fulfils the second innermost loop in the butterfly diagram, which is the second most prioritized loop.

The following loop in the butterfly diagram is reusing and redistributing. Both the theoretical and empirical basis showed that reusing is a possible option for wind turbines and there exists a secondhand market for entire wind turbines as well as components. The empirical result showed that RWE Renewables has experience in reselling wind turbines and components from onshore wind farms on the secondary market, mostly to countries outside of Europe which represents redistribution of products from one market to another and supports developing markets according to Woo and Whale (2022). In addition, RWE Renewables reused one of their own onshore wind farms, which was moved from Germany to Spain. The company is positive about the sale of used wind turbines on the secondhand market. However, the purchase of already used wind turbines is more complicated in terms of required capacity, quality and safety. Which to some extent can be connected to the research of Geissdoerfer et al. (2018) regarding reduced customer product quality perception of secondary products. In other words, RWE Renewables supports the reuse of wind turbines, but mainly through sales. Moreover, when it comes to the secondary market of individual components it can be difficult to match reused components with existing components since many technical aspects must be considered for a well-functioning wind turbine.

The next loop of the butterfly diagram describes refurbishing and remanufacturing. Regarding refurbishing, the result showed that it can be applied to wind turbines to some extent. For instance, the gearbox component can be replaced but it can be complicated to find a gearbox that matches the wind turbine in question. This can be explained by the limited number of gearbox models that fit a specific wind turbine model and these gearboxes might not be produced any longer when the time has come to replace the gearbox. When it comes to remanufacturing, the re-engineering of products or components that no longer function, this alternative has not been observed as a common solution in the study neither in the theoretical nor the empirical material. For instance, when a Swedish onshore wind farm stopped functioning RWE Renewables disassembled it and the suppliers were probably interested in investigating the components afterwards to figure out the reason behind the problem. In addition, taking into account the size of the wind turbines and the costs associated with dismantling the wind turbine, transporting it to the remanufacturing factory, transporting it back to the wind farm location and reconstructing it, the alternative is not very profitable. Moreover, due to the technical development of wind turbines it is more profitable to invest in new turbines compared to the remanufacturing option. The remanufacturing option may be better in other markets than the markets in which RWE Renewables operates, for instance, in the secondary market.

The last loop in the butterfly diagram is the recycling option, which represents the least wanted loop. Recycling can be applied to most parts of the wind turbines. The result showed that recycling is a high priority for RWE Renewables, which is for example shown in their circular economy policy. Recycling of steel from the tower and foundation is already well established and towers and foundations often contain some recycled steel. Moreover, the recycling of the blades is possible with the new blades from Siemens Gamesa and it might also become feasible to recycle old wind turbine blades by a new recycling technique developed by the supplier Vestas. Thus, the possibility for recycling all of the larger components of offshore wind turbines look promising, which can be linked to the description of Bocken et al. (2016) regarding closing resource loops. Furthermore, the company has made some special investments in recycling regarding recyclable blades in the Kaskasi and Sofia wind farms and green steel towers in the Thor wind farm. However, the aim of circular economy is to prevent products from becoming waste and currently there is no option for removal of the monopile foundation below the seabed and therefore significant parts of monopile foundations are planned to be left in the seabed after decommissioning. The same goes for the cables. As a result, wind turbines cannot be considered 100 % circular according to the butterfly diagram at the moment, since some parts of the wind turbine generate waste. However, it is relevant to ask the question whether it is feasible and profitable to completely avoid the generation of waste within any product system and remain within the butterfly diagram.

In summary, the results showed that several of the processes from the butterfly diagram can be applied to wind turbines. However, all of the processes from the butterfly diagram are not suitable for wind turbines. This can be connected to the research by Atasu et al. (2021) and Rashid et al. (2013) on finding a strategy respectively a unique circular business model that addresses areas within the scope of the business, is consistent with the company's resources and capabilities and adapted to product systems' enormous diversity. For instance, RWE Renewables is considered very good at carrying out the measures they are capable of within the butterfly diagram. However, when compared with, for example, other construction projects, the conditions may be very different and the possibilities of carrying out the measures within the butterfly diagram may therefore vary. Consequently, it is difficult to comment on the possibilities for other developers in the construction sector to apply the same measures within the butterfly diagram as RWE Renewables. Thus, the research by Atasu et al. (2021) and Rashid et al. (2013) regarding adapted circular business models is also considered suitable to apply to different types of construction projects and construction developers with regard to the great complexity and diversity that exists within the construction sector.

7.2 RWE's circular measures in the construction value chain

Design

The result showed that RWE Renewables supports circular design through the following initiatives:

- Cooperation with suppliers towards circular solutions.
- Sustainable procurement of suppliers.
- Investment in recyclable blades in the Kaskasi and Sofia wind farms.
- Investment in towers made of green steel in the wind farm Thor.
- Takes into account the end of life stage by meeting waste management requirements in future decommissioning of wind farms.

In addition, they have implemented a circular economy policy with the purpose to reach their aim of full circularity by 2050. The circular economy policy fulfils Geissdoerfer et al. (2016, 2017, 2018) criteria for sustainable development with regard to the implementation of the concept of circular economy in comparison with the concept of sustainable development and through the long-term perspective regarding circularity. Moreover, the result showed that the design phase is an important part of their policy and it is explained that circularity in the design phase will be promoted by supporting their partners to include circular measures during the design phase, such as increase the repairability and lifespan and produce components that can be reused and recycled. In addition, they aim to increase refurbished, reused and recycled materials in their material inflow. An example of this is their investments in towers made of green steel at the Thor wind farm, which corresponds to an effective strategy to implement a circular economy according to Akanbi et al. (2018).

All the initiatives mentioned above contribute to increased circularity and maximum utilization of products, yet it is somewhat unclear how the principles in the circular economy policy are to be achieved. Based on the theoretical basis, for example from Foster (2020), it has become clear that the design of products is decisive for the future circularity of the products. Thus, a larger investment should be implemented to achieve the principles mentioned in their circular economy policy. At the same time, it is important to consider that RWE Renewables does not design their own wind turbines and thus has limited power to influence the design. This supports the need for stricter regulations from the European Union and governments against manufacturers with respect to the manufacturing of repairable, reusable and recyclable products that will have a longer lifespan and consist of a certain percentage of secondary materials. Moreover, alternative design of offshore wind turbines that requires less material should be supported. For instance, Ng and Ran (2016) have described the possibilities with two-bladed offshore turbines, which would require less material and thus favors a circular economy.

Manufacturing

As RWE Renewables is not a manufacturer of wind turbines, they mainly influence the manufacturing process through their purchasing department, and it is also here that they have the main opportunity to influence the design of wind turbines. The result showed that RWE Renewables currently has no circular parameters included in their selection of suppliers, which according to the literature review (Cai & Waldmann 2019; Munaro 2019; Kelly et al. 2019) should be applied as it is an important aspect of circular measures in manufacturing. Moreover, it is described as difficult to influence the design of the products and where the products are manufactured. For instance, while most of the components are manufactured in Europe, it was presented that some of the components are made in India and China, which is related to more emissions related to transportations. This represents a flaw based on Schmidt et al. (2021) reasoning regarding prioritization of local manufacturers. According to the literature review (Leising et al. 2018), take back management should be introduced to support a circular economy. The result showed that it currently does not exist take back management of components and due to the long lifespan of turbines it can be difficult to implement this. For instance, some of the previous wind turbine suppliers do not exist any longer.

Furthermore, it was discovered that the circular components often have a higher price, which therefore clashes with another important business objective. Even if the current main factors that are evaluated during the selection of suppliers are pricing, availability and quality, circular criteria will probably become a part of the evaluated parameters in the future. However, it is mentioned in the circular economy policy that the more circular suppliers or products will be chosen if there is an equality in a relevant criterion such as the price. This represents an identified challenge since circular products are currently more expensive. As a consequence, it seems difficult to compete with less circular products at the moment. However, there is a chance that circular factors might become standard in a few years, which could change the pricing and increase the competitiveness of circular products, which Liu et al. (2021) and Migliore (2019) have emphasized the importance of.

Construction

Something that is distinctive about wind turbines is that they mainly are prefabricated, which can enable several positive benefits previously identified by research (Jaillon & Poon 2010; Serena & Altamura 2018; Benachio et al. 2021) such as resource efficiency, quality control and less interference in the process. In addition, waste reduction, reduced resource needs and less rework can be achieved. In that sense, there is a high probability that circular principles can be applied or already are being applied in the construction of wind turbines as it is possible to apply Lean production in the manufacturing of the components. This means that wind turbines are produced in a more controlled manufacturing process in comparison to production in a construction site environment.

The following circular measures have been identified in the construction process:

- Promoting sustainable installation techniques at the Kaskasi wind farm.
- Installation of recyclable components and components that contain recycled material.
- Installation of new collars that increase the bearing capacity and improve the foundation's structural integrity, which can possibly extend the lifespan of the foundations.
- Prefabrication of components.

Apart from Lean production with offsite construction, the study showed that there is room for improvements regarding how circularity can be improved in the construction phase. However, considering the complexity of construction projects where, among other things, there is an incredible diversity of installation techniques and building materials, it can be difficult to formulate measures that work within all kinds of construction projects.

Operation and maintenance

The result showed that maintenance of wind turbines is a natural part of the operation of wind turbines as they require continuous supervision and maintenance in order to function. The regular and well-planned maintenance performed by RWE Renewables is supported by research since Dewagoda (2022) and Benachio et al. (2020) have concluded that this represents an important circular measure in the construction value chain. Performing maintenance supports a circular economy, however, there are certain principles and measures in RWE Renewables' maintenance work that are considered particularly good for a circular economy, those are:

- A comprehensive and detailed maintenance plan that is updated regularly.
- Proactive and regular maintenance.
- Regular troubleshooting, visual checks and measurement of values.
- Carry out their own measurements to determine when it is time to replace components instead of just following the manual.
- Aims to use the wind turbines beyond their design life by analyzing their condition and investigating how to apply for an extended permit.
- Focuses on sharing internal experience from the operation and maintenance stage in order to improve maintenance plans.
- Supports biodiversity by allowing the growth of algae and mussels on foundations and creating an artificial reef.

The above measures describe a carefully planned maintenance which can be described, among other things, as proactive, frequently modernized and preventive, which is in line with research of circular measures in the maintenance phase by Akanbi et al. (2019), Benachio et al. (2020) and Dewagoda (2022).

Regarding the structural parts of the wind turbines, the empirical findings showed that these components have different needs for maintenance. The tower requires limited maintenance. Gravity based foundation also requires limited maintenance such as regular checks of the erosion protection, cables as well as the sacrificial anodes, which at some point must be replaced. The result showed that the blades represent the structural component with the greatest need for repairing, since these are suffering from erosion damage. However, the replacement of blades is both expensive and difficult.

End of life

The result showed that the experience of decommissioning offshore wind farms is non-existent within the company, apart from some tests that have been carried out. However, they have experience of decommissioning onshore wind farms as well as developing decommissioning plans for offshore wind farms where waste management is described, which is described as resource assessments by Condotta and Zatta (2021) in the literature review. Regarding their experience in decommissioning onshore wind farms, different options in the waste hierarchy have been used. For instance, they have reused wind turbines and components by selling them on the secondhand market as well as reusing them within the company in another country. The result showed that onshore foundations are typically left in the ground after decommissioning, which supports research by Chen et al. (2022) regarding the impossibility to prevent all the construction material from becoming waste.

Regarding the blades, which represents the most challenging component, RWE Renewables has tried different alternatives. Recovering the blades by using them in cement production was described as the mainstream option, while repurpose of the blades was not considered as an optimal alternative. So far, they have not recycled any blades, however, disposal in landfills have probably been used. In addition, a demolition technique at wind farm sites has been described, which results in small pieces of waste that can later be transported with normal trucks instead of expensive special vehicles. This represents an example shown in research by Sanchez and Haas (2018b) where financial costs associated with the disassembly make it difficult to choose disassembly over demolition.

Furthermore, the result showed that towers and cables from onshore wind farms have been recycled and that the concrete foundations can be used in street constructions. In addition, RWE Renewables plans to recycle towers and monopile foundations in offshore wind farms, however it is not possible to extract the entire monopile from the seabed. As a consequence, a lot of steel goes to waste, which does not correspond to a circular economy. In addition, most of the cables are also planned to be left in sites after decommissioning.

The identified positive measures that RWE Renewables applies in the end-of-life phase are as follows:

- Prioritizing lifetime extension.
- Prioritizing the secondhand market compared to recycling.
- Have experience of selling wind turbines and components on the secondhand market.
- Describing waste management in decommissioning plans.
- Try to avoid waste in landfills as much as possible.

The result showed that the respondents believe that there is a potential to apply lifetime extension to RWE Renewables' offshore wind farms, which according to Wind Europe (2022) represents a common method at the end of life stage. On the other hand, the current time period in which the permit is valid poses a challenge in terms of the lifespan that the wind turbines should be designed for, as well as other risks linked to the uncertainty surrounding extended permits. The form of the permits also poses a risk for the application of repowering, since repowering usually means that all components need to be replaced. Consequently, this usually results in fewer but larger wind turbines with a different layout, which leads to the need for a new permit.

7.3 Challenges

The result showed that there are several challenges with the transition to a circular economy regarding offshore wind farms. The main challenges are described below.

The impact of permit applications

The study showed that there are examples of how the permitting process and factors linked to permits of wind farms constitute an obstacle to a transition to a circular economy. For instance, it takes around 10 years to receive a permit for the construction and operation of offshore wind farms in Sweden, which delays the transition to renewable energy sources. Moreover, the permit to operate wind farms is usually only valid for 25 years, which limits a longer use even though the study showed that wind turbines most likely can be in operation for a longer time. Consequently, the permit prevents wind turbines from being maximally utilized, which does not promote a circular economy. However, there is a possibility to receive a new permit for lifetime extension or repowering, yet there are uncertainties and risks linked to this. For instance, it is not a certainty to receive a new permit and there can also be uncertainties regarding the remaining capacity of the turbines in case of lifetime extension. As a result, it can be more beneficial to decommission an old wind farm and build a new one instead.

Another challenge regarding the permits is the difficulty to make estimates about the size of wind turbines so far in advance in the permitting process. Consequently, it can be challenging to achieve optimal capacity conditions in new wind farms, especially in Sweden due to the length of the permitting process. Furthermore, the length of the permitting process differs between countries, which creates an uneven expansion of renewable energy depending on the country. However, the study also showed that there are proposals to change the permit of offshore wind turbines by extending the time period for the operation of wind farms as well as shortening the permitting process. This was observed in the Netherlands and in Germany and the literature review also showed proposals regarding this subject from the Swedish government (2023) and the European Union (Thomsen 2014).

The stakeholder involvement

The study showed that there exist challenges for RWE Renewables to achieve a circular economy without the help from other stakeholders. For instance, the company has limited ability to influence the design and manufacturing of wind turbines, which are crucial stages for the fulfilment of the circular economy concept. Furthermore, RWE Renewables alone does not generate enough waste from blades to make the wind turbine blade recycling industry profitable. Therefore, there is a need to cooperate with other companies in the industry to deliver enough quantities and a continuously even amount of waste, which is in line with research by Rashid et al. (2013) regarding active stakeholder participation in the implementation of circular business models.

Furthermore, there is a need for stricter regulations with regard to circularity and greater focus on sustainability and circularity in tenders and auctions. Therefore, it is vital that governments make demands on sustainable rather than financial aspects to support circular materials and methods as these often are more expensive in comparison to fewer circular alternatives. However, there are several proposals from the European Union and the Swedish government regarding a circular economy which could support the transition from a linear to a circular economy.

The financial aspect

When it comes to profitability, the circular goals are not always in line with financial goals. For example, circular solutions usually are more expensive or less profitable compared to other options. For instance, it was discovered that the recyclable blades from Siemens Gamesa are more expensive compared to other blades, however, there are opportunities to make profits by selling the recycled material in connection with decommissioning and to get advantages in tenders regarding sustainability, which should be taken into account.

Moreover, the support of circular measures such as applying for lifetime extension of wind farms requires financial resources, consequently it can be more attractive to invest in new turbines with greater capacity from an economic perspective. In addition, to prioritize inner loops in the circular economy usually means keeping the components in their original form which is connected to high transportation costs compared to if the components have been broken down into smaller more manageable parts. These economical aspects all support the research by Osobajo Oluyomi et al. (2020) and Gálvez-Martos et al. (2018) regarding the challenge to make circular measures cohere with other business objectives.

Recycling of the blades

Although the study showed that RWE Renewables has invested in recyclable blades in two projects, it also showed that there currently are obstacles in producing the requested quantity of recyclable blades due to material scarcity. Another challenge is that the material obtained after Siemens Gamesa's recycling process cannot be used in the manufacturing of new rotor blades and that new rotor blades typically do not contain secondary material. In order to increase the circularity of rotor blades, this is something that needs to be improved. However, the supplier Vestas' new recycling technique might represent a more circular solution.

Spare parts availability

Another challenge that emerged in the study was that the lack of spare parts can result in difficulties to keep the wind turbines in operation. In particular, it can be challenging to find a gearbox that matches the wind turbines; however, a new gearbox gives new life to a wind turbine. Moreover, it is usually the gearbox that needs to be replaced once during the lifetime of the wind turbine. Furthermore, the study showed that some wind turbines are at risk of being taken down because it is difficult to find matching gearboxes. Consequently, it is very important to ensure that spare parts are available especially if the wind turbines are planned to be in operation for a longer period of time in the future, since the lifespan of the gearbox should not limit the lifespan of the entire wind turbine. The study also showed that there do exist companies that repairs gearboxes and if that is a reliable option it should be prioritized in comparison to keeping a stock of spare parts in accordance with circular principles.

The technological development

The rapid technological development is also an obstacle to circularity. In combination with an increased demand for higher capacity, this results in increasingly larger wind turbines that require more material. A significant challenge is that there are not sufficient quantities of recycled material to produce new wind turbines. Consequently, the manufacture of new wind turbines is dependent on primary materials, which contributes to resource scarcity, which corresponds to one of the underlying causes of circular economy.

Furthermore, the technological development of wind turbines means that RWE Renewables does not fully understand how new models function, which involves certain risks and thus it can be difficult to optimize the maintenance and understand how long they can keep the wind turbines in operation. Moreover, due to the technological development it is not profitable for the company to buy wind turbines from the secondary market because they cannot compete with the new technology.

7.4 Suggestions for improvement

In this subchapter some suggestions are presented on how RWE Renewables as well as other stakeholders in the industry can support the transition towards a circular economy, since the study showed that this transition is dependent on several actors in the industry. The proposals are based on identified improvement areas from the study and it should be investigated more closely how these proposals can be implemented.

RWE Renewables can implement the following measures in order to promote circular economy:

- Include circular factors in the selection of suppliers regarding the amount of secondary material in components. Moreover, they should add requirements on repairability and durability. In addition, all the components they procure should be recyclable in order to reach their own target regarding full circularity by 2050.
- Support the development of longer periods of permission to operate wind farms, which in turn would contribute to designing wind turbines with a design life over 25 years.
- Support research regarding alternative materials in the components that facilitate recycling and thus a circular economy.
- Support research and explore opportunities with suppliers regarding alternative design of offshore turbines such as two-bladed turbines, which require less material and represent a feasible solution offshore.
- Support proposals regarding shorter processing times for permit applications to accelerate the expansion of renewable electricity facilities.

- Assess whether they can preserve spare parts of components that often break such as the gearbox and whether this can be a strategy if future wind turbines are to be in operation for a longer period of time.
-Explore the benefits of choosing wind turbine models that they are familiar with from previous projects to optimize maintenance which could potentially lead to a longer lifespan and maximize the utilization of components.
- Improve the collaboration with stakeholders within the industry to support the transition towards a circular economy. For instance, by investigating the possibilities of generating sufficient quantities of rotor blade waste to support the development of a local recycling industry for this purpose.

Although there are aspects that RWE Renewables can improve, the transition to a circular economy is highly connected with regulations. Thus, the involvement of governments in the industry is crucial. Below are some proposals that would improve the possibilities for a circular economy.
- Reduce the time of the permitting process by locating suitable places where developers can build wind farms and appointing an authority that is solely responsible for examining the applications.
- Increase the time span of permits to extend the operation of wind farms, which would support maximum utilization of wind turbines.
- Prioritize sustainable material and solutions in auctions and tenders to promote sustainable development and make it more beneficial for developers and suppliers to implement sustainable investments.
-Set requirements on manufacturers of wind turbines regarding emissions and the use of secondary material in manufacturing processes as well as requirements on recyclability, repairability and durability.
- Introduce take back management that will make suppliers responsible for the waste management of their products.

Chapter 8 Conclusions

The study showed that circular economy can be applied to wind turbines to a certain extent. This conclusion can be drawn because RWE Renewables very extensively applies the second innermost loop in the butterfly diagram and aims for maximum utilization of the wind turbines. However, the circular economy is not considered completely fulfilled because large parts of monopile foundations are planned to be left at sites after decommissioning wind farms as there currently do not exist methods to remove them. Even large amounts of cables are planned to go to waste. Moreover, one of the aims of the circular economy is to prevent products and components from becoming waste and at the moment there are difficulties in recycling the blades as well as other composites and certain electronic parts in the wind turbines. Nevertheless, the development looks positive regarding the recycling of blades, which means that large parts of the wind turbines will probably be possible to recycle in the future. Moreover, the company prefers to sell wind turbines on the secondhand market compared to recycling, which represents a better option according to the circular economy.

Furthermore, another conclusion is that RWE Renewables applies several circular measures in the various areas within the construction value chain. However, there is potential to improve those measures especially within design and manufacturing where the company should place higher demands on their suppliers as these areas are of great importance for the circular economy. Moreover, it was found that RWE Renewables applies several important measures in the maintenance and end of life stage. Nevertheless, the design of the permits limits the possibilities regarding certain options at the end of life phase, such as lifetime extension and repowering.

The study also showed several existing challenges in the transition to a circular economy and highlighted the need for cooperation between stakeholders in order to overcome obstacles together. In particular, requirements for a certain proportion of recycled material in new components are considered to be crucial in order to combat material scarcity. Furthermore, the study showed that there is great opportunity to implement the identified circular solutions in future projects and that the company invests in circular measures regardless of where they operate.

In relation to other infrastructure projects, wind turbines stand out by being relatively standardized. For example, developers work against the same client within a country. Furthermore, the manufacturing processes are relatively controlled as the components are prefabricated and usually consist of the same material. Moreover, there are established construction methods that are typically used in the installation phase. In addition, there are only three suppliers that are relevant in the market for RWE Renewables' projects. As a result of these factors, the chances to implement circular measures are considered to be greater for wind turbines in relation to many other infrastructure projects, since there are better opportunities for improvements given the limited number of actors in the market.

Chapter 9 Proposed future research

Due to the limitation of the research study regarding the scope of the data collection there are more areas within the research topic that can be explored. In future research within the topic, it would have been possible to study a different basis, such as another wind developer, other wind farm projects or projects in other parts of the world than Europe to assess if this had changed the result.

In the research study, attention was drawn to several areas within the wind energy industry that can be explored more closely. For example, the study was limited to focusing on offshore wind turbines, but since there are other conditions for onshore wind turbines, it would have been interesting to explore the possibilities of using alternative materials in onshore wind turbines. Furthermore, it would have been interesting to assess where it would have been appropriate to build a recycling station for rotor blades and what quantities of rotor blade waste would be needed to create profitability in this area.

Another research topic is to explore the possibilities for wind developers to procure spare parts such as gearboxes as a strategy for lifetime extension. Furthermore, it would have been interesting to evaluate how wind turbine suppliers and governments work to implement circular measures in the construction value chain of wind turbines.

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Appendix 1: Interview questions for the Head of Sustainability Offshore

Design

- Can you describe how you implement circular measures in the design stage?

- Do you have any specific objectives regarding the proportion of recycled material in new wind turbines? Do you know if the tower, foundation and blades in offshore wind turbines consist of recycled material?

-Are there any components that are difficult to design with recycled materials?

- An important aspect in the circular economy is to maximize the utilization of products. Do you consider that wind turbines are fully utilized today and does the company aim to use wind turbines for a longer period of time than 25 years in the future?

- In what way is the end of life stage taken into account in the design stage regarding circularity?

- In the Kaskasi project, the world's first recyclable blades are used. Does the company intend to use these blades in future projects? Are there any disadvantages regarding these blades such as price, loads etcetera?

End of life

-Have you been involved in a decommissioning of old wind turbines within the company?

- Do you know what happened to the blades, tower and foundation after decommissioning the wind turbines?

- Is there any strategy regarding the end of life stage, such as a certain option that is preferred amongst lifetime extension, repowering or decommissioning?

-Do you think that the foundation and tower can be used for a longer time than 25 years?

-According to the circular economy, products should be fully utilized, do you think that the second-hand market is a better option compared to recycling?

- Do you know if there is any circularity between the waste from the wind turbines and the production of new wind turbines, for example if new components contain recycled material from old components? Are the suppliers interested in the old components or is there perhaps a demand from another industry?

-Is it profitable for an industry to recycle blades and is there enough waste?

Circularity

-What do you think the company can do to increase circularity in the construction value chain?

- What kind of challenges are there in the transition towards a circular economy?

-Do you think you need more support from certain stakeholders to increase the circularity of wind turbines, if so which stakeholders?

-Is there any other measure within the construction value chain that the company applies to reduce waste and increase circularity?

-Is there anything else you want to address on this topic?

Appendix 2: Interview questions for the Procurement Analyst

Procurement

- Can you describe the internal sustainable policies that the company applies in the selection of suppliers?

- Are there any external sustainability requirements that might affect the procurement and purchasing process?

- Have you heard about a circular material agreement where the manufacturers retain the ownership and can reuse the building materials after the construction’s end of life? Do you think this could be implemented in the future or do you recognize any challenges with this?

- Do you know if the manufacturers reuse secondary materials in the production of the components? Do you have any requirements about this in your procurements or do you think this could be implemented?

-Do you think there is a need for some sort of industrial symbiosis, where the company cooperates with other sectors in order to develop products together that covers both parties' demand and supply?

- Have you heard about material passports and do you think that such material passports would be beneficial in this industry?

- Do you prefer to choose local manufacturers and suppliers in order to reduce the energy and emissions connected to transportation distances in the procurement process?

- In the procurement process, do you evaluate any of the parameters; secondary building materials, durability, recyclability, repairability and quality?

- Are there many suppliers that offer sustainable products on the market and how many suppliers are there on this market that can manufacture offshore wind farms?

- How is the cost of secondary building materials? Is there a significant difference in cost for materials that contain recycled materials and for recyclable blades?

-How does the company prioritize regarding the choice between price and sustainability? Do you often notice that sustainability measures clash with other business objectives?

-Do you know if the foundation and tower usually consist of recycled material? What is the percentage of recycled materials in the new components?

Circularity

- What is your opinion regarding the company's sustainability work within the procurement process?

- Do you have any thoughts about how the circularity in the company can be improved?

- Is there any need for extended cooperation with any group or unit within the company to promote circular measures within the procurement process?

- Do you have anything else you would like to address on this topic?

Appendix 3: Interview questions for the Senior Project Manager

The Kaskasi wind farm

-Can you tell me about the Kaskasi project and what makes it unique compared to other projects within the company?

-Can you describe the sustainable measures in the Kaskasi project?

-Who initiated the sustainable concept in this project, have you cooperated with other stakeholders?

-How long did it take to receive the permit for the Kaskasi project and what are your thoughts on the German permitting process, do you think it can be improved? Is the wind farm located in the exclusive economic zone?

-Which components in the project contain recycled material?

The recyclable blades

-How long is the warranty for the turbine and the blades? Do you have a supplier/contractor who carries out operation and maintenance or is it carried out internally?

-Was Siemens Gamesa the main supplier of the entire wind turbines?

-Do you know if the repairing of the new recyclable blades is different in comparison to the repairing of blades from other projects?

-Are there any disadvantages regarding the new blades? Maybe the price or their function?

- Do you know if there is any circularity between the waste from old wind turbines to the production of new ones? For instance, is Siemens interested in taking back the blades from Kaskasi after the decommissioning? Or is there perhaps a demand from another industry?

- Do you know what kind of products that will be manufactured from the blades?

End of life

-For how long is the wind farm planned to be in operation?

-Do you know if the company plans to repower the turbines or carry out lifetime extension measures at the end of life phase or if decommissioning will be applied?

- An important aspect in the circular economy is to maximize the utilization of products. Do you consider that wind turbines are fully utilized after 25 years?

Circularity:

- Do you think that the Kaskasi project represents the ideal circular offshore wind farm or is there room for improvement? Do you have any ideas on how the circularity could improve?

- Do you know if there is any waste sorting during the maintenance of the wind turbines for metals, batteries, oil etc.?

- Do you think that this project can inspire other future projects within the company? What are the chances of applying the mentioned circular measures in a Swedish project?

-Do you have anything else you would like to address on this topic?

Appendix 4: Interview questions for the General Manager

<u>Operation and maintenance</u>

-Can you describe the wind farm Kårehamn, is it located inside or outside the territorial border, how many wind turbines are there, what kind of foundations are used for the wind turbines?

-Can you describe the maintenance routines of the Kårehamn wind farm?

-Can you describe the wear of towers, foundations and rotor blades and the maintenance they require?

-Is there any component that is difficult to repair?

-Are there certain components of wind turbines that are more sensitive to wear?

-How are operation and maintenance routines determined? What are the advantages/disadvantages of this?

- Is there any feedback regarding maintenance from other projects within the company?

-Would you describe the maintenance as preventive?

- Are there any specific rules to be followed when carrying out maintenance offshore?

<u>Circular economy</u>

-What is the technical lifespan of the wind turbines? How long is the warranty period from the suppliers? Do you plan to have the wind turbines in operation only during the design lifetime or longer?

-Do you think that wind turbines can be designed to be used for a longer period in the future? There are, for example, studies about using the foundation and the tower much longer than today. Do you recognize any challenges with this?

-Are the maintenance plans updated regularly, or is it the same plan throughout the entire service life?

-Do you think there is room for improvements regarding the maintenance in order to make it more sustainable and possibly to extend the lifespan of the wind turbines?

-Is there a need for increased collaboration with any group or unit within the company to promote circular measures in operation and maintenance?

-What obstacles are there in trying to extend the life of wind turbines, e.g. cost or stakeholders?

-What is your opinion of RWE's sustainability efforts?

-Anything else you want to address regarding this topic?

Appendix 5: Interview questions for the Permit Expert and the Project Development Manager

<u>End of life</u>

-What experience do you have in decommissioning of wind turbines?

-What happens when wind turbines have reached their technical lifespan? Do you carry out any evaluation regarding the possibility of lifetime extension?

-Is there any strategy regarding whether the company should invest in repowering?

- Do you know what has happened with the tower, the foundation and the rotor blades in previous decommissioning?

- Can you describe specific permits or regulations that apply to decommissioning?

<u>Circular economy</u>

- Do you know if there is any circularity between the waste from the wind turbines and the production of new wind turbines, for example if new components contain recycled material from old components? Are the suppliers interested in the old components or is there perhaps a demand from another industry?

-How is decommissioning carried out? Do the components remain intact or is it common for components to be damaged in connection with the dismantling/demolition?

- Do you know if RWE prefers repowering or lifetime extension?

- Do you know what has happened with the rotor blades from previous cases of decommissioning within the company?

-Do you think that wind turbines can be designed to be used for a longer period in the future? There are, for example, studies about using the foundation and the tower much longer than today. Do you recognize any challenges and opportunities with this?

- Are there other obstacles such as costs and stakeholders?

-Do you recognize any potential to improve the circularity at the end of life stage?

-Is there a need for increased collaboration with any group or unit within the company to promote circular measures at the end of life stage?

- Is there feedback on this topic from other projects within the company?

-What is your opinion of RWE's sustainability work?

-Anything else you want to address regarding this topic?

Permits

Can you describe the permitting process for offshore wind turbines?

What advantages and disadvantages do you recognize with the permitting process?

Do you think it would have been better with a different permitting process with regard to sustainability?