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Circular Economy in the Offshore Wind Industry

Understanding the Predominant Focus on End-of-Life Strategies

Master's thesis in Industrial Economics and Technology Management
Supervisor: Arild Aspelund
Co-supervisor: Pankaj Ravindra Gode
June 2023

Master's thesis

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Abstract

The offshore wind industry's rapid growth and inadequate recycling systems contribute to the global crisis of waste accumulation and unsustainable raw material extraction. Adopting a circular economy is stressed as a solution to this issue and theoretical research advocates that industries should adopt a full life cycle perceptive when implementing a circular economy. However, the offshore wind industry predominantly focuses on adopting circular economy principles when wind farms reach end-of-life. Therefore, this study investigates why this is the industry's main focus when theoretical research has proven the benefits of early-stage circular economy adoption. A qualitative research approach is adopted, conducting semi-structured interviews with three manufacturing firms, three developer firms, four end-of-life handling firms, and three facilitators with comprehensive industry knowledge. This study shows that the offshore wind industry actors primarily focus on circular economy adoption at end-of-life because external stakeholder pressure and legislation are pushing actors to develop new solutions on issues related to decommissioning. Additionally, the findings emphasize that the industry is highly cost-driven, and to increase the level of circularity, policymakers have to include circular economy, also for beginning-of-life, as a competitive element in tender criteria. This study provides valuable theoretical contributions to the literature on offshore wind and circular economy by explaining why industry actors primarily focus their circular efforts on the end-of-life phase. In addition, this study provides implications for policymakers and managers on how to increase circularity in the offshore wind industry.

Sammendrag

Den raske veksten i havvind-industrien og mangelen på gode skalerbare resirkuleringssystemer bidrar til en betydelig fremtidig global krise når det kommer til avfallshåndtering og utvinning av råvarer. Å innføre en sirkulær økonomi pekes på som en løsning på dette problemet, og teoretisk forskning hevder at industrier bør ha et helhetlig livssyklusperspektiv når de implementerer en sirkulær økonomi. Likevel fokuserer havvind-industrien hovedsakelig på å iverksette prinsippene for sirkulær økonomi når vindparker når slutten av levetiden. Derfor ser denne studien nærmere på hvorfor dette er industriens hovedfokus når teoretisk forskning har vist at det er fordeler ved adopsjon av sirkulære prinsipper i tidlig fase. En kvalitativ forskningsmetode er benyttet, og det er gjennomført semi-strukturerte intervjuer med tre utstyrsleverandører, tre utviklere, fire firmaer som håndterer turbiner på slutten av forventet levetid, og tre fasilitatorer med omfattende bransjekunnskap. Denne studien viser at aktørene i havvind-industrien i hovedsak fokuserer på å innføre en sirkulær økonomi ved slutten av levetid på grunn av press fra eksterne interessenter og lovgivning som tvinger frem nye løsninger for håndtering av brukte turbiner. I tillegg viser funnene at industrien er sterkt kostnadsdrevet, og for å øke graden av sirkulær økonomi må myndigheter derfor inkludere sirkulær økonomi, også i begynnelsen av levetid, som et konkurranseelement i anbudsprosesser for nye vindparker. Denne studien gir også verdifulle teoretiske bidrag til litteraturen om havvind og sirkulær økonomi ved å forklare hvorfor aktørene i industrien hovedsakelig fokuserer sine sirkulære satsninger på hvordan å håndtere brukte turbiner. I tillegg gir denne studien implikasjoner for myndigheter og ledere om hvordan man kan øke sirkulariteten i den offshore vindindustrien.

Preface

This master's thesis represents the culmination of our Master of Science degree program at the Norwegian University of Science and Technology (NTNU). It was written in the spring of 2023 for the Strategy, Innovation, and International Business Development section within the Department of Industrial Economics and Technology Management. The decision to focus on a circular economy in the offshore wind industry was driven by our passion for contributing to the energy transition and a more sustainable future.

Prior to writing this thesis, a systematic literature review of the state-of-the-art literature on collaborations for the circular economy was conducted in the fall of 2022, which served as a foundation for investigating circular economy adoption and collaboration in greater depth.

We would like to express our gratitude to all those who have contributed to completing our master's thesis. We are especially thankful to our supervisors, Arild Aspelund and Pankaj Ravindra Gode, for their guidance and feedback throughout the project. Your contributions have been immensely valuable. We would also like to extend our thanks to the case companies and interviewees for their time and input in this research.

Lastly, we are grateful to our family and friends for their patience and support during this semester.

Trondheim, 7th of June 2023

Sofia Skjolde and Ida Vinningland

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1 Introduction

United Nations' goal of achieving sustainable management and efficient use of natural resources by 2030 (Sachs et al., 2022) stands in contrast to the immense waste streams and raw material extractions necessitated by the construction of offshore wind farms. The forecasted installation of 322-540 GW new offshore wind capacity by 2040 (Agency, 2019) implies the extraction of between 129.0-253.0, 8.2-14.7, and 3.8-25.9 million tonnes of steel, iron, and concrete, respectively (Li et al., 2022). Moreover, wind turbine blades demand a substantial quantity of rare earth elements (REEs) and other scarce resources, which currently present significant recycling challenges (Li et al., 2022). The escalating demand for materials and limited recycling capabilities create a global crisis, necessitating urgent solutions in the offshore wind industry for sustainable resource management.

Circular economy (CE) is highlighted as a strategy for moving away from the current production and consumption patterns by minimizing natural resource extraction and waste accumulation by optimizing environmental, social, and economic values throughout materials, products, and components whole life cycle (Ghisellini et al., 2016; Merli et al., 2018; Velenturf & Purnell, 2021). The concept of CE encompasses a comprehensive approach that spans from circular business models and designing products with circularity in mind to extending the lifetime of products and facilitating the efficient recycling and recovery of materials (Potting et al., 2017). To achieve the benefits of adopting CE, Potting et al. (2017) emphasize smarter product manufacturing and usage, and Mendoza et al. (2022) underlined that circular design is essential *"to create long-term material custody and generate greater resource and environmental savings than product-based offerings"* (p. 12). Moreover, Jensen et al. (2020) and Hall et al. (2022) underline the criticality of having a CE mindset from the early planning and designing of offshore wind farms to increase the circularity and gain environmental and economic benefits. In other words, emphasizing CE principles at beginning-of-life (BoL) is crucial for achieving a high level of circularity (Hall et al., 2022; Jensen et al., 2020; Mendoza et al., 2022; Potting et al., 2017).

In contrast, Velenturf (2021) shows that most research on CE within the offshore wind industry is focused on decommissioning and end-of-life (EoL)-handling of wind turbines and not on how to increase circularity from BoL. Additionally, Jensen et al. (2020) stressed that recycling is depicted as the main strategy to limit future impacts of the offshore wind industry today. The disparity between what research suggests for enabling a high level of circularity and what the industry is focusing on in practice raises this study's research question:

"Why is the offshore wind industry predominantly focused on circular end-of-life strategies, despite the theoretically proven benefits of early-stage circular economy adoption?"

In order to address this question, it is necessary to closely examine certain aspects of the industry. Firstly, an investigation of the CE principles that industry actors employ in their operations is required to determine whether recycling is viewed as the primary strategy for enhancing the industry's circularity. Secondly, it is crucial to map out the drivers and barriers of CE adoption to identify why the industry is inclined towards EoL solutions rather than embracing CE principles that offer higher levels of circularity. Lastly, numerous studies emphasize the critical role of collaboration in promoting circularity (Donner et al., 2020; Eisenreich et al., 2021; Fontoura & Coelho, 2022; Geissdoerfer et al., 2018; Kazancoglu et al., 2021; Köhler et al., 2022; Meath et al., 2022; Sousa-Zomer et al., 2018; Vilkė & Gedminaitė-Raudonė, 2020). Therefore, an investigation of the linkage between collaborative efforts and CE adoption has to be conducted to clarify whether collaborations have influenced the industry's focus on EoL and decommissioning. As a result, the following sub-questions are defined:

SQ1: *What are the CE principles adopted by the actors in the industry today?*
SQ2: *What motivates industry actors to adopt CE principles?*
SQ3: *What are the barriers for industry actors to further extend the adoption of CE?*
SQ4: *Under which circumstances are industry actors collaborating to adopt a CE?*

The forthcoming section provides an overview of the theoretical background for this study, further explaining why this study's research question is necessary to analyze. This involves introducing key terms and discussions of the research field. In Section 3, the adopted qualitative research methodology is thoroughly explained. Subsequently, Section 4 presents the derived results of this study, first by each type of actor, followed by a cross-actor analysis. Section 4 presents the discussion of this study's findings, and finally, Section 6 provides the conclusion and answer to the research question.

2 Background and Theoretical Context

2.1 Circular Economy

The adoption of CE is an emerging concept that has gained considerable attention among academic researchers and policymakers in recent years because of its ability to reduce environmental impacts and create new business opportunities (Velenturf et al., 2019). However, already in 1989, the concept was introduced by Pearce and Turner (1989) who looked at how natural resources influenced the economy by using it as input for production and consumption. Since then, the concept has been incorporated with many characteristics and contributions from several ideas that share the principle of closed loops (Geissdoerfer et al., 2017). For example, McDonough and Braungart (2010) stressed that technical and biological loops could be closed in *cradle-to-cradle* economy and Stahel (2010) focused on closing technology loops to distinguish between the reuse of goods and recycling of materials. Today, CE represents an economic model aimed at reducing waste and minimizing the consumption of raw materials by keeping resources in use for as long as possible (Ellen MacArthur, 2015). It presents an alternative to the traditional linear economy, which follows a linear path of take, make, use, and dispose (Ghisellini et al., 2016).

Conceptually, CE has been defined in various ways. Kirchherr et al. (2017), based on a comprehensive literature review of 114 definitions, defined CE as *"an economic system that replaces the 'EoL' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes"* (p. 229). Additionally, Geissdoerfer et al. (2017) characterized CE as *"a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops"* (p. 766). Despite the diverse definitions, there is a common objective across them, which is to *"decouple global economic development from finite resource consumption"* (Ellen MacArthur, 2015, p. 2). For this study, the definition provided by Ellen MacArthur (2015) will be used.

According to the aim of CE, the best practice involves creating an economic model where *"the products that we use today are tomorrow's resources, which results in the creation of a cycle that encourages development in this world running by a limited amount of resources"* (Zhang, 2021, p. 17). This results in both environmental and economic benefits. Environmentally, the extraction of raw materials (Esmaeili et al., 2016; Linder & Williander, 2017; Paquin et al., 2015), construction of waste streams, and emissions of carbon and greenhouse gas emissions (Nasir et al., 2017) are reduced as productivity and resource optimization increases the efficiency of resource management when adopting CE (Linder & Williander, 2017; Nasir et al., 2017).

Economically, CE increases financial profitability compared to the traditional linear economy (Linder & Williander, 2017; D. Liu et al., 2012). This is primarily due to resource productivity through waste reduction and design for optimal material use (Ghisellini et al., 2016; Linder & Williander, 2017), leading to substantial cost savings, given the reduced necessity for virgin material procurement or waste disposal. Furthermore, waste can be repurposed as an input for other industries (Lehr et al., 2013) or utilized for energy (Chaabane et al., 2012), paving the way for additional revenue streams.

2.2 Implementation of Circular Economy

To gain the greatest economic and environmental benefits from adopting CE, it is vital that businesses develop new innovative business models that fit the CE context (Lieder & Rashid, 2016; Potting et al., 2017). In an ideal CE situation, materials can be applied repeatedly, and there is a need for smaller amounts of natural resources to produce new primary materials (Lieder & Rashid, 2016; Potting et al., 2017). To achieve that, Potting et al. (2017) created a framework for how businesses can implement CE, as shown in Figure 1. Potting et al. (2017) highlight that smarter product use, designs, and manufacturing relates to the highest level of circularity as these activities reduce the need for virgin resources and make it possible to expand the lifetime, which is the next highest level of CE. However, without designing products for CE, it is hard to extend the lifetime through reuse, repair, refurbishment, remanufacture, and repurposing (Potting et al., 2017). The lowest degree of circularity relates to recycling and recovery at EoL. Put differently, the degree of circularity will increase if implemented from the beginning of a product life cycle.

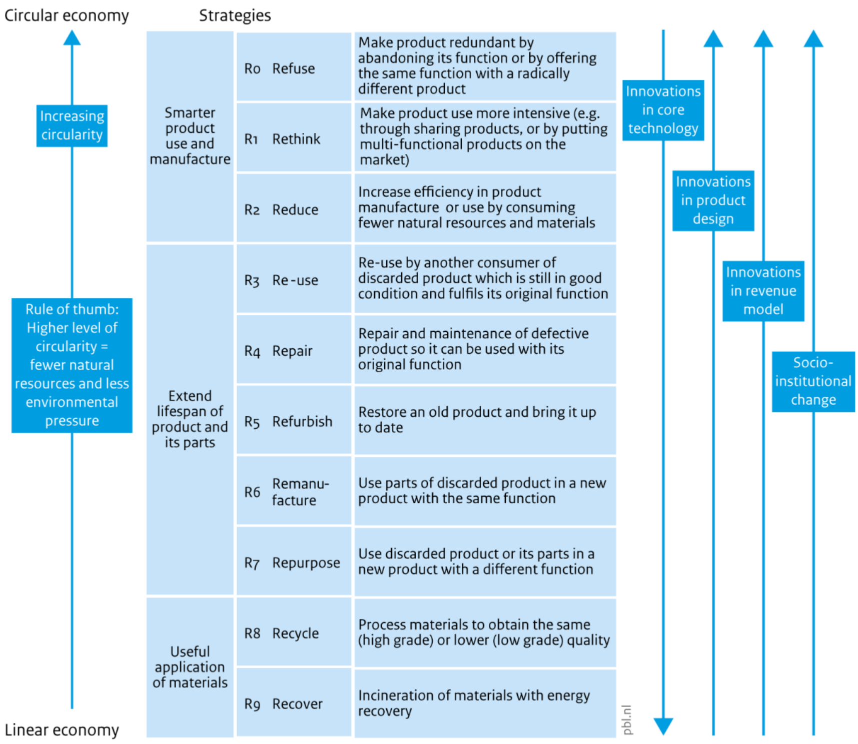

Figure 1: Overview of the 9R Framework (Potting et al., 2017)

Building upon the theoretical framework proposed by Potting et al. (2017), Bocken et al. (2016) distinguish CE principles into three distinct systems of resource loops: the *narrowing, slowing* and *closing* loops. Potting et al. (2017)'s highest degree of CE can be compared with Bocken et al. (2016)'s narrowing loops, as narrowing aims to use fewer and more sustainable resources per product. Here both potential environmental and economic benefits are the highest, as it results in lower costs and environmental impacts related to material usage (Bocken et al., 2016; Potting et al., 2017). The same comparison can be made for slowing and closing, as slowing relates to extending the lifetime and utilization period, and closing relates to completing the resource loops at EoL.

Bocken et al. (2016) stresses that products must be designed with CE in mind because once products are made *"only minor changes are usually possible"* (p. 310). Therefore, to gain benefits, products have to be designed to enable the slowing and closing of the resource loops later on. This is in line with Potting et al. (2017) 's framework, as without smarter product use and manufacture, it is hard to extend the lifetime and close resource loops through recycling and recovery. Therefore, it is arguable that companies who aim to increase circularity in their value chain and achieve economic and environmental benefits need to be aware of CE from the beginning of a product's lifetime by aiming to use fewer resources per product and designing the products for slowing and closing resource loops.

2.3 Circular Economy in the Offshore Wind Industry

In 2010, X. Liu et al. (2010) stated that wind power followed the path of sustainable development and CE. However, a decade later, Jensen et al. (2020) revealed that CE needed to be more widely integrated into the development of offshore wind farms. Moreover, Velenturf (2021) criticized X. Liu et al. (2010) for their claim, pointing out that only six publications were found on Scopus when searching for "circular economy" and "offshore wind" in June 2021.

Velenturf (2021) conducted a literature review focused on enabling the integration of CE in the offshore wind industry. The review showed a need for more research taking a whole life cycle perspective when examining CE in this industry, as most existing research focuses on decommissioning and EoL. This trend was also observed in the research on CE for the wind industry more broadly, as the majority of academic articles focused on material recycling and recovery in general, blade materials, and critical raw materials (Velenturf, 2021). However, as described earlier, recycling and recovery are emphasized as the two CE principles with the lowest CE potential (Potting et al., 2017).

Two years later (20.04.23), only five new publications have been found for the same Scopus search as used in Velenturf (2021). Among these, only one publication by Hall et al. (2022) is relevant to how the offshore wind industry adopts CE. Hall et al. (2022) analyzes the potential environmental impacts of offshore wind decommissioning. Meanwhile, Ciechanowska (2020), Henry et al. (2022), Jakubelskas and Skvarciany (2022) and Sevindik et al. (2021) have other focuses than CE in the offshore wind industry specifically. Hall et al. (2022) propose that having a CE mindset from the wind farm design phase can minimize adverse impacts of materials, and early planning and design can mitigate negative decommissioning impacts. This is in line with Jensen et al. (2020) who showed that offshore wind turbines must be designed for durability, reuse, and remanufacturing, but this is something the actors in the offshore wind industry fail to ensure as they are not taking a long-term and joined-up perspective on EoL management or resource extraction. Hence, the theoretical research and frameworks on CE in general (Bocken et al., 2016; Potting et al., 2017) and for offshore wind specifically (Hall et al., 2022; Jensen et al., 2020) stress that CE has to be implemented from the design phase for achieving the highest environmental and economic benefits, but within the offshore wind industry the largest focus is on the decommissioning and EoL phase (Velenturf, 2021). To enhance circularity within the offshore wind industry, it is essential to investigate and understand the reason for the disparity between academic recommendations for adopting CE and the industry's predominant focus on decommissioning and EoL considerations.

2.4 The Importance of Cost Reductions in the Offshore Wind Industry

First and foremost, it is worth noting that offshore wind has historically been relatively expensive compared to other energy sources (Williams et al., 2022). In 2010 the levelized cost of electricity (LCOE) for offshore wind was $188/MWh compared to $39/MWh for hydropower (IRENA, 2022). However, with rapid technology development and up-scaling in production, the costs of offshore wind have declined by 60 % until 2021, having a price of $75/MWh. Alone in 2021, the decline was 13 %. Already in 2016, the industry achieved a milestone by making offshore wind power economically competitive with coal and gas (Orsted, 2021). The significant decline in costs relates to the rapid technological developments of the turbines. During the last decade, turbine components have increased significantly, with a diameter growth of nearly 50 % to 163 meters in 2020 and an average size increase of 138 % to 8 MW (Williams et al., 2022). Furthermore, future projections suggest that turbine sizes will continue to expand, surpassing the 12 MW mark by 2025. Additionally, during the coming years, the average annual growth rate is projected to increase to 6.3 % in 2026 and 13.9 % at the beginning of the next decade, resulting in an even higher predicted decrease of the LCOE for offshore wind. In other words, the industry has always been driven toward reducing costs to compete with other more cost-friendly energy sources. However, with a significant decrease in LCOE over the last decade, the offshore wind industry has become a cost-competitive energy source.

Despite these positive developments, the offshore wind industry faces challenges due to broader commodity and cost pressures (Williams et al., 2022). The global supply chain disruptions caused by the COVID-19 pandemic have resulted in bottlenecks and increased prices for essential materials like copper, steel, and REEs. These challenges threaten the industry's ability to accelerate offshore wind delivery and effectively compete with other energy sources on cost. Nevertheless, these market dynamics have impacted most value chains, and the LCOE for offshore wind have remained competitive compared to other renewable energy sources, as well as traditional coal and gas energy options (BloombergNEF, 2022; DNV, 2022).

2.5 Drivers and Barriers to Circular Economy Adoption

Further, to understand why offshore wind actors primarily focus on CE within the EoL, the drivers and barriers to adopting CE have to be investigated to understand whether these affect why actors work with CE at EoL to a larger extent than at BoL.

Academic research has identified a wide range of drivers to pursue CE implementation within the thematic categories of *social*, *economic*, and *regulatory* drivers. For example, economic drivers include benefits such as cost savings, improved resource efficiency, and new business opportunities (Aid et al., 2017; Brown et al., 2019; Cantele et al., 2020; Donner et al., 2021; Sousa-Zomer et al., 2018), whereas social drivers encompass stakeholder pressures and societal expectations (Aid et al., 2017; Brown et al., 2019; Geissdoerfer et al., 2018). Regulatory drivers include laws and requirements (Brown et al., 2019; Geissdoerfer et al., 2018). In other words, a wide range of factors drives CE adoption, but there is no evidence of which CE drivers are most prominent in different industries or in the offshore wind industry. Therefore, there is a limited understanding of the factors influencing the offshore wind industry's preference for EoL considerations over CE principles focused on BoL.

Further, academic research has identified various barriers that industry actors encounter in pursuing CE implementation. The barriers are usually separated into categories such as *economic*, *organizational*, and *technological*. Firstly, economic barriers include the concern of increased costs, high investments, and limited demand for recycled products (Aid et al., 2017; Bocken et al., 2016; Brown et al., 2019; Tukker, 2015). For the organizational barriers, limited knowledge and awareness about CE principles and challenges associated with integrating circular practices into existing business processes are underlined (Bocken et al., 2016; Tukker, 2015). Lastly, within the technological barriers, inadequate recycling infrastructure and technical limitations are central (Brown et al., 2019; Geissdoerfer et al., 2018; Tukker, 2015). As for the CE drivers, there is a wide range of barriers to CE implementation, with no prominent factor.

In conclusion, there is a diverse specter of drivers and barriers to CE implementation, also in the offshore wind industry, and it remains unclear what the most dominating factors push and hinder CE adoption. This makes it challenging to identify why offshore wind actors are driven toward EoL solutions and do not focus on CE principles with higher circular potential. Therefore, to understand why the offshore wind actors primarily focus on EoL, the actor's drivers and barriers have to be mapped.

2.6 Succeeding with Circular Economy and the Role of Collaboration

To promote circularity, numerous researchers have emphasized the critical role of collaboration (Donner et al., 2020; Eisenreich et al., 2021; Fontoura & Coelho, 2022; Geissdoerfer et al., 2018; Kazancoglu et al., 2021; Köhler et al., 2022; Meath et al., 2022; Sousa-Zomer et al., 2018; Vilkė & Gedminaitė-Raudonė, 2020). For instance, Kazancoglu et al. (2021)

assert that *"the most important responses [for overcoming the problems of a CE] were found to be integrated business processes for cross-functional collaboration, .."* (p. 13). Similarly, Meath et al. (2022) propose that the stakeholder networks are critical to realizing CE outcomes. The attention allocated to EoL considerations by offshore wind industry actors could be attributed to their collaborative efforts centered on this particular phase of the turbines' life cycles. Nevertheless, further examination is necessary to validate this hypothesis.

Moreover, despite assertions of collaboration being important to implement CE, several studies have uncovered a shortage of explanations about the mechanisms, relations, conditions, and contexts under which collaboration is essential for facilitating CE (Eisenreich et al., 2021; Köhler et al., 2022; Krmela et al., 2022; Meath et al., 2022; Sousa-Zomer et al., 2018). Consequently, while the importance of collaboration for CE may be widely accepted, it rests on a limited evidentiary foundation, and the specific connection between collaboration and the adoption of CE remains unclear.

However, drawing on resource-based theory (Grant, 1991), it is argued that companies should leverage their unique and valuable resources and capabilities to gain a competitive advantage. Moreover, Das and Teng (2000) suggests that firms should engage in collaboration when they possess shared goals that cannot be accomplished independently with their internal resources and capabilities. Consequently, it can be argued that companies will pursue collaboration to adopt CE when they lack internal capabilities and perceive a competitive advantage in collaborating with other companies that have similar goals. Nevertheless, no existing academic study has examined this aspect within the domain of CE. Therefore, this study aims to clarify the reasons, circumstances, and actors involved in collaboration for CE within the offshore wind industry.

3 Methodology

This section presents the methodology used to address the research question of this study. First, the research strategy is presented, which encompasses the research process in Section 3.1. Then, the research design is described in Section 3.2 before the research method is elucidated in Section 3.3. Further, the data analysis process is presented in Section 3.4, and finally, the quality of the research is evaluated in Section 3.5.

3.1 Research Strategy

Clark et al. (2021) present research strategy as a broad orientation to the conduction of research based on the relationship between theory and research. More specifically, if theory guides the research or if the theory is the outcome of the research conducted. It is common to distinguish between two strategies; *qualitative* and *quantitative* research. For this study, a qualitative research strategy is chosen, and the reason for this choice will be further elaborated in Section 3.1.3. To define the research strategy, the steps of the research process are first presented followed by the literature search and selection process.

3.1.1 Research Process

As seen in Figure 2, the process of defining the research question and its sub-questions is an iterative process in line with the approach suggested by Dubois and Gadde (2002). The process is based on *systematic combining* grounded in an *abductive* logic. To initiate the research process, a systematic literature review on CE and collaborations was conducted, which will be presented in Section 3.1.2. This literature review established the basis for this study's focus areas and research questions. However, the research question and its sub-questions were revisited and adjusted throughout the research process as the understanding of the industry was continuously improved. Anyhow, available interview data were reviewed to better understand the offshore wind industry and the different challenges and opportunities actors in the industry face. Then, a targeted literature search was made. As a next step, the interview data were analyzed in more detail, and publicly available information for each interviewed company was reviewed and analyzed. Additional interviews were conducted to supplement the already reviewed interview data before they were transcripted and analyzed.

3.1.2 Literature Search and Selection

As mentioned above, the definition of the research question and the initial theoretical frameworks used in this study is based on two literature reviews. The first is a systematic literature review used to get an overview of the research field of CE and collaboration for CE, in addition to identifying research gaps. The second review is a targeted search for literature within the field of CE adoption in the offshore wind industry, which was conducted to narrow down the theoretical context and redefine the research question. The theoretical background presented in Section 2 is based on both of these reviews.

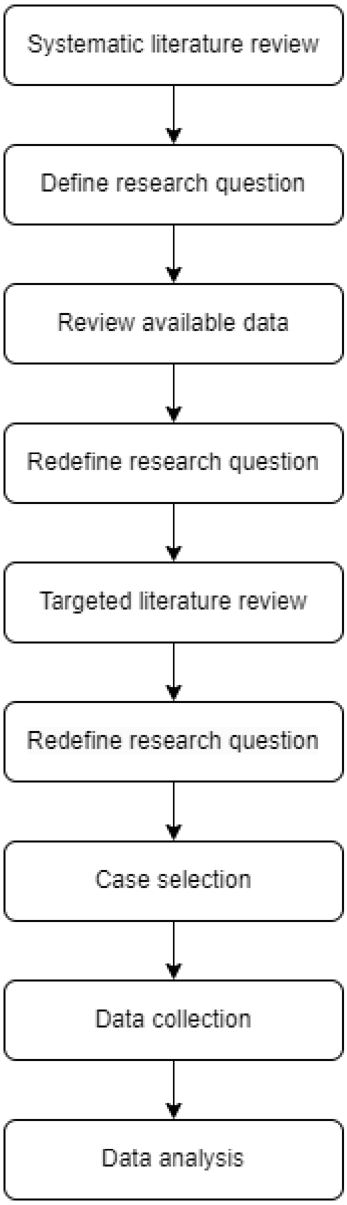

Figure 2: Overview of the Research Process

Initial Systematic Literature Review

The initial literature review was done as part of a project for the course *TIØ4562 Strategy, Innovation, and International Business Development* at NTNU in the fall of 2022. The project aimed to identify areas of agreement and disagreement in the emerging field collaboration for CE and promising areas for further research. It was determined that a systematic state-of-the-art literature review was critical to answer the project's research question, following the principles presented by Hart (2018). This review presents the current state-of-the-art research and analyzes the selected papers to identify gaps in the research field and locate key theories, concepts, and ideas. The steps followed include developing a research question, conducting a literature search in Scopus with predefined keywords, screening out irrelevant articles, and performing a systematic thematic analysis. The steps of the initial review are illustrated in Figure 3.

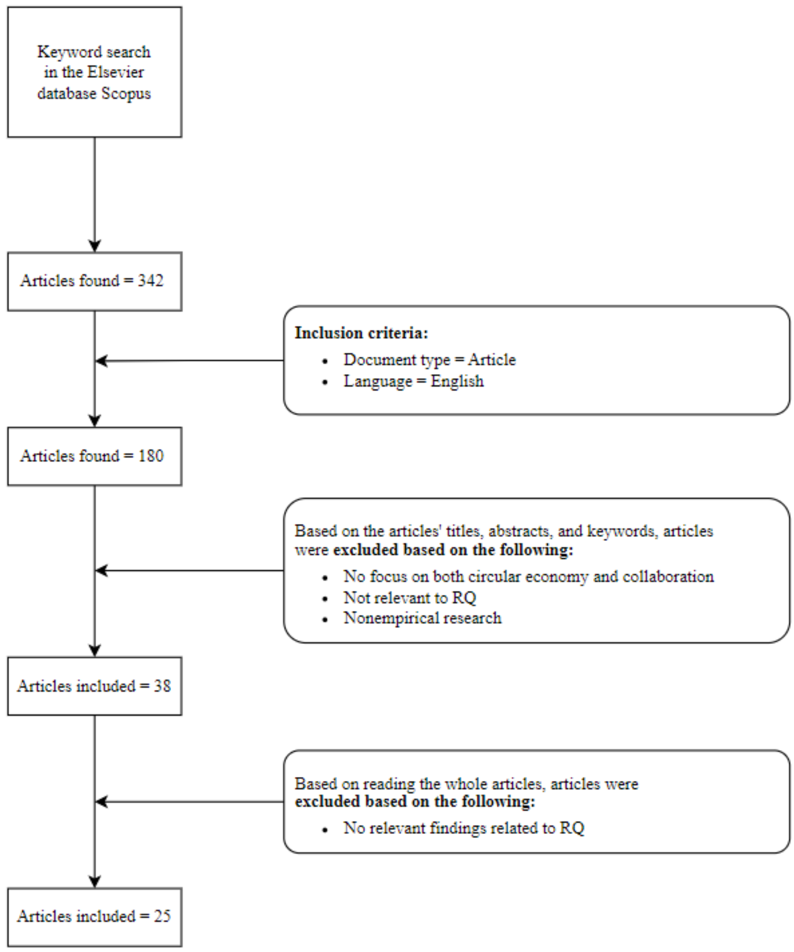

Figure 3: Overview of the Literature Selection Process

The article collection process began with a keyword literature search in the Elsevier database Scopus, using the search string *TITLE-ABS-KEY((collaboration* OR cooperation* OR alliance* OR partner*) AND circular* AND ((business AND model*) OR economy*) AND innovat*)*. The search was limited to English articles and yielded 342 results, which were narrowed down to 180 after excluding non-English articles. Two rounds of screening were then conducted to eliminate irrelevant articles, resulting in a final list of 25 papers. The methodology of Pittaway et al. (2004) was followed, combining keywords and synonyms with *AND* and *OR*. The search was not broadened to include keywords like *sustainable* to avoid irrelevant articles, nor were keywords like *inter-organizational* used to avoid excluding relevant papers. The objectives, study questions, methods, findings, and outstanding research needs for the remaining 25 papers were carefully registered in an Excel file. The most crucial elements and study areas within the field were then determined by carefully going over the articles.

Targeted Literature Review

The targeted literature review followed an iterative process and included several targeted searches. After selecting the adoption of CE in the offshore wind industry as the direction of this study, a targeted search on this theme was made to start defining the theoretical context and identify a research gap in the research done on CE in the offshore wind industry. Second, a targeted search on CE adoption and collaboration for CE within the offshore wind industry was made to further define the theoretical context to set the analysis in. As a result, it has not been a systematic review like the first one but rather a focused literature search for pertinent data on a particular topic. The literature was located during the entire research process, whenever necessary, as explained in Section 3.1.4.

3.1.3 Choice of Research Strategy

A qualitative research method with an inductive approach was chosen for this study. This means that words were emphasized over quantification of data collection, and the analysis focused on the relation between theory and research (Clark et al., 2021). The authors chose this research strategy because of the epistemological and ontological considerations of the study, in addition to the nature of the research question.

Epistemological considerations are related to what is defined as acceptable knowledge in a research discipline (Clark et al., 2021). There are different epistemological positions, such as *positivism*, *realism*, and *interpretivism* (Clark et al., 2021). In this study, it is implied a perception that there are several competing recognitions of reality and that it does not exist one true recognition of it. Therefore, the epistemological stance in this study is interpretivism. On the other hand, ontological considerations are about the nature of social entities and whether these can and should be considered objective entities existing separately from social actors (objectivism) or as social constructions (constructionism) (Clark et al., 2021). The ontological stance in this study is constructionism, as the social reality is viewed as continuously created by social actors and in a constant state of revision. This study is therefore based on interpretivism and constructionist positions, which are normally associated with qualitative research strategies, as chosen for this study (Clark et al., 2021).

3.1.4 The Relationship Between Theory and Research

This study uses a case study research approach based on systematic combining as described by Dubois and Gadde (2002). Systematic combining can be described as *"a nonlinear, path-dependent process of combining efforts with the ultimate objective of matching theory and reality"* (Dubois & Gadde, 2002, p. 556). This is an approach to the relationship between theory and research grounded in an *abductive* logic. Dubois and Gadde (2002) argue that merging several data sources, including interviews, surveys, and secondary data, enables the authors to produce novel insights and theories.

The approach consists of three steps: (1) individual data source analysis, (2) cross-data source analysis, and (3) developing a new understanding (Dubois & Gadde, 2002). Dubois and Gadde (2002) emphasize the importance of continuously moving between the empirical world and the theoretical framework in all the research steps. Research should move between asking questions, generating hypotheses, and comparing insights continuously instead of following a process of planned subsequent phases. Dubois and Gadde (2002) argues that moving back and forth in this way allows the researcher to expand their understanding of both the theoretical framework and the empirical phenomena studied.

In conducting this study, the authors have adhered to the guidelines proposed by Dubois and Gadde (2002) to meticulously evaluate the data's implications for existing theories and concepts. The authors have consistently revisited the relevant theoretical insights by analyzing individual data sources. Moreover, during the cross-analysis of multiple data sources, the authors have considered how these sources complement or challenge one another, remaining open to generating novel insights and theories through these interactions (Dubois & Gadde, 2002). Furthermore, in developing a new understanding, the authors have synthesized the insights derived from the cross-analysis with the existing theory to create a new understanding of the investigated phenomenon.

3.2 Research Design

A research design provides a framework for collecting and analyzing data, and the choice of it reflects how the authors weigh each dimension of the research process (Clark et al., 2021). Further, the research design guides the research and data analysis method as described in Section 3.3 and Section 3.4. This section delineates the research design employed in this study by first presenting a description of the unit of analysis, followed by a description of the research design itself.

3.2.1 Unit of Analysis

This study focuses on companies operating in the offshore wind industry engaged in activities related to adopting CE. Since using the same unit of analysis as existing literature enables meaningful comparisons with previous findings (Yin, 2018) and current literature predominantly use companies as the unit of analysis, the same is chosen in this study. Furthermore, examining companies individually facilitates the investigation of their strategic objectives and strategies, offering a more focused perspective compared to studying entire networks or the industry as a whole.

In order to answer the research question, a whole value chain perspective is needed to understand how the industry works to adopt CE. Therefore, companies from different parts of the value chain are studied, and these are categorized into three different types of actors; (1) manufacturers, (2) developers, and (3) EoL-handling firms. The manufacturers include the companies producing wind turbine components, developers are the actors responsible for engineering, procurement, construction, and installation in addition to the operation of wind farms, and the EoL-handling firms handle the components at post-usage. In addition, a group of industry facilitators has also been interviewed to supply a holistic view of the value chain and provide an additional source of evidence to reduce the construct validity, as will be described in Section 3.5.1.

3.2.2 Multiple Case Design

For this study, an embedded multiple-case research design is chosen, where more than two organizations are studied in the same manner (Yin, 2012). This choice is based on Yin (2018) three conditions for choosing research design; (1) the form of the research question, (2) the control the authors have of the actual behavioral events, and (3) the degree of focus on contemporary as opposed to entirely historical events. Based on the *why*-form of this study's research question, which is an explanatory question, the fact that the study looks at contemporary and historical events and that there are no behaviors that can be manipulated in this study, Yin (2018) supports the usage of the case study research method. Further, the multiple case study design was chosen over a single case study design since it is more compelling and robust (Yin, 2018). Additionally, a multiple case study allows for a cross-case analysis that aligns with the research focus in this study of taking a full value chain and life-cycle perspective.

3.2.3 Anonymity

In order to encourage participation and foster genuine responses from the companies and organizations involved, their identities have been kept anonymous in this study (Clark et al., 2021). Identifying specific companies was not deemed necessary for the purposes of this study, and anonymity is a common practice in multiple case studies, as it allows for a more open exchange of information and insights (Clark et al., 2021). In the offshore wind industry context, maintaining anonymity can facilitate greater willingness among actors to share valuable information. To maintain consistency and clarity, the companies and facilitators interviewed have been denoted as A1C1, A1C2, and so forth, where A defines the type of actor, and C represents the specific case company or organization. Additional details regarding the different actors will be provided in Section 3.3.1, and a comprehensive overview of the cases is shown in Table 1.

3.3 Research Method

The research method describes how data is collected (Clark et al., 2021). This section includes how cases are selected and how data is collected through interviews and by analyzing publicly available information such as LinkedIn, web pages, and sustainability reports.

3.3.1 Case Selection

The case selection in this study was separated into two parts. First, some cases were naturally selected as the author's co-supervisor had conducted relevant interviews. Second, additional interviews were conducted to gain a broader basis for the data analysis, as the data received through the already conducted interviews were not considered sufficient to answer the research question of this study. The sampling approach used to select additional cases was generic and purposive, meaning criteria concerning what kind of cases are needed to answer the research question are established before cases are identified and sampled (Clark et al., 2021). Purposive sampling refers to conducting the sampling in light of the research questions in order to choose the units of analysis based on standards that will enable the research question to be answered (Clark et al., 2021). Further, one issue with qualitative research is that it might be challenging to determine from the outset the minimum number of subjects that must be interviewed (Bryman, 2016). However, when additional interviews with a certain type of actor did not provide new information, it was decided not to conduct more interviews with similar actors as the added value would not be significant, especially when the time frame of this study was limited.

As this study focuses on the offshore wind industry, the actors interviewed are therefore operating in this industry or in relation to this industry. Cases were selected after researching websites, LinkedIn, and sustainability reports, to locate companies and organizations focusing on sustainability and potentially CE. As explained previously, three different types of companies from the offshore wind industry were interviewed, in addition to facilitators. The final sample of cases is presented in Table 1 below. *A* indicates type of actor, where A1 are developers, A2 are manufacturers, A3 are EoL handling firms, and A4 are facilitators. *C* indicate which case company or organization it is within each actor category. Further, *S1* and *S2* indicate whether it is interview number 1 or 2. For example, *A1C1S1* is the first source, the first interview with case company 1 within the group of developers.

3.3.2 Data Collection

According to Yin (2018), one of the most important sources of evidence in a case study is interviews, which have been the main source of evidence in this study. However, interviews with facilitators and publicly available information have also been additional sources of evidence. This is in line with Yin (2018) recommendation of having more than one source of evidence.

Table 1: Overview of Cases Included in this Study

Type of Actor	Interview ID	Case ID	Date	Duration
Developer	A1C1S1	A1C1	23.03.23	62 min
	A1C2S1	A1C2	11.03.23	73 min
	A1C3S1	A1C3	19.09.22	-
Manufacturer	A2C1S1	A2C1	10.10.22	-
	A2C1S2	A2C1	14.11.22	-
	A2C2S1	A2C1	13.10.22	-
	A2C2S2	A2C1	10.11.22	-
	A2C3S1	A2C3	25.10.22	-
EoL handling firm	A3C1S1	A3C1	13.03.23	89 min
	A3C2S1	A3C2	24.04.23	51 min
	A3C3S1	A3C3	24.04.23	60 min
	A3C4S1	A3C4	21.09.22	-
Facilitator	A4C1S1	A4C1	20.03.23	64 min
	A4C2S1	A4C2	24.04.23	82 min
	A4C3S1	A4C3	02.05.23	69 min

Semi-structured Interviews

To ensure the possibility to compare cases in a multiple case study, as in this study, Clark et al. (2021) argue that it is necessary with a degree of structure. Therefore, semi-structured interviews are the main mean used in this study to collect data. At the same time, having an abductive approach required some degree of flexibility. Semi-structured interviews allow for a combination of pre-defined questions and follow-up questions. The pre-defined questions or topics are listed in an interview guide, but the questions do not need to be asked exactly as outlined in the guide (Clark et al., 2021). Additionally, questions not included in the guide can be added as the interviewee replies. This approach enables the authors to gather in-depth information on a particular topic while also allowing participants to share their own experiences and perspectives.

Due to geographical differences and practical reasons, all interviews were conducted digitally over the video conference software *Teams*. The interviewees selected from each case company were those most involved with the company's work related to CE and sustainability. All interviews were recorded and transcribed as recommended by Clark et al. (2021), which all interviewees agreed upon. Recording the interviews allowed the interviewers to follow up with relevant additional questions and transcribe them for a more structured analysis, as described further in Section 3.4. Both authors of this study participated in all interviews, simplifying the process of both following the interview guide and asking follow-up questions. In total, 15 interviews were included in this study, where seven were supplied to the authors at the outset of the research period, and eight were conducted during this study's period.

Interview Guide

First, a standard interview guide was made for each type of actor, meaning all cases of manufacturers have one guide, all cases of developers have one, etc. The interview guides were created using Bryman (2016)'s guidelines, which offer a flowchart for creating questions for qualitative research. This involved identifying a few topics that were to be covered in order to address the research questions, followed by the creation of questions that addressed those topics from the viewpoint of the respondents. As a result, the guides, which can be found in Appendix A.1, were developed across numerous iterations to make sure the questions would cover the required breadth. In addition, most of the queries were open-ended to prevent bias toward the respondents. The interview guides have a number of 13 to 20 questions.

Then, prior to each individual interview, the guide was adjusted, and a 20-30 minutes long meeting was held with the initial contact person at the case company to ensure the interview was being set up with the most suitable person in the company, in addition to allowing for better preparations for both parties. This was done because the diverse activities and collaborations each company participates in allowed for different insights to be given. The modifications were made after looking into the company's website, LinkedIn pages, and sustainability report. Since some organizations had more publicly accessible information than others, researching the case companies in advance helped to prevent wasting time on queries that could have been answered elsewhere. The interview guides were also modified during the data collection phase, between interviews, as some questions showed to be more relevant than others. Using such a systematic combining approach enabled emphasis on various sections of the interview guide in accordance with the regions that the case firm or facilitator determined to be the most intriguing to study.

When interviewing the facilitators, the same interview guide was used. However, to acquire a more comprehensive and all-encompassing understanding of why and how strategies, processes, and collaborations related to the CE were performed in the industry, the questions were the same as for the firms, but with different wording, such as "what is your impression of companies focus on ...".

Documentary Information

According to Yin (2018), documentary information is an exact, stable, and broadly covering source of evidence. In this study, such information includes publicly available information about the companies and organizations found on their websites or in news articles. This information was used to prepare for the interviews and to form the actor descriptions. Most of the information was gathered ahead of the interviews to avoid ineffective use of time in the interviews, but the interviewees also sent some information after finishing the interview as it was not publicly available or challenging to locate.

3.4 Data Analysis

In this section, an overview of how data analysis was performed is presented. When analyzing qualitative data, there are no clear rules (Clark et al., 2021), but Yin (2018) emphasize the importance of treating evidence fairly, ruling out interpretations, and making compelling analytical conclusions. As presented in Section 3.1.4, the general strategy in this study is an abductive approach based on systematic combining (Dubois & Gadde, 2002), which means the analysis relies on a theoretical framework. However, such frameworks can sometimes be *too tight* (Dubois & Gadde, 2002) and therefore were the first analytical steps inductive. According to Tjora (2021), starting with inductive steps can also help avoid jumping to conclusions and avoid research confirmation bias.

3.4.1 Process and Steps

As mentioned previously, this study employed a systematic approach known as systematic combining, where the data underwent an initial coding and inductive grouping process. These groups were then compared to a theoretical framework to generate concepts. Notably, no predefined constructs were established beforehand, and the data was coded based on its empirical proximity, aligning with the method proposed by Tjora (2021). The analytical process is depicted in the Figure 4.

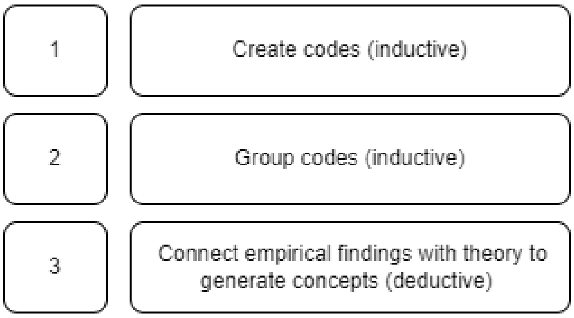

Figure 4: Overview of the Analytic Process

The initial phase of the process involved coding the interviews, with a specific focus on utilizing *empirical close* codes. This coding process was conducted using NVivo, a computer-assisted program designed for qualitative data analysis. The number of codes was not restricted, and NVivo was chosen due to its ability to efficiently manage large volumes of data while ensuring transparency throughout the process (Yin, 2018). According to Tjora (2021), empirical close codes refer to codes that closely relate to the empirical data and accurately describe its content, going beyond mere thematic discussions within the relevant parts of the interviews. These codes often employ *native concepts*, which are concepts that already exist within the data material. They frequently include direct quotes or phrases spoken by the interviewees, facilitating the understanding of the codes for other researchers without the need to read the entire transcriptions. When two statements significantly overlapped, they were grouped under the same code. In cases where the statements did not overlap significantly, new codes were created.

The next step of the data analysis process was to group the codes inductively. In this step, the codes were grouped thematically as suggested by Tjora (2021). Also, codes not relevant to the research question were placed in a residual group separate from the other code groups to exclude large amounts of irrelevant data (Tjora, 2021). All code groups are presented in Appendix A.2.

The third stage of the data analysis procedure involved comparing the group of codes with relevant theories to generate concepts. The case findings were documented and subsequently analyzed by case, actor, and then at a cross-case level, in conjunction with the theoretical frameworks. According to Tjora (2021), the concept development process entails examining the code groups or primary themes established in the previous step and asking, *"what is the underlying essence of these findings?"* (Tjora, 2021, p. 211) while considering pertinent theories and perspectives. As the systematic combining method prescribes, this phase necessitated a dynamic interaction between theory and empirical investigation (Dubois & Gadde, 2014).

3.5 Quality of Research

According to Yin (2018), the most prominent tests for evaluating the quality of empirical social research are construct validity, internal validity, external validity, and reliability. In the following subsections, the quality of the research design in this study is assessed through these tests.

3.5.1 Construct Validity

Construct validity is an important aspect of the quality of social research as it assesses the extent to which a measure or a research study accurately represents the underlying construct that is being studied. In other words, it measures the extent to which a study measures what it is supposed to measure (Yin, 2018). There are tactics available to increase construct validity when conducting case studies, such as the use of multiple sources of evidence (Yin, 2018). Therefore, multiple sources of evidence, both interviews and documentary information, were used in this study to minimize subjectivity. However, one interview was conducted with two interviewees from the same case company instead of separately, which reduces the construct validity as it makes them more likely to agree when answering.

Further, in semi-structured interviews, there is a risk of having a different understanding of discussed topics between the interviewer and interviewee and different interpretations of information, which reduces the construct validity. To avoid this, the use of long questions and ambiguous terms was avoided as recommended by Clark et al. (2021). Moreover, some interviews were conducted in Norwegian as that was the mother tongue of both interviewer and interviewees. In the process of translating these to English, some meanings could have been lost in translation. To limit this, the interviews were coded in Norwegian, and only direct statements were translated.

3.5.2 Internal Validity

According to Yin (2018), internal validity assesses the extent to which the results of a study can be attributed to the independent variable and not to other extraneous factors. In other words, internal validity measures the degree to which a study has established a causal relationship between the independent and dependent variables. Internal validity is most relevant for explanatory case studies where one is trying to explain how one event leads to another. For case study research, these concerns are related to the broader issue of making inferences (Yin, 2018), which happens every time an event cannot be directly observed. A suggestion for increasing the internal validity in case study research is pattern matching. Therefore, the data analysis in this study includes the matching of empirical findings and theory through the systematic combining process. In this way, the last step of the data analysis process follows pattern-matching logic, which increases internal validity. Moreover, open-ended interview questions were used to not lead the interviews and hence avoid affecting the internal validity (Yin, 2018).

3.5.3 External Validity

External validity holds significant importance in ensuring the quality of social research as it evaluates the degree to which study findings can be applied to other populations, settings, and time periods (Yin, 2018). Essentially, it measures the generalizability of research outcomes. In the context of case studies, analytical generalization is commonly employed, wherein researchers aim to generalize a set of results to a broader theory. To enhance external validity in case studies, it is advisable to incorporate replication logic into the research design, particularly in the case of multiple-case studies. Furthermore, Clark et al. (2021) contends that external validity poses a challenge in the case of studies due to the limited sample sizes, complicating generalizability.

In this specific study, convenience and availability guided the selection of numerous cases with the case companies being sampled from different points along the value chain. Consequently, the dissimilarity among the case companies may impede the application of replication logic and, subsequently, limit external validity (Yin, 2018). However, given the company's variations in products, sizes, and processes, exploring whether different companies within the same value chain exhibit similar thinking and behavior can present opportunities for generalization within the study.

3.5.4 Reliability

Reliability has the objective that one would get the same results from research if it is repeated under the same circumstances and by following the same procedures (Clark et al., 2021). To increase reliability, errors and biases have to be minimized. To achieve this, Yin (2018) suggests conducting the research process as if someone looks over your shoulder and documents it thoroughly. However, since the cases in this study are kept anonymous, it is impossible to go through the exact same process again, meaning an external researcher could not replicate the study exactly. Additionally, Dubois and Gadde

(2014) highlight the challenge of achieving identical results in qualitative research due to the dynamic nature of the world and the evolving nature of individual cases. Clark et al. (2021) further argues that conducting a true replication in qualitative studies is nearly impossible, primarily because the investigator is the primary data collection instrument. As a result, the investigator's personal preferences significantly influence what is observed, heard, and the specific focus of data collection (Clark et al., 2021).

Nevertheless, the research process has been thoroughly documented, and efforts have been made to enhance reliability by adhering to the three strategies proposed by Yin (2018): (1) establishing a case study database, (2) developing a case study protocol, and (3) utilizing computer-assisted qualitative data analysis software for the analysis. Initially, as recommended by Yin (2018), a case study database was created during the early stages of the study. This electronic repository encompasses the case study protocol, including notes made throughout the research process, comprehensive information about the cases, interview guides, data collection plans, and all transcribed materials. However, the audio files were stored locally rather than within the database for privacy considerations. Then, as per Yin (2018) recommendation, a case study protocol was developed early on to document all decisions made during the research. This measure aimed to ensure the data collection and analysis maintained high quality and allowed for potential study replication with appropriate consent from the interviewees. The protocol prevented individual research biases and confirmation biases by outlining the research objectives and providing an overview of the process. It also encompassed tentative research questions, information about the case companies and facilitators, and a preliminary study outline. However, it is worth noting that certain aspects of the protocol, such as the research question, interview guide, and study outline, underwent changes throughout the research process. Finally, NVivo was used to analyze the interview data. NVivo allows for the storage of codes and code groups created in the research process and the information storage of code groups. In addition, it allowed storing all research data within one file, making it easier for other researchers to access the data if needed.

4 Results

This section outlines the empirical findings derived from the research conducted, categorizing the companies included into four primary actors: (1) developers, (2) manufacturers, (3) EoL-handling firms, and (4) facilitators. The findings from each actor will be presented separately in Section 4.1, Section 4.2, Section 4.3, and Section 4.4, while Section 4.5 assesses the findings on a cross-actor basis.

4.1 Developers

Developers are companies that are responsible for designing, constructing, and operating offshore wind farms. Typically, these companies enter a project when governments release sites and usually follow through with the design and construction phase before operating the wind parks. In some instances, they sell down shares of the farms at the beginning of or after the start of operation. Their key activities include applying for licenses, conducting engineering and feasibility studies, procurement, construction, installation, and ongoing maintenance and operations of the wind farms. In this process, the manufacturers supply most of the central equipment of a wind turbine to the developers, although some developers may also construct some equipment themselves. The developers typically own all the components bought in this process and are responsible for handling or selling them at EoL.

In this study, three developer companies are analyzed, where two mainly operate in the offshore wind market (A1C1, A1C2), while one only operates onshore (A1C3). The studied companies exhibit varying degrees of focus on CE. One of the developers (A1C1) demonstrates a distinct comprehension and organized approach toward adopting CE. CE represents a central element of their sustainability reporting, and they have set forth explicit objectives and strategies to increase circularity (A1C1S1). Through their work, they have identified three primary areas across the entire value chain of wind farms where they perceive the most significant potential to influence resource usage (A1C1S1). Consequently, their sustainability team is currently engaging the rest of the organization to implement changes in operations in line with these focus areas.

In contrast, the other two studied companies (A1C2, A1C3) do not display the same focused approach to CE (A1C2S1, A1C3S1). They have not identified their hotspots for adopting circularity in a structured manner compared to A1C1. Nevertheless, during the interviews, both companies acknowledged the importance of CE and its potential to enhance the sustainability of their operations. For instance, A1C2 acknowledged that:

> *"In order to achieve that [transition to renewable solutions], we must have an awareness of material usage, as it is a limited resource. It is impossible to envision successfully expanding renewable energy without recycling, as it is both economically advantageous and, of course, the best way to protect the environment and ensure good resource management"* (A1C2S1).

Moreover, it is shown that a structured focus on CE has gained momentum in recent years (A1C1S1, A1C2S1). Specifically, A1C1 hired its sustainability manager intending to build its CE strategy two years ago (A1C1S1). Both A1C1 and A1C2 acknowledge their responsibility as offshore wind farm developers to promote CE adoption within the industry. For example, A1C1 stated:

> *"I would say we have a very big role as developers. One thing is how we require our suppliers to design and source their materials. But I think we have an even bigger responsibility regarding how we operate our wind farms, especially how we decommission them"* (A1C1S1).

In addition, A1C1 stresses the shared responsibility and importance of collaboration and dialogue among all actors involved, including customers, governments, states, and users also have to prioritize circularity when issuing tenders, creating competition in the market (A1C1S1).

4.1.1 The Developers Adoption of Circular Principles

The developers directly influence how to extend the lifetime by focusing on the service and maintenance of the wind turbines after they have been constructed and started operating. However, they are also engaged in developing new recycling solutions to increase the circularity at EoL.

Services: Repair, Refurbish, and Remanufacture

The studied developers have been working with lifetime extension of its assets by repairing, refurbishing, and remanufacturing as a part of its operation for years (A1C1S1, A1C2S1, A1C3S1). Typically, during the initial five-year period, manufacturers furbish equipment through a service agreement that includes responsibility for repair, refurbishment, and remanufacturing if necessary (A1C1S1, A1C2S1). After the five-year agreement, the operators are doing the maintenance themselves. A1C1 highlighted that after they have constructed and installed the wind farms, they have more or less full control over how it is handled:

> *"what we do with broken components, how well we maintain our wind farms, how long we want them to carry on, should we go for lifetime extension and so forth and especially when we are decommissioned the wind farms. We will have the sole responsibility of ensuring that things are actually recovered and circulated into new production loops and not just ending up on landfill"* (A1C1S1).

Further, both A1C1 and A1C2 maintain several research and development programs that continually aim to optimize the maintenance and operations of wind farms (A1C1S1, A1C2S1). These programs seek to optimize repair and replacement processes (A1C1S1), prevent erosion, and safeguard wind turbines against excessive forces (A1C2S1). A1C1 and A1C2 emphasize that this aspect constitutes one of the most crucial facets of their roles as operators.

EoL handling: Recycling

The developers highlight that they will always try to find solutions for the lifetime extension of their assets before sending them to a partner for EoL-handling (A1C1S1, A1C2S1). However, when it comes to handling the post-usage of the wind turbine, the developers focus most on recycling (A1C1S1, A1C2S1). It is highlighted that approximately 90-95 % of all materials utilized in the offshore wind industry *can* be recycled (A1C1S1). However, they also acknowledge the need for further development of recycling solutions for blades, as current approaches are *"immature and not commercially available"* (A1C2S1). A1C1 stresses that with better recycling technology in the future, it is desirable to keep recycled materials within the offshore wind loop to have secure access to materials for future wind farms (A1C1S1).

Although the studied developers are not directly involved in recycling, they are highly interested in developing better recycling technology (A1C1S1, A1C2S1). They are allocating considerable resources towards fostering research to identify more effective blade recycling solutions (which will be examined in Section 4.1.4 collaboration). Rather than recycling equipment at EoL, A1C1 suggests that:

> *"if there's any way to keep those components alive without recycling them, that's something we need to consider., ..., obviously it would be interesting if it could be used as furniture for something that A1C1 could use that, right?. Otherwise, I don't know how scalable it is"* (A1C1S1).

Conversely, A1C2 stresses that when repurposing wind turbine components, *"it's important that we don't just move the problem. Then there must be something that can again be recycled in the next round"* (A1C2S1).

4.1.2 The Developers Motivation to Adapt Circular Economy

The developers are motivated to adopt CE by several factors. The main factors identified are the stakeholder pressure from the media and investors, the possibility of ensuring secure access to materials, new legislation that forces the companies to prioritize CE, and possible cost reductions.

Stakeholder pressure

A key motivation factor for developers to prioritize CE in their operations is to meet stakeholder expectations (A1C1S1, A1C2S1). A1C1 underlined that they initiated strategic and structural efforts towards CE in response to significant global media attention two years ago (A1C1S1). Furthermore, as wind farms are not self-financed (A3C1S1), A1C1 and A1C2 emphasize that it is essential to be attractive to investors and that CE is an aspect that investors increasingly focus on (A1C1S1, A1C2S1).

Secure future supply

Given the high resource demand, circularity is a powerful tool for ensuring secure material access (A1C1S1). By adopting recycling measures, it is feasible to *"take back as many materials from your old wind farms and use them in your new wind farms, you'll suddenly have all the materials you need"* (A1C1S1). This objective is closely linked to the desire for independence from China regarding critical raw materials, such as rare earth elements and permanent magnets (A1C2S1), which is vital for securing sufficient materials for further wind farm projects.

Legislation

Simultaneously, the developers concur that legislation is among the primary drivers for introducing CE solutions (A1C1S1, A1C2S1). *"There is no doubt that we have come under scrutiny, and when authorities impose requirements, there is nothing that sharpens our focus more"* (A1C2S1). Today, more and more nations are integrating circularity into their tender criteria, mandating developers to incorporate it into their wind farm plans (A1C1S1, A1C2S1). For instance, in Norway, developers competing to construct offshore wind farms at Utsira Nord must include a decommissioning plan. Additionally, more countries are integrating landfill bans, forcing developers to use other EoL solutions.

Cost Reduction

The work with lifetime extension through repair, refurbishment, and remanufacturing is something the developers have been working with for years (A1C1S1, A1C2S1). However, the motivation here is mainly cost reduction. This is shown in the statement by A1C1:

> *"and to be honest, I think the driver here is very much cost optimization, right, because the less you have to maintain or the less you have to repair and change and replace spare parts and so forth, the less cost, the fewer times you have to go back and forth to an offshore wind farm"* (A1C1S1).

4.1.3 Developers Highlighted Barriers to Adopt Circular Economy

The developers highlight several barriers to adopting CE principles, where the lack of recycling technologies, the fear of increased costs, the lack of a market for recycled products, and insufficient understanding of CE's potential are the most prominent.

Technological Barriers

To increase the supply of recycled materials available in the industry and develop better EoL solutions than landfilling, the lack of recycling technologies, especially for blades

(A1C1S1, A1C2S1), is emphasized as a barrier; *"when it comes to decommissioning, some barriers would be a lack of recycling technology"* (A1C1S1). With today's technology, it is possible to recycle steel (A1C1S1), but plastics, magnets, fibers, and resin are challenging (A1C1S1, A1C2S1).

Economic Barriers

"How cost competitive the industry is today" (A1C1S1) is highlighted as a central barrier for adopting circular solutions for the developers (A1C1S1, A1C2S1, A1C3S1). In some countries, like Norway, CE is included in tenders. However, the entire industry is still *"impacted by the demand for low-cost energy"* (A1C1S1), and new projects are mainly based on delivering the lowest price (A1C1S1, A1C2S1). Additionally, other CE principles, except lifetime extension strategies as repair, refurbish, and remanufacture, are looked at as an increased cost (A1C1S1, A1C2S1, A1C3S1), shown by A1C1: *"in that game of reducing cost in the development phase, it is always a little bit tricky to also do things extremely circularly at the same time. Mainly because things are not business as usual"* (A1C1S1). A1C2 also highlighted the cost aspect as a barrier to adopting CE today; *"I think that we are looking at circularity as a cost, but in the future, it may be a cost not focusing on CE"* (A1C2S1).

Furthermore, the developers point to the lack of a developed market for utilizing recycled materials as a barrier to increasing circularity in the industry (A1C1S1). A1C1 also highlighted that today and in the future, there will be a shortage of recycled materials available in the market to meet the entire demand for materials used to build green energy production.

Value Chain and Society

A1C1 acknowledges that a notable obstacle to adopting CE is the insufficient comprehension of its potential advantages (A1C1S1). To overcome this challenge, they recommend enhancing industry awareness and knowledge of how incorporating recycled materials or other CE practices in operations can reduce emissions. They explain this: *"we need to understand a little bit better what the potentials are"* (A1C1S1).

4.1.4 Collaboration for Technology Development and Design of Legislation

To ensure a circular industry, the developers are collaborating with other industry actors, mainly for technology development and the design of legislation.

Technology Development

As mentioned, the recycling of blades remains an unsolved issue, encouraging developers to collaborate with other industry actors to develop solutions as they are responsible for the blades post-usage. A1C1, for instance, has joined a collaboration with 10 other companies to examine various recycling routes for blades (A1C1S1). A1C1's primary motivation for engaging in this collaboration is *"not only ensuring that A1C1's blades can be recycled but ensuring that the whole industry can deal with the challenge together"* (A1C1S1). A1C1 provides a customer perspective to this collaboration, assessing *"is this something that we as a customer would actually like to utilize"* (A1C1S1). However, since this is a structured member-heavy collaboration, A1C1 highlighted that:

> *"it also becomes a very heavy project management task to do any kind of work when you attend 10 big companies collaborating. Going forward, I think we will see smaller collaborations between, let's say, bilateral partnerships with just one developer and one manufacturer, for example, because time is essential here"* (A1C1S1).

Moreover, A1C2 has partnered with an EoL-handling firm focused on recycling and repurposing to stimulate actors in the value chain to go together to create *"good, circular solutions"* (A1C2S1). Today, collaboration evolves around knowledge and resource sharing. The developer has valuable knowledge about the operation and how to manage a business on an industrial level, whereas the EoL-handling firm is specialized in recycling and repurposing. Therefore, the knowledge shared between the companies is complementary and will gain for both parties.

Legislation

A1C1 and A1C2 stress that there is a need for more legislation and requirements forcing the whole industry to shift focus from cost to sustainability and circularity (A1C1S1, A1C2S1). They are collaborating with different industry actors and industry associations to promote this. For example, a European landfill ban is something industry actors engaged in WindEurope are collaborating to implement, in addition to discussing potential non-price tender criteria for new projects (WindEurope, 2021). They recognize that:

> *"one thing is you want to add something around sustainability as a criterion. Another thing is how do you actually do it? Should we put a requirement, like there are so many ways you can actually integrate it? So that whole space around how well-designed non-price criteria on sustainability, how does that look like? There is an ongoing dialogue between us, the whole industry, and the different markets where we operate"* (A1C1S1).

4.2 Manufacturers

The manufacturers are companies that can be defined as original equipment manufacturers. For this study, all the interviewed manufacturers are working with designing, manufacturing, sales, and services of wind turbines or wind turbine blades (A2C1S1, A2C2S1, A2C3S1). The equipment is sold to the developers through a one-time purchase, usually including a five-year service agreement, and the raw material is bought from upstream suppliers. After selling the equipment to the developers, the manufacturers have no responsibility except for the service agreement. The three case companies in this study supply main equipment such as wind turbines and wind turbine blades, and they deliver worldwide.

The studied manufacturers all have a certain focus on CE, resulting from a broader focus on sustainability. They clearly aim to reduce carbon emissions and be carbon neutral, also resulting in a focus on CE (A2C1S1, A2C3S1). For example, their focus on waste management stems from their goal to be carbon neutral. A2C1 and A2C3 strive to develop zero-waste equipment (limited to production waste) and create fully recyclable equipment (A2C1S1, A2C3S1), and A2C3 also sees it as essential to reduce the usage of raw materials (A2C3S1).

Although the manufacturers aim to develop more circular equipment, they generally agree that the developers have the power and responsibility to decide to use these solutions in their wind parks (A2C1S1, A2C2S2). A2C1 argues that *"because you [the manufacturers] can only offer the solutions [recyclable blades] as well. Also, with this right, it's up to the owners whether they want to use it or not"* (A2C1S1). Additionally, the choice of EoL strategy is also a decision made by the developers, which the manufacturers cannot influence, since they *"haven't seen the blade in many years"* (A2C1S1).

4.2.1 The Manufacturers Adoption of Circular Principles

The manufacturers work to develop and adopt CE solutions through a focus on the design, service, and recycling of their manufactured components. Manufacturers significantly influence the utilization of raw materials in equipment design and construction. Further, the manufacturers are actively engaged in promoting lifetime extension of their products through the delivery of robust equipment and five-year service agreements. Additionally, they attempt to contribute to the development of circular solutions by designing fully recyclable blades.

Product design: Reduce

First, in the product design and production phase, the manufacturers work with reducing the usage of raw materials (A2C1), extending lifetime (A2C1, A2C2), and reducing waste in production (A2C1, A2C2, A2C3). The manufacturers aim to design and construct equipment with minimal waste and use of raw materials (A2C1S1, A2C3S1), which are some of their top priorities (A2C1S1). They also highlight that they are focusing on constructing equipment with robustness to extend its lifetime. These initiatives reduce the material used per produced TWh of electricity. A2C1 has, for example, increased the design lifetime of blades from 20 to 25 years over the last five years, so *"that robustness of what is there is also a part of what we can offer to the customers [developers]"* (A2C1S1).

Services: Repair, Refurbish, and Remanufacture

As mentioned, the manufacturers deliver a service agreement where they are working with lifetime extension by offering repair, refurbishment, and remanufacturing services during the first five years of operation (A1C1S1, A1C2S1, A2C2S1). For example, A2C2 *"have 8000 colleagues working in our service business working every day on optimizing the performance of the assets that we have in operation and finding ways to increase the performance and lifetime"* (A2C2S1). If a part of the sold product has a crack, the manufacturing firm will take it back, fix it and keep it as a spare part ready to be used if another similar component gets a crack (A2C2S2). In addition to delivering the five-year-service agreement, A2C1 and A2C2 offer consulting expertise to the developers so they can continue using the equipment as long as possible (A2C1S1, A2C2S1).

Recycling

Recycling is essential to the manufacturers' waste reduction strategies (A2C1S1, A2C2S1, A2C3S1). A2C1 explains that:

> *"the paradox in this industry is that we [the manufacturers] are not taking care of the blades at the end of a lifetime. That's the customer [the developers]. It's their property, and we don't know what they want to do with it"* (A2C1S1).

However, A2C1 also stresses that *"we need to make it possible for them to recycle the blade"* (A2C1S1). Consequently, all studied manufacturers allocate significant resources to the technology development of recyclable components. For example, A2C2 began developing a fully recyclable blade in 2018, which was produced in 2021 (A2C2S1). Additionally, A2C1 and A2C3 are committed to actively pursuing better recycling methods for their production waste (A2C1S1, A2C3S1).

4.2.2 The Manufacturers Motivation to Adapt Circular Economy

The manufacturers are motivated to adopt CE by several factors. The identified factors are stakeholder pressure from customers, social responsibility, new legislation, and possible cost reduction.

Stakeholder Pressure

The manufacturers are pushed to focus on CE by the developers (A2C1S1), as they require them to set more *"concrete [circular] targets"* (A2C1S2) and challenge them to adopt circularity in their production of equipment (A1C2S1). For example, A1C1 frequently enquires whether using recycled materials instead of raw materials in the equipment is feasible (A1C1S1). In addition, A1C2 challenges its manufacturers to adopt circularity in the design of their equipment during commercial contract meetings (A1C2S1).

Social Responsibility

The manufacturers are increasingly motivated to work with CE principles in order to minimize negative environmental impacts since they operate within the green renewable industry (A2C1S1, A2C2S1, A2C3S1). A2C1 argued that *"if we can't take our own medi-*

cine, we can't be part of the renewable industry, you have to lead the way" (A2C1S1). This social responsibility is also linked to the companies' carbon-neutral goals where a certain focus on CE is needed to achieve these goals.

Legislation

Another motivation for manufacturers to think of circularity when designing and constructing wind turbines is stricter regulations (A2C1S1, A2C2S2). For example, a landfill ban in many countries pushes the actors to think more circularly, as A2C1 argues that:

> *"it's very, very difficult to be allowed to put anything in a landfill. So this is a good thing, I think because that forces the innovation into how can you then how can you reuse, how can we repurpose or how can you find other ways of getting it used again"* (A2C1S1).

Also, A2C2 thinks that *"if there's no regulation demanding recyclability, there's no incentive apart from ethics and good morale; which is not the only driver to develop for circularity"* (A2C2S2), showing how regulations are needed to push actors to adopt CE. Also, the manufacturers point to requirements for decommissioning when constructing a wind park as an incentive.

Cost Reduction

Cost reduction is a major motivation factor for manufacturers to reduce waste in their production. For example, A2C1 highlighted that they are receiving a positive cash flow through reducing waste, which is essential for focusing on CE (A2C1S1). They first saw the development of recycling blades as a cost, but this view changed after they experienced that carbon neutrality *"was not a cost but a benefit to the company. We were actually saving money by going carbon neutral"* (A2C1S1).

4.2.3 Manufacturers Highlighted Barriers to Adopt Circular Economy

Even though all three case companies are working with CE in their operations, they are also highlighting several barriers to adopting a CE. The barriers can be categorized into technological, economic, and institutional barriers.

Technological Barriers

Technological barriers such as inadequate recycling technologies are underlined as critical for adopting CE by the manufacturers (A2C1S1, A2C2S2). A2C1 stresses that, for example, *"there's still technology challenges on making sure we get to the right resins system"* (A2C1S1). Additionally, they argue that *"it's a little bit the same with the glass because it also gets fatigued during operation. So, at the end of a lifetime, you have less strength"* (A2C1S1), meaning that the decreased strength of the turbine component presents an obstacle to using it at EoL.

Economic Barriers

For the economic barriers, both the increased cost of developing and offering a fully recyclable blade (A2C1S1, A2C2S2), the challenge of value-setting CE initiatives (A2C2S2, A2C3S1), and the low volume of decommissioned blades (A2C1S2, A2C2S1) are underscored as obstacles to adopt CE.

One problem is that recyclable blades are extra expensive (A2C1S1). Still, the main barrier to adopting more circular solutions, in the design and construction of equipment, is that:

> *"the value of recyclability comes at EoL and that is 30 years from now, and then you apply net present value scenario, even before high inflation rates you would heavily depreciate the value of something 30 years from now, right? So there is a dilemma for us [the manufacturers] from a commercial or financial point of view in designing for recyclability when you have a long lifetime"* (A2C2S1).

Additionally, A2C2 highlighted that:

> *"that we're missing right now is the value of the material coming out of the recycling is not high enough. The volumes are not there to get you to the point where you actually have a valuable and consistent stream of material"* (A2C1S2).

Therefore, for achieving a large-scale and profitable recycling industry, the volume of used blades is underlined as a challenge by the manufacturers (A2C1S2, A2C2S1), which makes it difficult to reach a high-value and low-cost recycling solution. A2C2 states that *"one of the main limitations is that there's no volume in the market, right? Nobody's taking down turbines today"* (A2C2S1) and A2C3 say *"we know it's tough to recycle materials. It's not a good business case, but if there's more demand for recycling materials, then hopefully you'll also be a good business and cheaper to recycle"* (A2C3S1).

Institutional Barriers

Different legislation across countries is emphasized as a barrier for manufacturers to adopt CE (A2C1S1, A2C2S1, A2C3S1). The varying legislation makes it difficult to reuse and recycle old blades because it makes it challenging to export used blades and difficult to have a standard EoL method as landfilling is allowed and cheaper than other alternatives in specific countries (A2C1S1). Additionally, different perspectives across regions of what is considered waste and toxic materials (A2C3S1) also make it hard to have one standard method for handling turbines at EoL. Again, this results in some markets being more costly and less attractive (A2C3S1). A2C3 stresses that *"the same materials in one country can be regarded as hazardous waste and the same material in another country can be regarded as a material that you can recycle and non-hazardous"* (A2C3S1) and *"you know it's the same waste. I would not say it is a hazardous material. We can actually recycle most of* *it. But the thing is that legislation and what you think is toxic will vary from country to country"* (A2C3S1).

Additionally, various dimensions and compositions of wind turbine components also present a barrier to refurbishing, remanufacturing, repurposing, and recycling of used wind turbine components as it is less predictable what material will be available to use for such purposes (A2C1S1). A2C1 state that *"if we all push for solutions in different directions, then the suppliers won't move right because it doesn't give them any benefit of scale. So there is a challenge about developing certain standards, I think"* (A2C1S1).

4.2.4 Collaboration for Technology Development, Information Sharing, and Design of Legislation

The studied manufacturers are collaborating with each other and with other industry actors to develop technology for recycling blades, to share information regarding the blade's composition so they can easier be treated at EoL, and to influence legislation related to CE.

Technology Development

All case companies are collaborating to develop methods and technologies for recycling blades (A2C1S1, A2C2S1, A2C3S1). To enable the development of a CE for turbine blades, different actors across the industry collaborate and share relevant information and knowledge needed to find the best possible EoL solutions. Notably, manufacturers are not competing in this project. Instead, they seek to establish a value chain for blade recycling since it is not a company-specific challenge but an industry challenge (A2C3S1).

Information Sharing

As a part of the cross-actor collaboration for developing recycling technologies for blades, the manufacturers are also collaborating to develop *material passports* (A2C1S2, A2C2S2, A2C3S1) for wind turbine blades. The project aims to make the recycling of blades easier for EoL-handling firms. A2C1 highlighted that they have:

> *"introduced a material passport for blades where basically we're going to start producing these documents for all of our blades going forward and make them available, at the end-of-life for products. And it actually contains the level of information that we've seen that recycling companies are interested in"* (A2C1S2).

Notably, the material passports only share information on the blades on a high-level plan (A2C3S1).

Legislation

All the manufacturers are members of WindEurope and have committed to ending landfilling practices by 2025 (WindEurope, 2021). In WindEurope, they all are engaged in cross-actor collaborations to promote CE principles in the industry and discuss new regulations and tender criteria for increasing the circularity.

4.3 End-of-Life-handling Firms

EoL-handling firms are responsible for managing the disposal of assets that have reached the end of their useful lifetime. Specifically, the EoL companies examined in this study are working with the recycling of wind turbines (A3C1), developing new recycling technology for wind turbine blades (A3C2), or repurposing old wind turbine blades into furniture (A3C3, A3C4).

All the studied companies handle onshore components from wind farms and plan to extend their services to handle offshore assets (A3C1S1, A3C2S1, A3C3S1, A3C4S1). While some carry out the wind turbine dismantling process (A3C1, A3C4), others outsource the job to external partners (A3C2, A3C3). Presently, the EoL-handling firms charge the developers fees for dismantling and demolition (A3C2S1, A3C3S1). However, the fees are expected to decrease over time as manufacturers develop more recyclable equipment, and the demand and price for old equipment will increase (A3C2S1, A3C3S1).

All the studied EoL-handling firms focus on CE in their operations as they seek to assist the offshore wind industry in identifying more circular solutions than landfilling (A3C1S1, A3C2S1, A3C3S1, A3C4S1). However, as they do not have direct control over which solution the developers choose for handling their assets post-usage, the studied companies have varying preferences for sustainable and circular solutions. For example, A3C2 has gained a lot of interest for its technology from many developers (A3C2S1), whereas A3C4 has received lower interest for its repurposed products (A3C4S1). However, A3C3 highlights that there has been a shift in the developer's and operators' view of choosing EoL solutions (A3C3S1). They emphasize that historically the developers would look for the cheapest solution, mainly landfilling, but now they have a greater understanding of sustainability and CE. At the same time, A3C1 underlines that:

> *"there's a large operator that's basically told us; we would like to pay a small price for a large reduction in CO2 footprint, but we will not pay a high price for a low CO2 footprint reduction. So, cash is still king"* (A3C1S1).

4.3.1 The EoL-handling Firms Adoption of Circular Principles

The EoL-handling firms directly influence how wind turbines can be handled at EoL and which CE principles are being industrialized and scaled. Today, the largest focus among EoL-handling firms in the offshore wind industry is on repurposing and recycling solutions.

Repurposing

For the companies working with repurposing, both A3C3 and A3C4 are making furniture out of old wind turbine blades, which slows the resource loops by increasing the lifetime of the blades (A3C3S1, A3C4S1). A3C4 highlights that they, in theory, can reuse 10 0% of the blades while making furniture, but *"sometimes we need to remove something from inside, from the part, you know. So I would say, 90-95 % is the highest possible"* (A3C4S1). A3C3 agree that they, in theory, can reuse 100 %, but in reality, it would be more around 98 % (A3C3S1). However, if the blades come in damaged, they cannot have such a high rate (A3C3S1, S3C4S1).

Recycling

A3C1 and A3C2 are engaged in the task of recycling old wind turbines (A3C1S1, A3C2S1). A3C1 has a history of operating as a recycling company across various sectors. Meanwhile, A3C2 was established to develop a technique for recycling composites, particularly those present in wind turbine blades. A3C1 confirms that they can recycle a minimum of 90 % of the total wind turbine back to the original materials, and the last percentage can be mixed together to create cement (A3C1S1). There is a large focus on the blades, but A3C1 highlights that the blades are only 1-2 % of the total mass (A3C1S1).

In contrast, A3C2 has developed a new technology that can theoretically recycle 100 % of the wind turbine blades (A3C2S1). They are not only *"burning them or crushing them to make some low-quality products but actually by reusing the materials you can recover some raw materials"* (A3C2S1). In practice, they can recycle up to 98-99 % of the whole blades, as fibers can transfer into usable fibers, whereas the last 1-2 % can be sent to cement production (A3C2S1).

The recycling processes A3C1 and A3C2 are working with are highly related to reducing the need for raw materials to create new wind farms (A3C1S1, A3C2S1). A3C2 highlights that their goal of creating the new technology of blade recycling was *"to support blade manufacturers to achieve a circular economy and improve eco-efficiency indicators in the wind industry by recovering raw materials and supplying them to manufacturers of various products to use instead of virgin materials"* (A3C2S1). Further, A3C1 is also looking at how some parts of wind turbines can be recycled and used as recycled materials in new wind turbines. For example, they have *"looked at, last year, the magnets and taking out the magnets from the rotors and finding triggers for them and getting them back into our circular economy"* (A3C1S1).

4.3.2 The EoL-handling Firms Motivation to Adapt Circular Economy

The EoL-handling firms are motivated to adopt CE because it presents new business opportunities and attractive markets.

Business Opportunities

All the studied companies entered the offshore wind market based on their perception of business opportunities in repurposing or recycling (A3C1S1, A3C2S1, A3C3S1, A3C4S1).

> *"It seems like a good business case, of course, and something worth trying to see what we can do about that. And it's connected to the circular economy and improving the inventible aspects for the windmills that are also very good and nice motivation to improve something in this world right"* (A3C2S1).

A3C3's interest in finding improved solutions for wind turbine blades at EoL stemmed from reading Bloomberg's article on the growing issue of landfilling blades (A3C3S1). Similarly, A3C2 and A3C4 also identified the EoL market as an opportunity due to the growing concern surrounding landfilling practices, mainly through landfill bans in many countries in later years (A3C3S1, A3C4S1).

A3C3 highlights that they easily saw the business opportunities since they had worked in the recycling industry for years (A3C3S1). Therefore, they knew that *"the fiberglass has always been the issue and landfill to our company into most of the industry is not an acceptable alternative. ... We always knew there was a better solution [than landfilling] out there. Well, we hoped"* (A3C3S1), which led them to continue looking at new solutions.

4.3.3 EoL-handling Firms Highlighted Barriers to Adopt Circular Economy

The EoL-handling firms highlight several barriers to adopting CE principles, where lack of standardization and information sharing are the most prominent.

Technological Barriers

Manufacturers continuously pursue technology development to increase wind turbine efficiency, resulting in larger turbine sizes and new materials and compositions used (A3C2S1). The EoL-handling firms have identified the absence of standardization in wind turbine design as a significant barrier to their work in repurposing and recycling equipment (A3C1S1, A3C2S1, A3C3S1, A3C4S1). Consequently, as *"every blade, even some of the, you know, the same model of the blade, you'd be amazed at how different they are inside"* (A3C3S1), it is hard to analyze and handle the blades. Additionally, A3C2 highlights that old blades have a *"a completely different structure"* (A3C2S1), resulting in *"a wide variety of the upstream materials, so then the technology must be dedicated to different kinds of materials, right? So, you can expect the unexpected because you never know what you will get in the blades"* (A3C2S1).

Organizational Barriers

Another significant barrier to working with recycling and repurposing wind turbine blades relates to the lack of information regarding the material composition of the blades (A3C1S1, A3C2S1, A3C3S1, A3C4S1). As presented above, the composition of wind turbine blades varies widely, and it is challenging to determine their content accurately. For the old blades:

> *"data sheets are not available for the blades, so we have no information on the blades. And then, we need to do extensive testing to find out what is actually in the blade so we can expect if any toxic things can harm people or the environment"* (A3C2S1).

Additionally, for new blades, the manufacturers *"cannot share information about the blades that are, for example, still in production, so this is the corporate confidentiality"* (A3C2S1). This lack of information makes it harder for EoL-handling firms to develop the most effective methods for repurposing or recycling the blades (A3C2S1, A3C4S1).

4.3.4 Collaboration for Technology Development

The EoL-handling firms are collaborating with developers and universities to develop their technology and their business.

Technology Development

A3C1 is engaged in a cross-actor collaboration for developing recycling technologies (A3C1S1) together with manufacturers and universities. Originally, the firm was not involved in the wind industry but joined the collaboration after a manufacturing firm asked if they could help as a scrapping firm. As a result, A3C1 shared knowledge regarding recycling and later got engaged in recycling wind turbine blades. In contrast to A3C1, A3C2 is developing the recycling technology itself (A3C2S1). However, they collaborate with different developers to promote their solutions, connect with potential customers, conduct testing, and receive advice (A3C2S1).

4.4 Facilitators

In this study, facilitators are a collective term for non-profit organizations that facilitate and promote innovation and technology development across the whole value chain of actors in the offshore wind industry and who are lobbying for the industry's interests. The studied facilitators have a broad knowledge of what the different industry actors are working with and how they adopt CE in their operations.

All the studied facilitators underline that CE is essential for the offshore wind industry (A4C1S1, A4C2S1, A4C3S1). However, they have different approaches to getting the industry actors to implement it in their operations. For example, A4C1 stress that CE is an important topic, but neither they nor the companies they are in contact with have a focus on it today (A4C1S1). However, *"concerning the EU-taxonomy, requirements regarding circularity are getting implemented, which will lead to a higher focus"* (A4C1S1). In contrast, A4C3 provides information regarding which circular solutions are available to its members and raises awareness of new solutions available in the market (A4C3S1).

Both A4C1 and A4C3 stress that the largest focus on CE is at EoL (A4C1S1, A4C3S1). However, A4C1 highlights leasing models, where the wind turbine manufacturers own the equipment, which may give them larger incentives to reuse turbines or design them to be more robust and easier to recycle (A4C1S1), supported by A4C3 who also highlighted that there is a need for shifting focus from EoL to *"an integrated approached [on CE] from the start of life"* (A4C3S1).

Historically, A4C3 underlines that the industry has been cost driven where *"the lowest bidder for that site wins the project"* (A4C3S1). However, more auctions are now based on *"non-priced criteria"* (A4C3S1), where sustainability and circularity are included. In other words, there has been a shift in the industry, going from only focusing on cost to including CE as a competitive factor in tenders. However, non-price criteria are not included in every country, as A4C2 highlighted that in the UK, for instance, there are still no criteria focusing on either sustainability or circularity (A4C2S1).

A4C1 believes that the developers are the ones in power to set requirements for their suppliers on circularity, as suppliers and sub-suppliers are then forced to follow up on this (A4C1S1). A4C3 further highlights that:

> *"at the moment, we are still figuring out, as an industry, who owes who what. This is where discussions get a bit harder. Should it be the manufacturer's responsibility to deal with the blades of 20 years ago? Or should it be the operator? Legally, it's the operator"* (A4C3S1).

4.4.1 The Facilitators Focus Regarding Circular Principles

The facilitators have a more holistic view on how CE and supports companies to further develop their operations, maintenance, repair, remanufactured, and life extension solutions in the offshore wind industry (A4C1S1), in addition to creating awareness of different CE strategies. They push companies to first consider re-use before repurposing, recycling, and recovering when handling wind turbines at EoL (A4C3S1). The facilitators also work to promote the reduction of material use by helping companies look into how to reduce the reliance on important rare earth elements and help companies review their manufacturing process and optimize it (A4C2S1).

However, their main focus is on highlighting the relatively high recyclability of wind turbines today and simultaneously working to find *"optimal policy framework to accelerate blade recycling in particular"* (A4C3S1). A4C3 explains that *"within the policy framework, talking primarily about blades, our main focus is waste policy, waste classification, and trying to get a framework that better allows our members to deliver on their ambitions of no longer sending decommissioned blades to landfill"* (A4C3S1). A4C3 posits that recycling is a more viable option for managing EoL wind turbines than reuse and repurposing for several reasons. First, recycling is deemed a more scalable solution than other

EoL strategies. Second, recycling offers the possibility to close materials loops as some materials can be recycled to again be used as originally. Third, when operators send their used blades to recycling companies, they no longer have legal responsibility for it which is a benefit for the developers.

4.4.2 The Facilitators Understanding of Actor's Motivation

The facilitators perceive that offshore wind industry companies are motivated by factors such as increased external pressure from investors, regulations and requirements, and cost reductions related to the adoption of CE strategies and solutions.

Stakeholder Pressure

A4C1 emphasizes that for companies to gain financial support from the EU, there will be increasingly important to consider circular solutions and think circularly, even from the design phase (A4C1S1). The EU taxonomy and investors are expected to increase its recycling requirements from 2025 on, separating green and brown wind projects (A4C1S1). A4C3 similarly argue that *"I think really the pull from policies, from the investments from the banks and the big investors and their demands trickling down in the supply chain, that is, I think, what really accelerates these notions of the circular economy"* (A4C3S1).

Legislation

The facilitators emphasize the significance of legislation and policies as crucial mechanisms to incentive companies to incorporate circular solutions. According to A4C3, the optimal approach to encourage companies to embrace these principles is not through direct appeals to individual companies but by engaging with policymakers (A4C3S1). A4C3 asserts, *"it's us going to politicians saying, politicians, we think that our industry is ready for more circular economy"* (A4C3S1).

A growing focus on sustainability and circularity in tenders through non-price criteria also motivates companies to develop and invest in such solutions. A4C3 states, *"if you don't have a circular economy approach, you're not going to win the auctions out there"* (A4C3S1). Facilitators are in discussions with actors who oversee the leasing applications for new offshore wind development, and they are discussing what should be added to the application process to make the developers think more about circularity (A4C2S1, A4C3S1). The facilitators believe including more criteria related to the CE in this process will be an important incentive for developers.

Reduced Costs

A4C2 observed that reduced costs are the primary motivation for companies to actively undertake a production waste review and implement measures to minimize waste (A4C2S1). In some countries, a considerable proportion of materials used in the offshore wind industry are imported, while the availability of resources and materials is declining (A4C1S1). This situation provides economic incentives to promote the reuse and recycling of materials, aiming to mitigate both costs and emissions. A4C2 argues, *"if we can just reuse as much as we have, then we're relying less on imports, which is relying less on virgin mining, which is then creating less environmental problems going forward as well"* (A4C2S1).

The facilitators also agree that the companies in the offshore wind industry have strong incentives to extend the lifetime of wind parks as it is a business opportunity (A4C3S1). *"Lifetime extension is, let's say, not a top priority for A4C3 to work on because it's actually very business driven. It's a business case. What we see is that there are many incentives for our members to extend their lifetime"* (A4C3S1).

4.4.3 The Facilitators Understanding of Actors' Barriers

The facilitators highlight several barriers hindering companies from adopting CE principles, where a lack of clear requirements and standards, fear of increased costs and the challenge to measure CE are the most prominent.

Technological Barriers

The facilitators stress that the offshore wind industry faces a challenge in adopting the principles of CE due to the lack of developed recycling technologies. The facilitators work to facilitate the development of technologies and give advice and support to help companies avoid landfilling (A4C3S1).

Economical Barriers

The facilitators observe that most actors in the offshore wind industry are, first and foremost, cost-oriented and choose the cheaper alternative, resulting in less resource-efficient solutions (A4C1S1, A4C2S1). The recyclable and circular components are often more expensive, presenting a barrier to choosing that alternative (A4C1S1).

A4C1 also highlights the lack of a development marked for used material from the wind industry as a barrier (A4C1S1). A4C1 state that:

> *"it must be able to be reused in some way, and there must also be a kind of market mechanism that ensures that what you purchase, how should I say? Well, the waste, the costs must be lower than what you can sell the product for, otherwise, there is no point in doing it"* (A4C1S1).

Additionally, the facilitators are unsure if the demand for outdoor furniture and similar products made from old turbines is large enough to handle the accumulation of used blades by repurposing them (A4C2S1, A4C3S1).

Organizational Barriers

Another challenge identified by the facilitators when pushing companies to pursue CE strategies is the difficulty of measuring CE initiatives (A4C3S1). A4C3 state *"emissions are quantifiable, more easily quantifiable"* (A4C3S1), as opposite of CE. There is a lack of ways to measure circularity and *"there's no simple, clear circularity indicator"* (A4C3S1).

Institutional

The facilitators believe governments must provide clearer requirements to push the industry to make better choices on recycling and reuse of materials (A4C1S1, A4C2S1). A4C2 argues that countries with more extensive legislation related to CE have successfully managed to push both industry actors and investors to consider CE to a broader extent (A4C2S1). However, only a few countries have legislation or requirements related to circular economy for the offshore wind industry today (A4C2S1). A4C1 thinks a landfill ban needs to be in place for actors to really have incentives to work on circular solutions (A4C1S1).

A lack of standards regarding the turbine sizes and compositions also presents a barrier to implementing circular solutions on a larger scale (A4C2S1). For example, when parts are damaged, it is difficult to get hold of spare parts as the manufacturers no longer produce them since the turbines have drastically changed (A4C2S1). A4C2 explains that:

> *"there were no spare parts available to replace the broken cogs anymore because they were so old, so out of production, that they tried to contact the manufacturers. They said we're not interested because we don't make, we've not made these for 10, 15 years. We're not interested"* (A4C2S1).

4.4.4 Collaboration for Circular Economy and Tender Criteria

A4C3 gather companies from the offshore wind industry to discuss how they work with issues and task related to sustainability, as for example, decommissioning (A4C3S1). Here, actors share their experiences and success stories, inspire each other, and raise awareness of circular solutions. In both thematic groups and larger events, they have seen that the focus has started to *"switch from thinking of the end of life to, let's say, an integrated approach from the start of life. So, circularity, by design, is getting more and more impact"*(A4C3S1). Moreover, the facilitators also collaborate with companies in the industry to design and influence tender criteria (A4C3) and to apply for financial support from the EU to look at CE solutions (A4C1).

4.5 Cross-Actor Analysis

To understand what the different actors in the offshore wind industry are working with related to CE and what are the most prevalent motivation factors and most significant barriers to adopting CE, the findings from 4.1, 4.2, 4.3, and 4.4 are analyzed on a cross-actor level.

For all actors involved in the offshore wind industry, including developers, manufacturers, and EoL-handling firms, sustainability is a key priority. These companies have sustainability goals and strategies, which are reported annually. The attention towards sustainability has resulted in an increased focus on CE in recent years. However, only a few of the interviewed companies have strategies and goals for increased circularity specifically (A1C1S1). In addition, most initiatives related to CE, such as strategies for waste reduction, are a result of goals to achieve carbon neutrality or other goals related to sustainability as a broad concept (A2C1S2, A2C3S1).

The findings also reveal that actors in the industry have a more active focus on CE principles related to EoL-handling of the turbines. Even though both manufacturers and developers work to extend the lifetime of the turbines, initiatives related to this are solely motivated by cost reductions. The more recently incorporated CE initiatives are focused on decommissioning of blades, such as no landfill policies and investment in the development of recycling technologies. Moreover, non-price tenders recently incorporated in tenders for new offshore wind projects focus on how turbines are planned to be handled at EoL.

Further, all investigated actors have identified developers as the primary actor responsible for integrating CE principles in the offshore wind industry. The manufacturers claim they can produce more circular equipment, but ultimately, the developer's choice of equipment is pivotal. Similarly, the EoL-handling firms argue that while they can develop solutions for handling equipment at the post-usage, the developers are the ones who have to choose and pay for it. Developers recognize their critical role in advancing CE in the industry, as stated by A1C1: *"we have a very big role as a developer"* (A1C1S1). However, A1C1 also highlighted that the responsibility for CE adoption extends beyond them, as:

"I think it's also a lot about our customers. So, governments, the states, the end users, if they do not prioritize sustainability and circularity in the tenders and how they evaluate our project proposals and how we compete in the industry, then it will be hard to deliver unless we can prove it is cost competitive. And most likely, it is not yet because it still requires quite a bit of innovation, and a lot of things have to be done in a new way, a new type of materials, and it all has an impact on cost" (A1C1S1).

Since most projects are primarily based on delivering the lowest price, it can be challenging to integrate circular solutions simultaneously as winning auctions.

4.5.1 The Actors Adoption of Circular Principles

Regarding how the industry is adopting different CE principles, Table 2 shows an overview of which principles different actors are working on directly in their operations, shown in green color. Further, principles that the actors are indirectly working on, through contributing with research or investments, are shown as a blue color.

Table 2: CE Principles Adopted by Actors in the Offshore Wind Industry

	Developers			**Manufacturs**			**EoL-handling firms**			
	A1C1	A1C2	A1C3	A2C1	A2C2	A2C3	A3C1	A3C2	A3C3	A3C4
Refuse										
Rethink										
Reduce										
Reuse										
Repair										
Refurbish			-							
Remanufacture			-							
Repurpose										
Recycle										
Recover										

As illustrated in Table 2, recycling has received the most attention among all actors analyzed. The emphasis on recycling is apparent among industry actors and highlighted by all facilitators. For instance, facilitator A4C3 states that *"a lot of our time today is spent on finding the optimal policy framework to accelerate blade recycling, in particular, [that is] priority number one"* (A4C3S1). A4C2 has also studied the recyclability of blades in their blade recycling project, and A4C1 has initiated an application for an EU project where *"what the project consisted of, was to test different [recycling] technologies and see which could have an industrial potential"* (A4C1S1).

Furthermore, the developers and manufacturers have significantly focused on CE strategies for service and maintenance, including repairing, refurbishing, and remanufacturing broken parts. However, this is something that they have done for years, and it is largely driven by cost reduction. A1C1 explains that optimized maintenance means less time and money spent going back and forth to wind farms (A1C1S1). Similarly, the manufacturers provide service and maintenance of their products as it provides an additional revenue stream (A2C1S1, A2C2S1, A2C3S1). The facilitators investigated in this study also highlight that companies are fully self-incentive to work with these principles simply because it saves them money.

It is evident that none of the actors in the offshore wind industry are currently working on implementing the CE principles with the highest degree of circularity, such as refuse and rethink, even though these are highlighted as crucial to adopt in order to achieve the goal of a more sustainable future (Geissdoerfer et al., 2017; Velenturf, 2021).

4.5.2 Actors Motivation to Adopt Circular Economy

There are identified five types of factors motivating actors in the offshore wind industry to adopt CE principles, as shown in Table 3 below.

The developers' and manufacturers' motivation for adopting CE is mainly driven by stakeholder pressure and legislation, such as stricter requirements for handling materials at EoL or non-price tender criteria related to CE. The facilitators also identify legislation as the

Table 3: Overview of Actors' Motivation to Adopt CE

	Developers			**Manufacturs**			**EoL-handling firms**			
	A1C1	A1C2	A1C3	A2C1	A2C2	A2C3	A3C1	A3C2	A3C3	A3C4
Stakeholder pressure	x	x								
Reduced costs	x	x		x						
Identification of new attractive markets							x	x	x	x
Social Responsibility				x	x	x				
Legislation	x	x		x	x					

industry's main driver of CE adoption. A4C2, for example, states that *"either we need a government policy or regulation to incentivize scrap to be reused locally, sold to steel manufacturers in the UK to be reprocessed and reused"* (A4C2S1). And while the developers point to stakeholder pressure, for example, from investors, as a motivation factor to focus on CE, manufacturers argue a perception of their social responsibility drives them.

However, all the EoL-handling firms are entering the offshore wind industry and working with CE because they see that the increasing focus on CE creates new attractive markets and business opportunities. For example, A3C2 state that entering the market of handling wind turbines at EoL *"seems like a good business case of course, and something that is worth trying to see what we can do about that"* (A3C2S1).

4.5.3 The Highlighted Barriers to Adopt Circular Economy

Table 4 provides an overview of the barriers the interviewed companies underline that hinder the adoption of CE in the offshore wind industry. Two significant barriers emerge as the most commonly highlighted among the developers and manufacturers, including the lack of developed technologies for recycling wind turbine blades and the fear of increased costs associated with implementing circular solutions. The challenge to measure the value of CE initiatives is also an obstacle pointed to by both manufacturers and facilitators, while EoL-handling firms are mainly concerned with the limited access to information needed and the lack of standardization.

As shown in Table 4, both A1C1, A1C2, and all manufacturers point to underdeveloped technologies for recycling blades at EoL and for designing recyclable blades as a barrier. However, that is something many of the actors have been working on in recent years. All manufacturers, in addition to A1C1 and A3C1, have worked together to develop new recycling technologies. But, for developers to increase circularity in the industry, they highlight the underdeveloped technology as a critical barrier as it is *"difficult to set requirements [to suppliers] without solutions available to realize them"* (A1C3S1).

During the interviews, it was also clear that most projects are primarily based on delivering the lowest cost simultaneously as most actors believe that CE comes with a cost. This makes the fear of increased costs a critical obstacle to investing in and adopting CE solutions in the offshore wind industry. Further, several actors also highlighted that it is

Table 4: Overview of Barriers to Adopting CE Principles

	Developers			**Manufactures**			**EoL-handling firms**			
	A1C1	A1C2	A1C3	A2C1	A2C2	A2C3	A3C1	A3C2	A3C3	A3C4
Technological Barriers										
Undeveloped technologies	x	x		x	x		x	x	x	
Lack of standardization				x			x	x	x	x
Economical Barriers										
Increased costs	x	x	x	x	x					
Validation of CE				x	x					
Volume for decommissioned blades				x	x		x			
Volume for recycled materials	x					x				
Organizational barriers										
Lack of information sharing							x	x	x	x
Lack of methods for measure CE				x	x	x				
Value chain and society										
Lack of understanding CE's potential	x									
Institutional Barriers										
Different legislation among countries			x	x	x	x				

difficult to value CE in the planning phase where CE solution might be prioritized or not, due to the uncertainty and risk related to predicting how wind turbines can be handled in 25-30 years' time.

The results indicate that the absence of measurement methods for CE poses a barrier to enhancing circularity within the industry. Manufacturers and facilitators express that CE is less quantifiable in comparison to carbon emissions, leading to a restricted emphasis on CE-related initiatives. This limitation arises from the difficulty of reporting and substantiating the efficient utilization of resources within the context of CE.

Further, EoL-handling firms point to a lack of information sharing and standardization of wind turbine components as the main barriers for them to adopt CE solutions. Limited access to information about the materials used and the composition of the turbines' main components makes extracting value from the used turbines more challenging. Further, as the rapid technological development has resulted in turbines increasing in size and changing regarding materials and technology, it is difficult for EoL-handling firms to establish a standard and scalable method for handling the used components.

4.5.4 Industry Collaborations for Circular Economy

The actors in the offshore wind industry are collaborating for several reasons, including developing recycling technologies, methods for standardized information sharing about the main components used, and influencing legislation and regulations related to CE.

The first two natures of collaboration are focused on making it simpler and more efficient to handle wind turbines at EoL, by developing and improving different recycling technologies and by developing a standardized information sheet. The actors involved in such collaborations are manufacturers, EoL-handling firms, universities, and research centers. The manufacturers that are direct competitors are not sharing sensitive information in-between them but share it directly with the university so they can draw the bigger picture and find a solution that fits all. Therefore, collaboration and direct information sharing are made between parties with complementary expertise (A3C1S1). Moreover, one of the studied EoL-handling firms collaborates with a developer to accelerate the development of recycling technologies handling wind turbine blades. Complementary knowledge and resources are shared, and the developer help promote the EoL solution and reach out to new partners (A3C2S1). However, they do not co-develop the technology itself but rather help develop the business case around it.

The facilitators interviewed have initiated collaborations to design and influence new non-price tender criteria on circularity for future offshore wind projects. Most developers participate in these collaborations to give their opinions on what should be included in the tenders (A1C1S1). Further, they have also collaborated to influence policymakers to introduce a landfill ban for blades (A4C3S1).

Moreover, a general observation made is that there is a trend towards fewer collaborations involving several large industry players and instead an increased number of bilateral partnerships between two industry players from different parts of the value chain. For example, A1C1 state that *"I think, what we will see going forward, is smaller collaborations between, let's say, bilateral partnerships with just one developer and one manufacturer, for example"* (A1C1S1).

5 Discussion

This study investigated why the offshore wind industry predominantly focuses on circular EoL strategies when theoretical research has proven the benefits of early-stage CE adoption. Through a comprehensive analysis of developers and operators, manufacturers, EoL-handling firms, and facilitators, this study indicates that all actors are directly or indirectly working to develop greater recycling solutions and that EoL-handling is highly focused on within the industry today. However, it is also shown that industry actors are working with narrowing and slowing resource loops, as shown in Figure 5, which have been a part of their operations for years as it reduces their operating costs. In general, the industry is found to be highly cost-driven, where initiatives reducing costs are prioritized, and those presenting a possible increased cost are avoided.

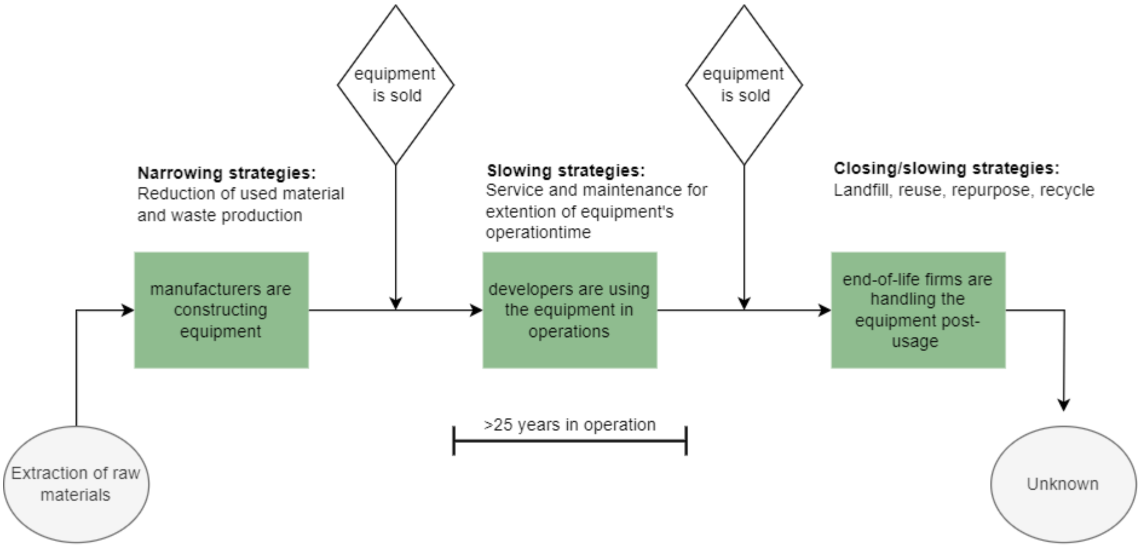

Figure 5: Overview of Today's Offshore Wind Value Chain

The most predominant reason why developers and manufacturers are most driven towards increasing circularity at EoL is the increased external stakeholder pressure and newly created legislation focused on decommissioning and EoL-handling. In contrast, the EoL-handling firms are mainly motivated to develop greater EoL solutions as these present new business opportunities. These findings are in line with the findings of previous CE studies (Aid et al., 2017; Cantele et al., 2020; Donner et al., 2020; Geissdoerfer et al., 2018; Köhler et al., 2022; Patricio et al., 2018; Sousa-Zomer et al., 2018), and will be discussed further in Section 5.1.

Further, the findings of this study show that fear of increased cost, the challenge to value CE initiatives at BoL, and the lack of well-developed recycling technologies are the main barriers for developers and manufacturers to adopt CE solutions, which is in line with previous studies (Bocken et al., 2016; Geissdoerfer et al., 2018; Tukker, 2015). Regarding increased costs, all EoL initiatives and the use of recycled materials at BoL are viewed as an increase in costs. Therefore, as most projects in the industry are solely evaluated on price, developers lack incentives to incorporate CE aspects when designing wind farms.

Additionally, the industry has been striving to reduce costs over time in order to compete with other energy sources. Therefore, concerns about higher costs when adopting CE may be linked to the mindset that efforts should be focused on continued cost reduction. Further, the manufacturers indicate that considering CE in the design phase is challenging as the benefit occurs 30 years later and is received by a different actor. In other words, there is a lack of frameworks and methods for how to value CE. Additionally, as Figure 5 shows, the lack of efficient recycling technologies contributes to the offshore wind value chain staying linear. Without such technology in place, the reuse of recycled materials in new constructions is very limited, presenting a large obstacle to increasing the circularity of the value chain.

For the EoL-handling firms, the lack of information-sharing and turbine standardization are underlined as barriers hindering them from succeeding with CE solutions at EoL. However, most manufacturing companies argue they already share as much information as possible, and they are struggling to share more relevant information as it is either intellectual property protected or not accessible any longer due to rapid technology development. Therefore, it is challenging to fully remove this barrier without implementing further standardization of wind turbines.

Furthermore, the findings show that all studied companies greatly focus on sustainability, while only a few have specific CE goals and strategies. Most CE initiatives relate to reducing carbon emissions and waste and result from a broader focus on sustainability. These goals typically focus on reduced production waste or recycling of materials at EoL. To increase the circularity in the offshore wind industry, actors have to develop more specific CE strategies and goals, both focusing on BoL and EoL.

Lastly, this study reveals four discoveries that require further examination and in-depth discussion to answer why the industry predominately concentrates its circular efforts on EoL solutions. First, external stakeholder pressure and legislation are the most dominant motivation factors for industry actors to adopt CE, and both are most focused on EoL. Second, the offshore wind industry is affected by rapid technological development in size and efficiency, and the issue related to decommissioning and EoL is predicted to have an enormous scale resulting in the need for closing resource loops. Third, the offshore wind industry is driven by cost, and the actors look at CE as an increase in cost, resulting in a need for a better understanding of how production and transaction costs are affected by the adaption to CE. Last, the industry actors are collaborating on developing greater recycling technologies. Here, the analysis shows that the dominating factors pushing actors to participate in collaborations for CE are large external pressure and the possibility of protecting companies' reputations by focusing on CE.

5.1 The Industry Mainly Focus on EoL Circular Economy Principles

The two most prominent reasons for actors being driven towards EoL is the increased external stakeholder pressure to avoid wind turbine blades being sent to landfill and new legislation for how to handle equipment post-usage.

The challenge of handling wind turbine blades at EoL gained significant media attention following an influential Bloomberg article that highlighted the lack of recyclability and the disposal of blades in landfills (Martin, 2020). This article created widespread media coverage and prompted policymakers, industry associations, researchers, and industry actors to invest in research and development efforts to enhance the recycling of wind turbine blades. Stakeholder theory, as emphasized by Brenner and Cochran (1991), underscores how companies are influenced and motivated to adopt responsible practices in response to stakeholder pressure, including the impact of media coverage. In this case, external stakeholder pressure was focused on how the industry actors handled their equipment post-usage rather than how they developed them in the design phase. Therefore, it became apparent that industry actors are responding to criticism and pressure by developing solutions to address the recycling issue without fully addressing the underlying problem created in the design phase or working to increase circularity in other parts of the value chain.

Furthermore, adopting recycling as a CE principle is also driven by new legislation and requirements, particularly EoL-handling requirements. This study reveals that numerous actors within the offshore wind industry are actively working towards implementing landfill bans. Additionally, an increasing number of countries are incorporating non-price criteria into tender processes, emphasizing recyclability and handling at EoL. Consequently, the pressure exerted by governments and industry associations primarily encourages industry actors to enhance circularity during the post-design and usage phases of equipment, thereby diverting attention away from innovations that foster a higher degree of circularity and necessitate a mindset focused on CE principles from the design phase (Potting et al., 2017).

Furthermore, adopting recycling as a CE principle is also driven by new legislation and requirements, particularly on EoL-handling. The studied developers underscore these factors as their main drivers for implementing circularity in their projects, highlighting the importance of legislation in driving the shift towards a circular offshore wind industry. First, it is shown that numerous actors are working toward implementing landfill bans, as WindEurope will have a landfill ban for all its members by 2025 (WindEurope, 2021). This pushes the members to develop better EoL solutions. Additionally, an increasing number of countries are incorporating non-price criteria into tender processes, emphasizing recyclability and handling at EoL. Consequently, actors are forced to include more circularity in projects to win new sites. However, the pressure exerted by governments and industry associations primarily encourages industry actors to enhance circularity during the post-design and usage phases of equipment, thereby diverting attention away from innovations that foster a higher degree of circularity and necessitate a mindset focused on CE principles from the design phase (Potting et al., 2017).

5.2 The Industry Focuses on Recycling as EoL Strategy

Another significant reason why industry actors in the offshore wind industry predominantly focus on EoL strategies, specifically recycling, when aiming to increase circularity, is the combination of rapid technological developments, the long operational lifespan of wind turbines, the industry's need for developing scalable solutions to handle all upcoming decommissioning, the risk related to extended responsibility of handling the equipment at EoL, and the need to secure access to future materials.

First, the findings in this study highlight the rapid development of wind turbine components making significant variations in terms of dimensions and compositions for new equipment. This rapid development and lack of standardization pose a barrier to reusing, refurbishing, remanufacturing, and repurposing used wind turbine equipment as it becomes less predictable which components will be available for such purposes and it complicates the identification of blade materials and suitable repurposing purposes. Moreover, changing to new components increases energy efficiency, making developers choose these over older and less efficient components. As a result, prioritizing lower degrees of circular solutions for handling post-usage equipment becomes a reasonable approach, as the most energy and economically efficient solution lie in utilizing the constituent molecules. These findings align with Geissdoerfer et al. (2018) research, emphasizing the challenge of reusing or refurbishing older wind turbine components due to their incompatibility with evolving technologies.

Second, recycling offers scalability compared to handling equipment post-usage with repurposing and reuse. A4C3 stress that the volume of old wind turbines will increase drastically, it can go up to five times today's volume, by the end of the decade (A4C3S1), presenting a need for a scalable way to handle the turbines at EoL. Most industry actors do not believe repurposing is a sustainable solution to handle the turbines at EoL as the demand for outdoor furniture and other products made through repurposing is not as high as the volume of upcoming decommissioned turbines. In contrast, technologies and facilities for wind turbine recycling can handle significantly larger volumes of upcoming decommissioned assets, as the production is easier to scale and the materials made through recycling can be used in a great variety of new products.

Third, repurposing activities entail extended responsibility for developers or manufacturers. When a developer sells its used turbines to a repurposing company utilizing this to construct outdoor furniture or a bike shelter, the resulting product may last 20 to 40 years. However, once this lifespan concludes, the question of EoL-handling arises once again. This risk must be considered by either the repurposing company or the developer selling the turbines, thus providing a rationale for favoring recycling as a preferred EoL strategy. Similarly, A4C3 argues that EoL-handling can become a liability and that the industry therefore will move towards more recycling solutions where manufacturers or developers are in control.

Forth, recycling offers an opportunity to close the loop of several raw materials, making it possible for developers to ensure secure access to critical materials needed in their future wind farms. In the offshore wind industry context, the prediction of installing 322-540 GW new capacity by 2040 necessitates a significant amount of raw materials for equipment, given current product design and technology (Agency, 2019). Therefore, industry developers highlight the importance of a secure supply of materials and independence from other parts of the world. For example, A1C1 state that there will be a significant focus on critical raw materials going forwards, and the recycling of these, to ensure independence from China and to develop the European industry (A1C1S1). Since greater recycling technologies can make it possible to recycle material back to its initial standard and quality, it can be used as input material for new wind turbine equipment and thereby reduce the need for extraction of raw virgin materials. In other words, good recycling solutions will contribute to reduced extraction of raw materials by enabling increased use of recycled materials in new wind turbines, keeping materials in a closed loop.

As a result, there are different arguments for why the industry actors primarily work with recycling as an EoL solution. Hence, recycling may not be the solution with the lowest circular potential in this context, as it presents a scalable solution that can reduce the need for extracting more raw virgin materials when building future wind parks. Therefore, future research should be directed towards understanding the potential of well-developed recycling technologies to determine the optimal utilization of recycling versus reuse and repurposing as the latter are predicted to have higher circular potential (Potting et al., 2017). Additionally, these findings indicate the need for further research and the development of frameworks that are specifically tailored to the characteristics and challenges of the offshore wind industry. Researchers should explore and refine circular frameworks that consider the unique aspects of rapid technological developments, long operational lifespans, scalability requirements, extended responsibility, and the need for secure access to future materials in the offshore wind sector.

5.3 There is a Need for a Full Value Chain Perspective

As industry actors predominantly focus on EoL and decommissioning, there is a lack of a full value chain perspective when transitioning to CE. The technological limitations of closing loops and fear of increased costs related to CE implementation hinder the transition to a circular value chain where CE is incorporated in all phases of a product's life cycle and not primarily on EoL.

In addition to developing adequate recycling technology to make it possible to have a circular value chain, the industry actors' concerns about increased costs must be analyzed. While Linder and Williander (2017), Ghisellini et al. (2016), and D. Liu et al. (2012) stressed that resource productivity through waste reduction and design for optimal material usage would lead to increased profitability, the studied companies assert that adopting CE will increase their costs. The possibly increased costs can be explained by increases in production costs, but can also be seen in the light of the transaction cost theory (Hobbs, 1996). First, the increases in production costs when transitioning to a circular value chain can be explained by new cost structures for recycled materials, additional costs for needed research, development, and engineering efforts for designing the equipment for disassembly, and logistics costs due to effective reverse logistics systems. Second, as the operations in today's linear value chain, shown in Figure 5, have been streamlined over many years, the current transaction costs are very low (Hobbs, 1996). Therefore, when adopting a circular value chain, as shown in Figure 6, the transaction costs will increase due to a higher need for collaboration, more extensive coordination, and the necessity of experimental business models that could ensure that extracted raw materials remain within the industry to create a closed system (Hobbs, 1996).

Additionally, transaction costs will increase due to, for example, the uncertainty surrounding transactions, as the findings of this study show that EoL-handling firms struggle to make customers trust the strength and quality of their repaired products. Hence, incomplete or asymmetric information may present a transaction cost in a circular value chain where the manufacturers are trying to increase the usage of repaired products (Hobbs, 1996). This will lead to increased transaction costs compared to what the industry actors face in today's linear value chain, making the circular value chain less attractive. However, there is great potential for reducing transaction costs in a circular value chain by developing trustworthy tests and certifications and increasing awareness around the strength and quality of circular products and solutions.

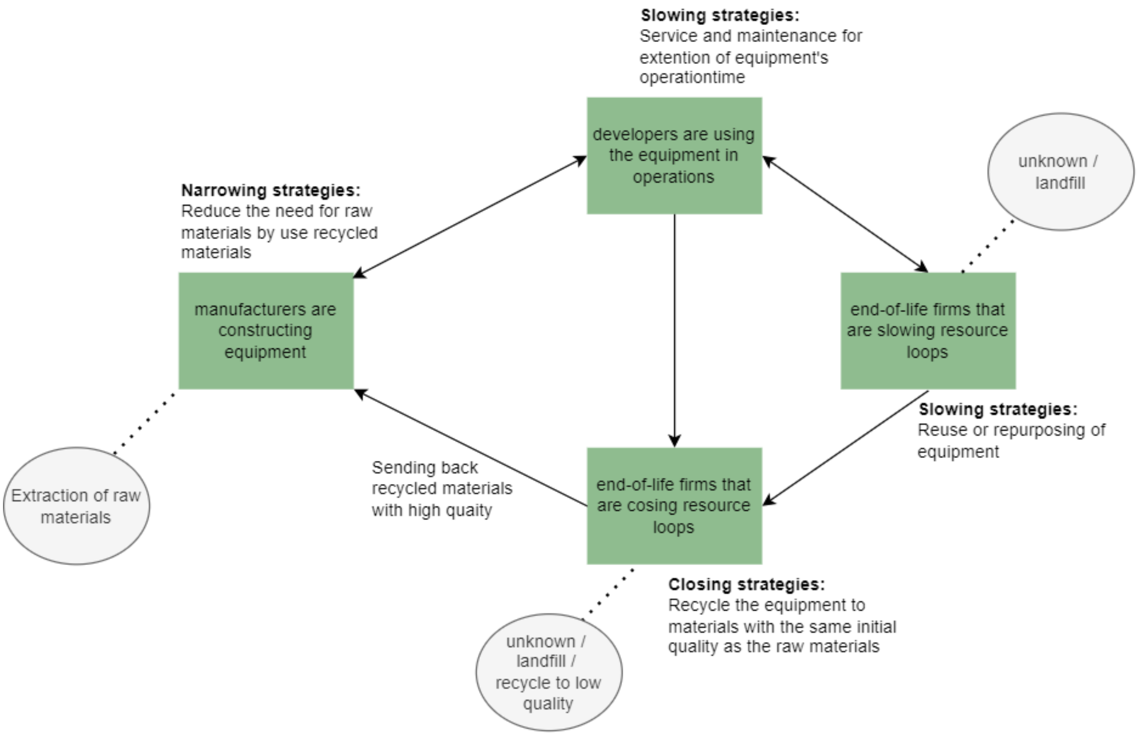

Figure 6: Overview of a Potential Circular Offshore Wind Value Chain

To increase circularity in the offshore wind industry, it is clear that the industry has to adopt a circular value chain and not only focus on CE at EoL. However, there is a significant barrier to overcome in order to enhance circularity by adopting a circular value chain, namely the fear of increased costs that industry actors often highlight. As shown, production and transaction costs are expected to increase during the transition period. However, these costs are projected to decrease as the offshore wind industry and its actors establish standardized business modes, a well-established circular value chain, and standardized contracts and methods for information sharing and coordination. Nonetheless, in order to facilitate this shift and alleviate the barrier of increased costs, further theoretical research is needed to demonstrate that production and transaction costs will be lower over time when a streamlined circular value chain is implemented and what initiatives should be implemented to ensure such streamlining. This research is crucial in order to convince industry actors to invest in, develop, and adapt to CE principles and develop a circular value chain within the offshore wind industry.

5.4 Factors Driving Collaboration Towards EoL Circular Economy

Lastly, this research has proven that offshore wind companies are collaborating to develop better EoL solutions, namely recycling solutions. It is also shown that when industry actors collaborate for recycling, they solve issues that require resources and knowledge outside their core capabilities and competitive advantage, in line with the resource-based theory (Barney, 1991; Das & Teng, 2000). In addition to the explanation resource-based theory gives for when actors are collaborating, this study shows that collaborative efforts are focused on EoL simultaneously as external stakeholder pressure and introduced non-price tender criteria push actors to find a solution to EoL-handling of turbines. Therefore, the findings of this study indicate that actors collaborate to ensure the credibility of their strategies for meeting CE criteria and their reputation of being focused on CE.

The findings of this study demonstrate that companies within the offshore wind industry are collaborating to achieve common goals, for which they lack the necessary economic incentives and do not possess the complete knowledge or resources to handle them independently. For example, manufacturers and developers have collaborated on technology development to recycle wind turbine blades. The development of recycling technologies is not something the manufacturers and developers are economically incentivized to work with, but external stakeholder pressure is forcing them to look at the issue. Neither the manufacturers who are designing the wind turbine blades nor the developers responsible for them post-usage have their core knowledge on recycling, resulting in a collaboration to leverage on each other's resources and capabilities. Additionally, they were motivated to collaborate to develop recycling technologies as they looked at EoL-handling of blades as a challenge for the industry as a whole and not specific for them as a single company. Hence, this observed phenomenon aligns with the resource-based theory that suggests that firms collaborate when they have common goals that cannot be achieved independently because of a lack of knowledge, resources, and capabilities, and the collaboration would not hinder them in protecting their competitive advantages (Barney, 1991; Das & Teng, 2000).

Additionally, this study reveals that external stakeholder pressure and the possibility of ensuring the credibility of their CE focus are dominating factors pushing actors to collaborate instead of independently developing solutions. In recent years, the tender criteria of offshore wind projects have, in some countries, shifted to include circular elements and circularity has become a competitive element in the industry. As a result, collaborations involving multiple competing companies working to achieve common goals have become less prevalent. With the introduction of non-price criteria, companies competing for projects are more inclined to partner with other actors focusing on CE to ensure the credibility of their sustainable and circular strategies. For instance, A3C2, a company specializing in blade recycling technology, forgoes collaboration with other recycling companies, likely because they consider the technology as their core competitive advantage. In contrast, they partner with developers who lack the necessary knowledge to develop the technology but can provide other types of support. The developers have high incentives to support and sponsor A3C2's development because their solutions could help them meet the new non-price criteria. A3C2 states that developers are partnering up with them to ensure the credibility of their strategies for handling the equipment at EoL put forward in the application to lease offshore wind projects. Therefore, actors are mainly partnering up with different actors when they are exposed to strong external pressure, which in this industry is focused on decommissioning and EoL, and when they are given a chance to increase the trustworthiness of their green profiles. However, further research is still needed to examine how the resource-based theory, external stakeholder pressure, and ensuring credibility are reasons and circumstances why actors in other industries prefer collaboration over independence while developing and adopting CE solutions.

5.5 Implications for Policymakers

It is shown that the actors in the offshore wind industry primarily concentrate their circular efforts on EoL strategies. To increase circularity in the industry, the value chain has to switch from linear to circular, and the industry actors must include CE in the design phase. To achieve this, strategic policy amendments are needed.

As the most predominant drivers of CE are shown to be external stakeholder pressure and the integration of CE criteria within tender evaluation processes, a greater CE adoption will require more non-priced CE criteria globally. In certain countries, such as Norway, non-price criteria are already incorporated, but the majority of offshore wind projects in other countries are still solely evaluated on price. Consequently, across different countries, it is recommended to provide initiatives that prompt industry actors to strengthen circularity in their new wind park projects.

However, the existing non-price criteria primarily emphasize decommissioning and EoL scenarios. For instance, for the Utsira Nord project in Norway, developers must present detailed decommissioning plans and specify the recyclability rate of materials at EoL. A policy shift towards BoL considerations, aligned with the framework proposed by Potting et al. (2017), and an adaption to a circular value chain, requires legislation also focusing on BoL. This could be achieved by implementing a non-price criterion assessing the use of recycled materials during equipment production. This criterion, quantifiable through measuring the rate of recycled materials used, facilitates the establishment of benchmarks and company evaluations regarding companies' adoption of CE principles at BoL. Hence, stakeholders and investors can establish more effective requirements and evaluations of companies' CE performance during the turbine production phase, which occurs many years before decommissioning, thereby reducing the associated risks.

Additionally, shifting focus to BoL requires improved measurement methods and frameworks to value CE principles effectively. The ability to measure circularity is a critical hurdle for manufacturers, as numerous circular solutions impose short-term costs and necessitate initial investments, and the value occurs 30 years later when equipment reaches EoL. Therefore, policymakers need to ensure that frameworks are developed to help companies value CE principles more accurately.

Lastly, transitioning from a linear to a circular value chain and ensuring extracted raw materials remain within the industry will require more stringent regulations and incentives from policymakers to help minimize the costs related to such a transition. This is because less costly solutions are to be found in today's value chain. For example, it is cheaper to send wind turbine blades to landfills than recycle them, and it is less costly to recycle equipment to low-quality materials than high-quality materials. Therefore, in a transition period, regulations and subsidies are necessary.

5.6 Implications for Managers

To succeed with a shift towards a circular offshore wind value chain where there is a focus on the product's whole life cycle and not primarily EoL, there are several actions managers can contribute with.

A large focus on cost is evident in today's industry, where industry players often prioritize initiatives that reduce costs even though these are not the most sustainable. This aligns with how the industry has acted over time to become cost-competitive with other energy sources, as discussed in Section 2.4. However, since the LCOE of offshore wind is cost-competitive with most energy sources today, and there is a shift towards sustainability and CE becoming a competitive element in the industry, managers should work to overcome the cost-driven mentality by developing a better understanding of how greater focus on CE can increase their competitive advantage and simultaneously contribute to sustainable production and consumption.

Further, external stakeholder pressure and newly created legislation focused on decommissioning and EoL-handling are identified as key motivators for industry actors to adopt CE and drive actors towards a focus on EoL. Due to this, managers should stay informed about evolving stakeholder expectations and regulatory requirements to mitigate risks, enhance reputation, and create a competitive advantage by proactively addressing these expectations. However, to achieve maximum environmental and economic benefits and stay ahead of future possible requirements for CE incorporation at BoL, managers should also consider adopting CE principles from the earlier phases of products' life cycles. This requires integrating circularity aspects into the design of wind farms and the transition to more circular business models.

To ensure the adoption of a circular value chain and secure access to materials for future wind farms, it is essential to have recycling technologies that can convert equipment back into resources of the same quality as their initial state. While some companies are already engaged in developing such technologies, it is crucial for managers to allocate additional resources towards innovation and the advancement of these technologies in order to meet future material needs.

Lastly, while sustainability is a common focus in the offshore wind industry, the study stresses that specific CE goals and strategies are lacking. Therefore, managers should develop clear and measurable CE goals that go beyond reducing carbon emissions and waste, which is the main focus today, to help the industry achieve a higher level of circularity. These goals should encompass both the BoL and EoL phases and address aspects like a design for circularity, material and waste reduction, lifetime extension, and high recyclability rates.

5.7 Limitations

Since this study adopts a qualitative research approach, it is subject to certain inherent limitations. Apart from the research quality considerations discussed in Section 3.5, the following limitations are acknowledged to have influenced the research outcomes.

One limitation of this study is the challenge of balancing the breadth and depth of the case study. Increasing the number of cases may have enhanced the theoretical saturation, thereby increasing the likelihood of accurately describing reality. However, this expansion comes at the cost of depth, which compromises one of the core strengths of qualitative studies: understanding situations from the perspectives of those being studied (Bryman, 2016). Therefore, the chosen sample size in this research is considered appropriate for providing sufficient insights into each company's orientation while bolstering the findings and external validity through multiple cases.

Further, another limitation arising from the case study approach is that data collection is based on retrospective interviews, capturing participants' past experiences. This retrospective nature introduces a potential for subjective biases (Bryman, 2016), given the backward-looking approach taken in this research.

Also, the presence of direct competitors among the case companies investigated in this study introduces a potential limitation as interviewees may have exercised caution in sharing sensitive information during the interviews. Despite maintaining anonymity and ensuring interviewees were informed of this, there remained certain information that they were unable or opted not to disclose due to competitive concerns.

The time frame of this study, being part of a master's thesis, also constitutes a significant limitation. The research duration has been constrained to a few months, thereby precluding the examination of long-term effects. Furthermore, since the data collection occurred at a specific time point and the studied context is characterized by rapid development, there is a potential risk of the information becoming outdated within a short time period.

Another limitation of this study is subjectivity, which refers to the potential influence of the researchers' perspectives, biases, and interpretations on the qualitative research findings. Despite efforts made to maintain objectivity, such as establishing a clear research design and a standardized data collection protocol, the researchers have brought their own preconceptions and assumptions to the data analysis process, which can impact the objectivity of the findings (Bryman, 2016).

Lastly, the transferability of the findings in this research presents a limitation. Transferability refers to the extent to which qualitative research findings can be generalized or applied to different contexts or populations beyond the studied sample (Bryman, 2016). The unique characteristics of the studied cases and the context-specific nature of this research limit the ability to transfer the findings to other settings or populations. However, diversity in the selection of cases has helped ensure that a wide range of perspectives, experiences, and contexts are represented in the study. This enhances the potential transferability of findings to different settings or populations.

6 Conclusion

This study investigated the research question of *"why is the offshore wind industry predominantly focused on circular end-of-life strategies, despite the theoretically proven benefits of early-stage circular economy adoption?"* by analyzing the full value chain of actors, including developers and operators, manufacturers, and EoL-handling firms. The study shows that all actors work directly or indirectly to develop greater recycling solutions and that EoL-handling is highly focused on within the industry.

From a theoretical standpoint, this study makes significant contributions to the literature on offshore wind and CE by presenting several reasons explaining why actors predominantly concentrate their circular efforts on the EoL phase. The two predominant reasons relate to external stakeholder pressure and newly created legislation mainly focusing on handling wind turbine equipment post-usage and not incorporating CE in the design phase. Additionally, rapid technological developments, the long operational lifespan of wind turbines, the need for scalable solutions for handling future decommissioned turbines and securing access to future materials are all factors found to be pushing actors to focus predominantly on CE at EoL. This study also shows that the industry actors are still extremely cost-driven and relate CE to increased costs, hindering the transition to a circular value chain as this presents increased short-term costs. Therefore, theoretical research exploring and demonstrating how production and transaction costs in a circular value chain can decrease over time is recommended.

From a practical and policy standpoint, this study indicates that managers and policymakers need to shift towards a greater focus on BoL CE solutions. Policymakers should incorporate non-price CE tender criteria globally and expand the criteria to also encompass the design phase, fostering actors to consider circularity from the outset of project development. For managers, it is therefore crucial to stay informed about evolving stakeholder expectations and regulatory requirements related to CE and consider adopting CE principles from earlier phases of the product's life cycle. Policymakers should implement more stringent regulations and provide incentives to minimize the costs of transitioning to a circular value chain to ensure the industry retains control over raw material extraction. Simultaneously, managers should move away from a cost-driven mentality, recognize the potential benefits of focusing on CE principles, and allocate resources for innovation and development of recycling technologies that can convert used equipment back into resources of the same quality as their initial state to help accelerate the transition towards a circular offshore wind value chain.

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A Appendix

A.1 Interview Guides

A.1.1 Interview Guide - Developers

1. Our understanding of X's position in the offshore wind value chain is as a developer, operator, and owner of offshore wind farms. Is this correct? And can you tell a bit about where in the process X usually enters and exit?

2. Can you tell us briefly about the activities you do related to offshore wind development and operation?

   (a) Are you doing service and maintenance yourself, or do you have other actors doing this for you?

   (b) What kind of services do you do?

3. As we can see from your webpage and what we talked about last week, I understand that you are working with A, B, and C. Can you tell me a bit more about how you are working with circularity related to offshore wind in X?

   (a) Can you describe how you are reusing components?

   (b) Can you describe how you are working with an extended lifetime?

   (c) Since it is not you that are designing or producing the components, how are you working for reducing the use of resources and key components? And ensuring recyclability upon decommissioning?

4. Who's responsibility do you think it is to ensure circularity in the industry or the companies designing the components?

5. Which requirements do you set for suppliers in terms of circularity?

6. When did you start working with circular strategies, and what was your motivation then?

   (a) What is X's motivation for working with these kinds of circular principles?

   (b) What are you doing because you wish to yourselves and it is giving you an advantage, and what are you doing because you are forced to by legislation?

   (c) Have your motivation to focus on circular strategies changed or developed over the last 10 years?

   (d) What advantages do you have by having a business model with a focus on circularity?

7. Do you see any barriers to working with circularity in the offshore wind or increasing circularity in the value chain?

(a) How are you working to overcome these barriers or what do you think has to be done in the industry to overcome the barriers?

8. Do you own the components in the wind farms (like the blades, the foundation, the tower, etc.) and thus also have the responsibility for them when they are no longer to be used for producing electricity?

9. So, we have talked a lot about you focusing on reuse, doing services, and so on. But when you cannot use the assets anymore as wind turbines, what do you do with them?

   (a) Which kind of companies are you giving the assets to? Are you selling them or are you paying anyone for taking them out of your loop?

   (b) Are most companies handling turbines at the end of life focused on recycling, or are there other options such as repurposing?

   (c) Which requirements and laws do you have to comply with when you have to take down the wind farm and handle the materials?

   (d) Which requirements do you set for third parties handling the wind turbines after the end of lifetime in terms of circularity?

10. We know that X and other actors have collaborated to develop an X. They indicate that X will have a higher cost than X they “normally” offer. Which X are you choosing, and why?

11. Now we will go over to the next part, namely collaboration. We see that you are a part of a project together with other large industry players. What was your motivation for joining this innovation project?

   (a) What are you contributing to the project?

   (b) How are you collaborating? Like, which information and knowledge are you sharing, and what activities are you collaborating on?

   (c) What is relevant for you as a developer and operator to get information about from the manufacturers and end-of-life handling firms in this collaboration?

   (d) How are you gaining value from the project? What are the specific benefits to you if the project succeeds?

   (e) Are there any barriers or obstacles to joining collaborations such as this and working with other actors in such innovation collaborations?

12. Are you part of any other collaborations related to CE?

   (a) What are you collaborating on?

   (b) What is your motivation?

   (c) How are you gaining any value?

   (d) What are the barriers/obstacles?

(e) How are you planning to overcome these obstacles? Or what can be done to overcome these?

13. Why are innovation collaborations important for X?

A.1.2 Interview Guide - Manufacturers

1. How are you related to the management of resources of onshore/offshore wind farms?
2. When and why did you decide to adopt a circular economy in your organization?
3. Can you describe how your organization is adapting CE (i.e., CE strategies, business models, and principles) and what role you are playing?
4. How do you implement CE in the wind energy value chain?
5. Could you tell us a bit about how your organization implements this strategy/ these strategies at different life cycle stages of the wind farm?
6. How do you measure the circularity of CE strategies in your organization? / How do you measure the readiness level of CE strategy in your organization?
7. How do you decide the CE strategy that you are pursuing is market deployable in different geographies?
8. Do you think the development of CE strategies is affected by geopolitical constraints?
9. How do you measure the environmental impact of logistics, i.e., CO2 footprint and waste management tracking, while measuring these strategies?
10. How are you pursuing this strategy /these strategies?Do you collaborate with other stakeholders?
11. Can you tell me who are they and how do you collaborate with them?
12. Do you take part in Extended Producers Responsibility (EPR), Design for Environment (DfE)or similar such initiatives?
13. What is the key hurdle while collaborating with different actors across the value chain?
14. What components of the wind farm pose a challenge to waste management by utilizing CE strategies? Why?
15. Did you have any challenges while transitioning from linear to circular economy, specifically regarding business development?
16. What are the current challenges and barriers that you are facing in implementing CE across the value chain?
17. How is your organization planning to overcome it?

18. Do you have any long-term CE goals? (i.e.,how are you planning to increase the circularity level in your organization?)
19. If so, could you tell me more about it?

A.1.3 Interview Guide - EoL-handling firms

1. What is your role in X related to circular economy?
2. Can you shortly describe your view on circular economy in the context of the (off-shore) wind industry?
3. What type of operations and activities are you performing when handling the turbines at EoL?
   (a) Who are you selling your products to?
4. How are you measuring the circularity rate of the materials you collect from wind turbine dismantling?
   (a) How many percentage of the wind turbines are you able to recycle or repurpose?
5. Are you performing any other activities related to wind turbines, such as for example repair or maintenance?
6. As I understand, you are a customer of the wind farm owners, so are they contacting you when the turbines reach end of life, or how do you receive projects?
7. Are the wind farm owners most often choose the cheapest solution? Or do they have a high focus on circular economy?
   (a) Are all customers interested in the all-in-one solution, or do you sometimes only go into some parts of it?
   (b) If the wind farm owners do not contact you after end-of-life, which opportunities do they have to handle the end-of-life of turbines?
8. What activities creates you revenue streams?
   (a) Have you considered owning parts of or whole wind turbines from the plant construction phase to gain more control of its wear and methods for repair and maintenance?
   (b) Are you making money selling spare parts for wind turbines?
   (c) Our understanding is that your customers are both wind farm operators in need of dismantling and recycling services on one hand, and then material or product buyers on the other. What kind of benefits are you providing for each type of customer?
9. When did you start adapting circular economy principles for the wind industry and intentionally act to increase circularity in the wind turbine value chain?

10. Are you focusing on other circular principles as reuse or repair?
11. What was your motivation or push factors for starting to offer recycling/repurposing services, and other circular strategies, in the wind industry?
12. Can you describe how you work with repurposing/reuse/rethink?
13. Is your focus on circular economy giving you any competitive advantage?
14. Have you experienced any benefits from having a business model aligned with circular principles?
15. What are the biggest obstacles/barriers for you working with circular economy in the wind industry?
    (a) How are you planning to overcome these obstacles? Or what should be done in the industry to overcome those obstacles?
16. Are you observing different ways of handling wind turbines at end of lifetime in different regions?
17. As you mentioned earlier, you are a part of a project with a lot of other industry actors. What was your motivation for joining this innovation collaboration? Or how did you join this project?
    (a) What is X contributing with into the project?
    (b) How are you collaborating? Like, which information and knowledge are you sharing, what activities are you collaborating on?
    (c) What is relevant for you as an end of life handling form to get information about from both the wind farm owners and the manufacturers?
    (d) How are you gaining value from the project? What are the specific benefits to you if this project succeeds?
18. Are you joining any other innovation collaboration projects? Or are you collaborating with other actors and stakeholders to increase circularity in the value chain of wind turbines?
    (a) How are you collaborating with these actors/stakeholders? And who are they?
    (b) Which activities are you collaborating on?
    (c) Which information are you sharing?
    (d) Why did you chose to collaborate with these actors/stakeholders? What was your motivation/push factor?
19. Do you have any collaborations with wind farm owners/operators? If so, with whom and about what?
20. What are the key obstacles when collaborating with different actors across the wind turbine value chain to ensure a circular value chain?

(a) How are you planning to overcome these obstacles?

A.1.4 Interview Guide - Facilitators

1. Since the wind industry has committed to achieve full recyclability of their turbines in line with the EU's Circular Economy Action Plan and the ambitions of the EU Green Deal, we are wondering how you, as an industry association, are working to help the industry achieve this goal?

2. Can you tell me of what kind of work or projects you do related to circular economy, and if possible describe some specific work?

   (a) Do you have any specific strategy or plan for meeting these goals?

3. Are you in some way looking at how business models can be changed to increase the circularity?

   (a) Are you arranging event to increase the awareness and knowledge about CE specifically?

   (b) Are you arranging discussions and meetings to facilitate innovative developments related to CE?

   (c) Are you facilitating for actors to partner up with the objective to develop or adopt circular solutions?

4. From your perspective, what is the industry actors motivation to develop and adopt CE solutions?

   (a) Why do you think the different actors, developers/operators, manufacturers, end-of-life handling firms, are motivated to implement and work with circular economy strategies in their work?

5. From your perspective, which circular economy principles or strategies are most common in the industry?

   (a) Which types of actors (developers/operators, manufacturers, end-of-life handling firms) are mostly working with the different strategies?

   (b) Do you think all actors are familiar with the different circular strategies?

6. What are you seeing as the most successful incentives to make actors implement such strategies?

7. How are legislation, tenders or requirements affecting the actors to work with CE?

8. Which barriers or obstacles are you seeing for industry actors for focusing and working with circular economy in their business, related to offshore wind?

(a) Will it be different barriers/obstacles for different industry actors? In other words, do you see that developers/operators, manufacturers, and end-of-life handling firms have different barriers for working with circular economy in their business?

(b) Do you see any geopolitical differences when it comes to implementing circular strategies?

(c) What do you think needs to be done to overcome these barriers, or get more industry actors to focus on circular economy in their business?

9. Is your experience that the actors in this industry is focused on CE and ready to adopt it?

10. Do you think some actors don't see the importance of CE and the benefits of developing and adopting circular solutions?

11. What is your impression of wind farm owners? Are they always choosing the cheapest solutions when talking about decommissioning and end-of-life? Or do they have a high focus on circular economy?

12. Many actors seem to have goals and strategies for reducing emission but not for circularity? Is this also your perception? Why is it like this?

13. What is your motivation for working internally with circular economy for the offshore wind industry?

14. Have you faced any barriers for promoting and increasing the circular economy in this industry?

15. I will now go over to the next section, namely questions regarding how you see industry actors collaborating with other industry actors to ensure circularity in the industry and how you engage with industry actors to ensure circularity. What collaborations are you facilitating to ensure circularity in the industry?

(a) What kind of collaboration is that? Which actors are engaged in the collaboration?

(b) What are you collaborating on?

(c) How are you collaborating?

(d) How are you meeting?

(e) How do you gain value out of the collaboration? And why do you think the other actors are gaining value from the collaboration?

(f) What information are you sharing?

(g) Are there any barriers or challenges with collaborating with industry actors?

(h) How can you overcome these barriers?

A.2 Code Groups

Table 5 presents an overview of the code groups created in NVivo during the inductive coding process. In Section 3.4, it was explained that the authors created *empirical close* codes, and these codes resulted in hundreds of single codes. Therefore, all empirical close codes were inductively sorted into Level 1 and Level 2 codes to organize them in groups. Level 1 is the first grouping of codes, whereas Level 2 is a higher level of sorted Level 1 codes. The number of references indicates how many empirical close codes relate to each level 1 code.

Table 5: Overview of level 1 and 2 codes extracted from Nvivo

Level 2 code groups	**Level 1 code groups**	**Number of references**
Thoughts about circular economy	The direct focus on circular economy have gained momentum during recent years	13
	We require our suppliers to look at circular solutions	8
	The developers have the highest responsibility for implementing a circular economy in the industry	16
	All plans for decommissioning are not developed today	7
	Circularity is mainly evaluated on price	6
	Today, more and more countries are including circularity as a competitive element	13
	Sustainability and circular economy goals	18
	The offshore wind industry is highly focused on costs	19
Work with circular economy principles	Service and maintenance are essential for lifetime extension	14
	Have several R&D programs for optimizing service and maintenance of wind farms	9
	Look at any opportunities to repair and reuse before sending equipment to end-of-life	7
	It is important to develop technology that can ensure materials are recycled to their initial quality	8
	Are creating furniture out of old wind turbine blades	16
	Recycling technologies for wind turbine blades	34
Motivation for adopting circular economy	Stakeholder pressure	19
	The possibility of reducing operation costs	18
	It results in new attractive markets	23
	Opportunity to meet social responsibility	14
	Meet legislations	31

Table 5: Overview of level 1 and 2 codes extracted from Nvivo

Level 2 code groups	**Level 1 code groups**	**Number of references**
Barriers for adopting circular economy	Undeveloped technologies	34
	Lack of standardization	31
	Increased costs	28
	It is hard to measure and value circularity	19
	There is not enough volume for decommissioned wind turbine blades	25
	There are not enough recycled materials to meet future demand	15
	There is a lack of information sharing regarding what is inside the blades	18
	There is not enough understanding of CE benefits	8
	There are different legislation in different countries	17
Collaboration for circular economy	Collaborating to develop great circular solutions	15
	Are sharing information and knowledge	12
	Collaborating to develop a global landfill ban	8
	The industry is dealing with an industry challenge	10
	Collaborating for developing circular tender-criteria	8
	Are continuously collaborating with industry actors to develop greater recycling technologies	26

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