The Influence of Drivers and Barriers in a CE transition for Offshore Wind

A comparative case study of the Netherlands and Denmark

MSc. Thesis

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Preface

The interaction between the European policy targets to become carbon neutral and have a circular economy by 2050 attracted me to investigate this for a specific research. Carbon neutrality can be reached through different pathways through reducing energy consumption, improving efficiency, storing carbon or limiting greenhouse gas emissions. Industry contributions towards emission reduction grabbed my interest and specifically the renewable energy source of offshore wind energy. The enormous potential of this industry and the interest in how circularity is integrated throughout the lifecycle interested me to start this research.

I started this research with limited knowledge about circularity in the offshore wind industry and I am very grateful for all informative and new insights about the industry and its contribution towards a circular economy.

First, I would like to express my gratitude to my supervisor Adriaan van der Loos. Specifically, the interesting discussions helped me to come with new insights. The constructive comments by Adriaan supported me to stay motivated within the progress. I would also like to thank Peter Mulder for being involved as a second reader and supporting this research with unbiased feedback for the thesis proposal. I am also thankful for the support of my family, roommates and close friends. They were assisted me with helpful feedback for addressing certain challenges. Last but certainly not least, I am very grateful for the contributions of individual interview participants as they shared there in-depth knowledge and experience about the industry and its contribution to a circular economy.

Abstract

Offshore wind farms (OWFs) are low-carbon energy systems that can decarbonize the electricity grid. Significant material use and limited lifespans of OWFs pose challenges for waste and material management. This stresses the urgency for the industry to transition to a circular economy (CE). However, a CE pathway is yet to be established. The CE-related drivers and barriers provide insights for the industry's transition. Therefore, this study aims to explore how drivers and barriers influence the CE transition within the offshore wind industry, with a particular focus on Denmark and the Netherlands. This way, the research also aimed to examine the CE performance of both countries. Semi-structured interviews with actors from the offshore wind value chain provided insights in the establishment of a CE transition. The research highlights that the institutional, market and supply chain environment can greatly influence the industry to become more circular. Circular procurement emerged as the most significant influential factor in fostering a circular offshore wind industry. It emerged that market opportunities arise, for both circular end-of-life (EOL) routes and circular design initiatives. Partnerships and knowledge exchange emerged as factors within the supply chain environment which stimulate a CE transition. The key barriers were formed by a lack of decommissioning policy, a lack of governmental expertise, CE-costs, investment insecurity, lack of standardization and a lack of downstream supply chain. Both Denmark and the Netherlands take initial steps to improve circularity throughout the value chain. While there is an emphasis on integrating CE for upcoming OWFs, circular EOL routes may be overlooked. Overall, this research presents the in-depths dynamics of drivers and barriers for a CE transition in offshore wind.

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List of Abbreviations

CE	Circular economy
EOL	End-of-Life
EU	European Union
GHGs	Greenhouse gasses
GW	Gigawatt
O&M	Operation and Maintenance
OWF	Offshore wind farm
LCA	Life cycle analysis
LCOE	Levelized cost of energy
m	meter
MW	Megawatt
REE's	Rare Earth Elements
T&I	Transport and Installation

1. Introduction

A transition to renewable energy systems is stipulated by the Paris Agreement to limit global temperature increases to below two degrees Celsius (Bertram et al., 2021; UN, 2015). It is crucial for countries to support an electric-powered economy and aim for a decarbonized electricity grid (Vrontisi et al., 2020). Offshore wind energy has emerged as a low-carbon energy technology that helps countries decarbonize their electricity grids (Bertram et al., 2021; Velenturf, 2021). Originating from small offshore wind farms (OWFs), the industry has grown significantly, with OWFs now spreading globally (Dedecca et al., 2016). Innovations throughout the sector have resulted in stronger and larger turbines, increasing the electric capacity of OWFs (Soares-Ramos et al., 2020). Currently, Europe has an installed capacity of about 34 GW offshore wind energy, and many countries aim to install more OWFs in the upcoming years (Wind Europe, 2024). Following this, Europe initially aimed to install 60 GW of offshore capacity by 2030, but recently increased its target to 111 GW of installed offshore capacity (European Commission, 2023).

While offshore wind energy shows promising results for renewable energy production, it also raises significant environmental concerns related to waste and material management (Jensen, 2018; Velenturf, 2021). Material usage in OWFs involves many kilotons of materials, which are associated with the emission of greenhouse gases (GHGs) and environmental degradation (Mendoza et al., 2022). OWFs typically reach their end-of-life (EOL) after 20 to 25 years of operation (Winkler, 2022; Jensen, 2018). According to Mendoza et al. (2022), a significant number of OWFs in Europe will reach their EOL stage by 2030, which is expected to generate a substantial waste stream of various components. Therefore, optimizing material use at the design, usage, and EOL stages is crucial (Jensen, 2018). This aligns with the concept of a circular economy (CE), which aims to minimize the input of virgin materials and radically reduce waste and emissions (Geissdoerfer et al., 2018). Currently, the most commonly applied CE strategy in the offshore wind industry involves recycling specific components (Jensen, 2018). For example, turbines' towers, foundations, and some parts of the nacelle have well-established dismantling and recycling schemes (idem). However, the blades, permanent magnets, and nacelle covers have less developed recycling schemes and are often incinerated or landfilled (Mendoza et al., 2022; Beauson et al., 2022). Such EOL outcomes (landfilling and incineration) do not contribute to a radical reduction of waste generation and are therefore not in line with the concepts of CE (Velenturf, 2021; Mendoza et al., 2022). Additionally, other EOL strategies, as opposed to recycling, contribute more to retaining the value of materials (Potting et al., 2017; Mendoza et al., 2022; Velenturf, 2021). This stresses the need for the industry to contribute to a CE.

Organizations within the offshore wind value chain have a central position in the CE transition (Lahti et al., 2018). These organizations are close linked to heavy industries, as they supply resources such as steel, aluminium and plastics (Wesseling et al., 2017). Steel, in particular, is the most widely applied material within OWFs as towers and foundations are made of this material (Jensen, 2018). The impact of heavy industries on material management is less explored in the literature because most research focuses on consumer-related products (Johnsen et al., 2021). This highlights the need to research energy-intensive and polluting heavy industries concerning their impact on the CE. Additionally, a holistic perspective on CE and the offshore wind industry is generally overlooked (Mendoza et al., 2021). CE offshore wind literature particularly focuses on recycling strategies for wind turbine blades (Beauson et al., 2022), which stresses the need for more holistic research avenues (Kramer, 2023).

Therefore, this research also addresses a wide CE approach and integrates all CE aspects, including circular designs product life extension.

The recent European commitment to the Green Deal stimulates countries to become carbon neutral and fully circular by 2050 (Fetting, 2020). Value chain organizations of manufacturing industries have a crucial role in becoming more circular. In order to comprehend a CE transition, it is essential to understand the factors influencing this transition (Kramer, 2023). Factors can either drive or impede a CE transition and can influence organizations both internally and externally (Lopez et al., 2019; Vermunt et al., 2019). While multiple studies focus on drivers and barriers for other industries, there is a pressing research gap regarding the drivers and barriers influencing a CE transition for offshore wind (Kramer, 2023). Governments have a stronger influence on the outside perspective of value chains, therefore this research focuses on external factors influencing a CE transition. Additionally, it is relevant to understand how the industry within a country performs (Dau et al., 2022). Moreover, a country comparison assists CE evaluations and the varying institutional differences can create new insights (idem). This research focuses on two countries, the Netherlands and Denmark, which are leading in the offshore wind industry and have well-developed market segments (Lin et al., 2012). Danish organizations flourish in the assembly of offshore wind turbine components (including towers, turbines, blades) (Karnøe et al., 2022), whereas Dutch organizations thrive in the sectors of transport and installation (T&I) and supply of monopile foundations (Knol & Coolen, 2019). Therefore, this research investigates how external drivers and barriers influence organizations within the offshore wind industry in the transition to CE, with a particular focus on Denmark and the Netherlands. Following this, the following research question is applied for this research:

"How do external factors impede or stimulate organizations within the offshore wind industry of the Netherlands and Denmark in a transition towards a circular economy?"

Following this, scientific relevance of this study is significant as CE research in offshore wind is scarce and limited research focuses on a holistic CE transition (Mendoza et al., 2022; Velenturf, 2021). Understanding how drivers and barriers are linked to the holistic approach of CE is of explicit relevance to the scientific knowledge base, since limited research is focussed on this domain. This, along with a country comparison focused on offshore wind value chains is aimed to gain scientific knowledge for an overlooked research domain. Societal relevance is also aimed by this research since there is strong objective to improve the knowledge base of policymakers and business decision makers. For policymakers, the results of this study are expected to give valuable information that could help in guiding the transition to a circular economy. This study is relevant for business decision makers as it provides a holistic perspective of CE routes and circular supply chain development.

2. Background: Offshore wind farms in the Netherlands and Denmark

This background chapter briefly explains the design of OWFs and the historical development of offshore wind in the Netherlands and Denmark.

The design of a wind farm typically includes a system consisting of a main export cable, a substation, inter-array cables, and individual offshore turbines (Jenkins et al., 2013), as visualized in Figure 1. Offshore turbines comprise a steel tower topped with a nacelle and three blades that drive electricity production from wind forces (Jensen, 2018). Nacelles house all crucial equipment for converting the mechanical energy from the rotation of the blades into electricity (idem). The turbines typically stand on monopile foundations made of steel tubes, which can weigh up to 65 kilotons (Sunday & Brennan, 2021). Both Denmark and the Netherlands have installed numerous OWFs. An overview of these, including capacity and foundation types, can be found in Tables 3 and 4 of Annexes I and II.

The designs for energy grid systems from offshore to onshore are the same between both countries, but the operational structure is different (Rodrigues et al., 2016). In the Netherlands, the grid system of the substation and the export cable is operated by TenneT TSO B.V., which secures the grid for the Netherlands (Luo et al., 2012). This means that developers for Dutch OWFs are only responsible for the lifecycle of turbines, foundations, and inter-array cables. In contrast, development of OWFs in Denmark includes all elements from energy production to onshore grid connection. Thereby, Denmark also includes substations and export cables as integral parts for developers responsibility of project development (Rodrigues et al., 2016).

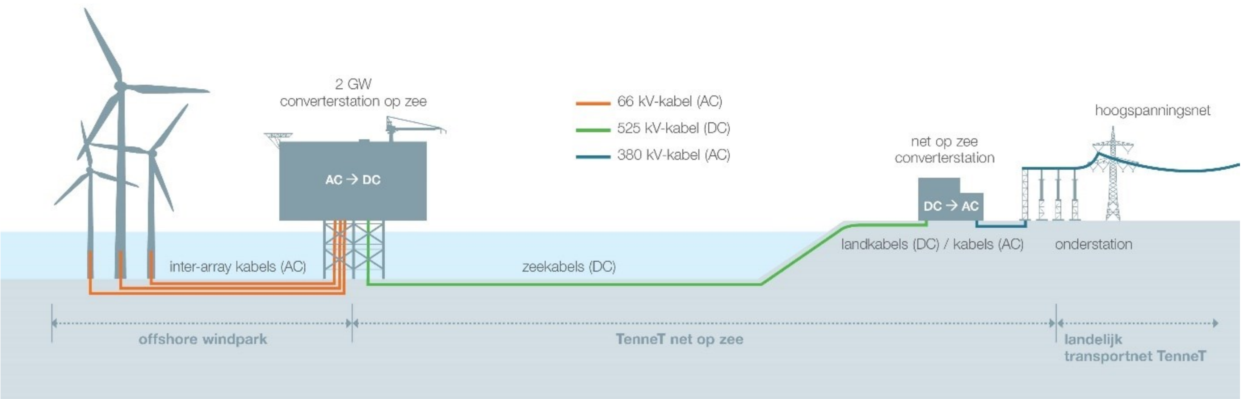

Figure 1: Schematic overview of an OWF and the offshore grid (substation, export cable and transformer station) (adapted from Tennet TSO B.V.)

Danish success within the offshore wind industry started from niche development of onshore wind energy (Johansen, 2021). Energy supply from wind originated in Denmark as local innovators developed small onshore turbines which supported agricultural households (Johansen, 2021). The oil crises and a raising environmental awareness caused Denmark to significantly support the wind industry in the 1970s (Rüdiger, 2019a). This support helped Denmark in renewable energy security and also stimulated growth of current largest wind turbine supplier Vestas and current largest OWF developer Ørsted (Van der Loos et al., 2020). Technical knowhow related to wind energy production has been present for multiple decades in Denmark, which helped in the rapid development of a strong market segment (Johansen, 2021). Within the Netherlands, market segments arose at the emergence of the offshore wind industry (idem). The Netherlands already had a strong segment for transport and installation (T&I) contractors, which originated from a long dredging history (Rodrigues et al., 2016). The market segment of monopile foundations originated from steel plate producers and development alongside niche development of OWFs (idem). The offshore wind industry started in Denmark, which was shortly after also experimented within the Netherlands. Both countries experimented with the development small OWFs in the period from 1990s to 2000s, characterized by limited turbines and capacity (Johansen, 2021). The development of offshore wind started slow for both countries as projects required governmental support and were criticized by the public (idem).

3. Theory

3.1 Circular economy

The concept of a circular economy (CE) refers to an economic system that emphasizes reducing, reusing, recycling, and recovering materials throughout their life cycles, thereby replacing the traditional linear approach (Kirchherr et al., 2017) (viewed in Figure 2). The traditional linear approach is formed by the “take-make-waste” model, where resources and materials are used once and then discarded as waste (Ellen MacArthur, 2013). Various challenges arise in such linear models, including waste management, environmental degradation and a potential for resource scarcity (Winans et al., 2017). A shift to CE is highly urgent in order to restore the environment (George et al., 2015). Central to the concept to reduce the dependence on raw materials, to keep material flows within a system and thereby reducing waste streams (Van Buren et al., 2016). In addition, the adoption of CE is also aimed to reduce the amount of greenhouse gas emissions (Nasir et al., 2017). While CE ideas date back to the 1960s (Boulding, 1966), they have been increasingly popular among researchers, legislators, and corporations in the last decade (Kircher et al., 2017). This study uses the CE definition of the study by Kircherr et al., (2017), where defined CE as “*an economic system that is based on business models which replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes”* (Kirchherr et al., 2017, p. 229).

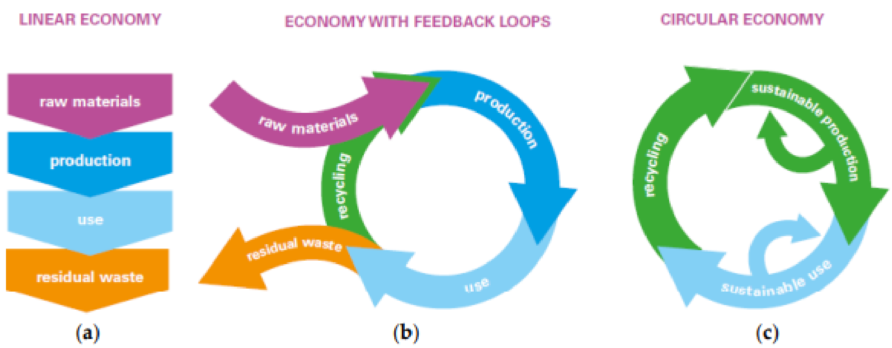

Figure 2: System diagrams of a linear economy, an economy with feedback loops and a circular economy (Rli, 2015).

The evolution of CE within policies and academic literature resulted in multiple frameworks, which varied in the number of R-strategies (Ghisellini et al., 2016; Morseletto, 2020). The most recent 10-R framework is adopted for this research, which applies a holistic lens for CE and is regarded as an extension of the 3-R framework (reduce, reuse, recycle) (Reike et al., 2018). The framework reviews ten CE strategies based upon three overarching themes: smarter product manufacturing and usage, lifetime extension of products followed EOL strategies recycling and recovery (Potting et al., 2017) (Figure 3). A hierarchical order of CE impact is used for the ten CE strategies, following: R0-Refuse, R1-Rethink, R2-Reduce, R3-Reuse, R4-Repair, R5-Refurbish, R6-Remanufacture, R7-Repurpose, R8-Recylce and R9-Recover (Morseletto, 2020, Reike et al., 2018). The framework uses a rule of thumb which implies that R0-Refuse is associated with less environmental pressure as compared to R9-Recover (Potting et al., 2017).

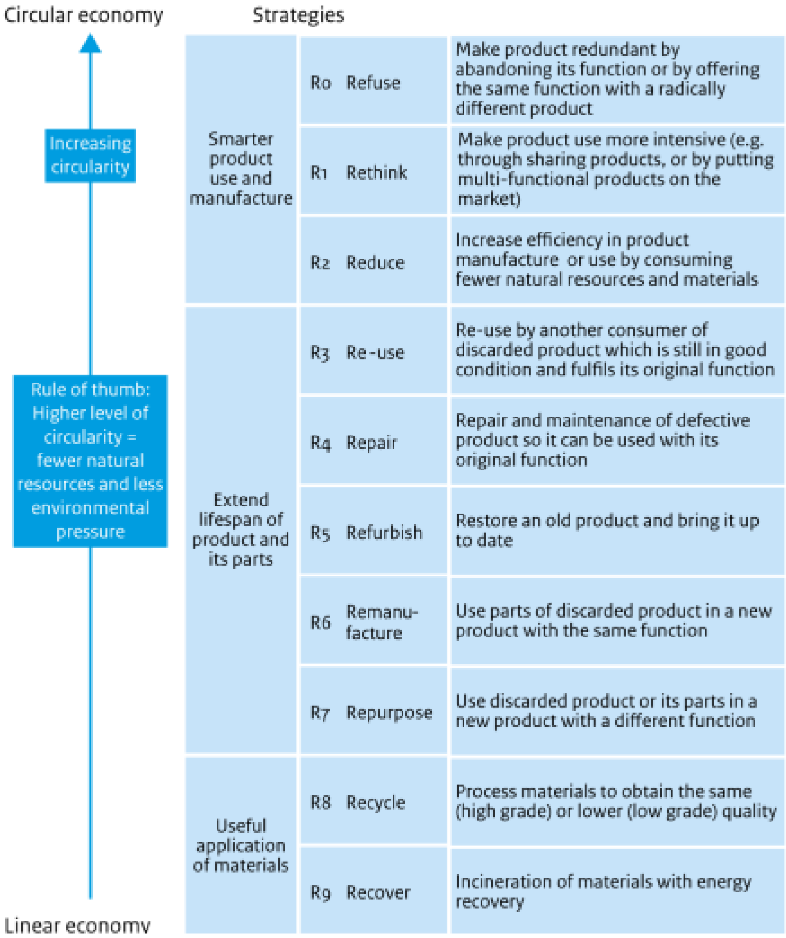

Figure 3: The 9R-strategies framework (Rli, 2015).

The first overarching theme 'Smarter product manufacturing and usage of products' can be linked to the design phase of products or components and is connected to the CE strategies: R0-Refuse, R1-Rethink, and R2-Reduce (Figure 3). According to Reike et al., (2018), R0-Refuse refers to the product design phase and signals that designers can refuse materials with an environmental impact or virgin material use. Thereby making its function redundant or offering another product (Morseletto, 2020). The second strategy, R1-Rethink, involves that products can be used more intensively (e.g. car sharing) (Potting et al., 2017) or that producers rethink their supply chain by altering production and distribution processes (van Buren et al., 2016; Morseletto, 2020). The latter involves rethinking the way a business operates and how it delivers, captures and creates value, thereby radically changing a business model (Potting et al., 2017). In addition, circularity can also be integrated throughout the design phase by reducing material usage (R2-Reduce). This third strategy refers to material optimization in product designs through changes in design shape or using alternative materials (Velenturf et al., 2021). Alternative material usage involves the substitution of non-renewable materials by recyclable or biodegradable materials (Goyal et al., 2018). Thereby this strategy reduces the input of input of virgin materials (Potting et al., 2017; Morseletto, 2020).

The second overarching theme "Lifetime extension of products and its parts" can be linked to the use phase of a product and is connected to the following R's: R3-Reuse, R4-Repair, R5-Refurbish, R6-Remanufacture, and R7-Repurpose (Figure 3). All these activities except from "R3-Reuse" aim to upgrade the value of a product (Vermunt et al., 2019). Reuse of products or components is applied in another context, where a product or component is used without altering the composition of the materials (Potting et al., 2017; Morseletto, 2020). The activities of inspection, cleaning and repairing parts are linked to this strategy, but does not involve refurbishment. This typically refers to a direct reuse, which makes the product second hand. (idem). An example includes the inspection of an OWF at EOL and direct resell to another party. The upgrading activities (repairing, remanufacturing and refurbishing) aim to improve a products condition while maintaining the function of a product (Prahinski and Kocabasoglu, 2006). The strategy R4-Repair is associated with replacement of a product's malfunctioning components, and hence with refunctioning of a product (Reike et al., 2018). Fifth strategy R5-Refurbish refers to replacing or repairing multiple components of a product without dismantling the overall structure of individual components (idem). Multiple components are replaced or repaired within a refurbished wind turbine, so the product is able to operate again (Ricardo, 2016). It does not mean that a product is restored to its original state, which increases the risk of other unreplaced components to fail at a certain point (idem). Strategy R6-Remanufacturing involves restoring a product to the specifications of the original equipment manufacturer (Reike et al., 2018). It involves the dismantling of an multicomponent product and includes inspection, cleaning and repairing or replacing all components with quality of an approved company. The end result of a remanufactured product recovers the same standard and guarantees functionality of a newly manufactured product (King et al., 2006). Strategy R7-Repurpose is not linked to upgrading activities. This strategy uses discarded parts or elements of a product for another purpose, by changing the function and without altering material composition (Morseletto, 2020; Velenturf, 2021). Examples of this strategy within the offshore wind industry include applying discarded blades within the designs of playgrounds, bike sheds or sound barriers (Diani et al., 2022).

The last overarching theme is related to the strategies R8-Recycle and R9-Recovery (Potting et al., 2017). According to Morseletto (2020), these strategies do not necessarily promote CE, but still recover some material or energy sources. Recycling products or components (R8) involves the collection, processing and transformation of materials into new products (Vermunt et al., 2019). Within recycling, the original material is broken down via mechanical or chemical recycling technologies, which leaves behind residual materials that can be used in subsequent manufacturing processes (idem). Mechanical recycling is the process of shredding or incinerating materials to smaller particles and using heating and cooling processes in order to make the recycled product. This process degrades a materials properties and loses its functionality within a few cycles (Reike et al., 2018). Chemical recycling is characterized to alter a material's chemical structure which often costs a lot of energy, but generally improves material recovery (idem). The lowest position on the hierarchy is for Recovery (R9) as the strategy is not aimed at material recovery but energy recovery (Morseletto, 2020). It involves energy recovery from incineration of waste, which is better known as burning of materials (Reike et al., 2018). As seen in Figure 3, landfilling is not included as a circular strategy as Potting et al (2017) considered this strategy to contribute to a linear economy.

3.2 Heavy industries

Heavy industries are generally formed by polluting industries that supply industrial products and materials such as steel, aluminium, cement, plastics and glass (Wesseling et al., 2017). The heavy industries that supply the materials for the main components of an offshore wind turbine drive on the input on fossil fuels, which results in significant carbon emissions (Johnson et al., 2021). For example, the steel industry, which supplies approximately 85% of a turbine's materials (Jensen, 2018), is the most polluting heavy industry from a global perspective (Urban & Nordensvärd, 2023). This industry emits up to 7% of the global carbon emissions through their production processes (idem). While environmental impact is significant for heavy industries, the transition to CE is also present for these industries (Conejo et al., 2020). Related to recycling, steel scrap is highly valuable for recycling and the market for secondary steel is significant (Wesseling et al., 2017). Steel recycling ratio is currently about 95%, which causes the steel industry to be regarded as the most circular industry (Conejo et al., 2020). The process for recycling steel applies a significant lower power input, which is associated with reduced GHG emissions (idem). A CE constraint is also present since recycling steel often lowers the quality of the materials, resulting in a limited number of recycling rounds (Fennell et al., 2022). Rare earth elements (REEs) are also associated with heavy industries, which have a significant environmental pressure due to the mining of these materials (Wesseling et al., 2017). Recycling of REE's have been historically very low at around 1% (Jensen, 2018). Various turbine types houses permanent magnets within the nacelle for generating electricity, which rely heavily on the REEs. The REE present in the magnets are iron, boron, neodymium and dysprosium (idem). Circularity is also limited for the blades of wind turbines, which are typically formed carbon fibre or glass fibre composites (Mendoza et al., 2022). It is extremely difficult to recycle these materials since the fibre composites are strengthened with an epoxy resin (Sakellariou, 2017). Mechanically recycling of fibre composites is the most widely applied method, which involves the incineration of the materials. However, incineration creates a leftover of 60% of the initial material which is not usable (Jensen, 2018). Chemical and thermal recycling of fibre composites have a significant higher output of recovered materials. However, chemically recycling is linked to an environmental harmful chemical solution and thermal recycling is very energy intensive (Fennel et al., 2022). Overall, the CE transition of the hard-to-recycle materials fiercely compete with the availability of cheaper virgin materials (idem). While technological developments of heavy industries improved the CE performance, there are still a lot of opportunities in the CE transition.

3.3 Factors influencing a CE transition

Organizations have a central role in the CE transition and its CE performance is influenced by driving and impeding factors (Vermunt et al., 2019; Lopez et al., 2019; Tura et al., 2019). Drivers and barriers have been reviewed in numerous systematic literature reviews, which were consulted for this research. These included the following studies: De Jesus and Mendonça, 2018; Geissdoerfer et al., 2022; Guldmann and Huulgaard, 2020; Pasqualotto et al., 2023; Vermunt et al., 2019 and Tura et al., 2019. The outcome and perspectives of the literature reviews varied, causing the authors to presents slightly varying general factors. Table 1 provides an overview of the general factors emerged in CE literature, which include environmental, institutional, social, financial, market, technical, organizational and supply chain factors. A major driver for organizations to become more circular is the internal drive to contribute to resource scarcity and waste management (Pasqualotto et al., 2023; Tura et al., 2019). From another perspective, numerous governmental instruments stimulate organizations in a CE transition, such as sustainable public procurement (Witjes and Lozano, 2016), subsidy funds (Tura et al., 2019) and legislative frameworks (De Jesus and Mendonça, 2018). The public procurement implies the acquisition of large scale projects by the government through a bidding process on a tender (Witjes and Lozano, 2016). Typically a government awards projects with the lowest price and a feasible design, but lately other specifications such as circularity criteria have been also included in tenders (Mendoza et al., 2022). In addition, subsidy policies or supportive funds with a focus on CE help organizations to develop CE technologies (Tura et al., 2019). Governments can also be more strict in a CE transition when legislation is set to achieve higher standards for waste and material management (Geissdoerfer et al., 2022). On the other hand, various institutional barriers can impede a CE transition for organizations. A lack of policies, overlapping regulation and missing legislation focused can impede a CE transition (Tura et al., 2019).

The market and supply chain factors were argued by Vermunt et al. (2019) to be the additional two external factors influencing a CE transition for organizations. They distinguished internal and external factors in a CE transition. Whereas internal factors relate to firm factors or the internal environment of an organization, the external factors refer to the factors outside the company that affect the CE transition (Mont, 2002). The market factor refers to the financial market an organization is subject to, which is a significant variable influencing CE performance (Guldmann and Huulgaard, 2020). Market barriers emerged in literature are low virgin material prices, market uncertainty, unclear customer demand or competition with the linear system (De Jesus and Mendoca., 2018; Geissdoerfer et al., 2022; Vermunt et al., 2019; Tura et al., 2019). Market drivers can be formed by the economic incentives that stimulate businesses to contribute to CE such as long term customer satisfactory or new business opportunities (Geissdoerfer et al., 2022; Vermunt et al., 2019). From the perspective of the supply chain, a strong focus on manufacturing with linear business models is perceived as a CE barrier (Gumley, 2014). Other barriers are formed by lack of knowledge exchange, high dependence on other parties, low availability of materials and lack of network support (Vermunt et al., 2019; Tura et al., 2019). This way a lack of circular supply chain network impedes a CE transition. On the contrary, value chain network support can also drive CE by strategic partnerships or an industry-wide alliance (Pasqualotto et al., 2023). Substantial impact can be made through partnerships and open knowledge exchange, which stimulates stakeholders to be innovative and achieve a circular strategic advantage (Gumley, 2014).

Vermunt et al. (2019) pressed the distinction between internal and external factors. This research focuses on external factors, but internal organizational factors were also highlighted to have substantial impact on CE performance. Therefore, this theoretical section does not ignore the internal factors emerging from the literature review. These include social, financial, environmental, technical and organisational factors, which can be visualized in Table 1. Public awareness, reputation and social sensitivity link to the social drivers of organizations in a CE transition (De Jesus and Mendoca., 2018; Geissdoerfer et al., 2022). The social driver of corporate public awareness narrowly links to corporate social responsibility, which is noted as an organizational driver. Other organizational drivers are formed by strengthening the brand and contribution to corporate strategy and goals (Geissdoerfer et al., 2022; Tura et al., 2019). Financial factors involve whether an organization has the financial means or drive to become more circular (Geissdoerfer et al., 2022). High costs, high risk, lack of purchasing power and an unclear business case are associated to financial barriers. On the contrary, financial drivers to contribute to CE are other revenue streams and business growth since circularity can extend product lines (Geissdoerfer et al., 2022; Pasqualotto et al., 2023; Tura et al., 2019). The last general factor influencing a CE transition for organizations is the technological factor. Barriers related to this factors include technical trade-offs, lack of data, lack of technological know-how and a lack of technology (Geissdoerfer et al., 2022; Tura et al., 2019). These barriers particularly link to R&D of CE technologies or new product designs (idem). Technology can also drive a CE transition by creating new opportunities for development of CE technologies (Geissdoerfer et al., 2022).

As highlighted, this research focuses on the external factors formed by the supply chain, the market and the institutional factors. The internal factors are also relevant to understand, but are not the main interest of this research. Interconnection between factors is substantially present. For instance, institutional support could alleviate financial means for organizations, thereby lowering the cost to invest in CE technologies.

Table 1: Overview of CE drivers and barriers (adapted from numerous articles)

Drivers	**Examples**	**Reference**
Environmental	Potential to prevent negative impact, scarcity of resources, waste management	Pasqualotto et al. (2023); Tura et al. (2019)
Institutional	Legislation, policies, taxes, incentives, legal compliance, guidelines,	De Jesus and Mendoca. (2018); Tura et al. (2019)
Market	Satisfy demands of customers, long term satisfaction, market opportunity	Geissdoerfer et al. (2022); Vermunt et al. (2019)
Supply chain	Partnerships, reduce supply dependence, open knowledge exchange	Pasqualotto et al. (2023); Tura et al. (2019);
Social	Social sensitity, reputation, public awaness	De Jesus and Mendoca. (2018); Geissdoerfer et al. (2022); Guldmann and Huulgaard. (2020); Tura et al. (2019)
Financial	Business growth, resilience, other revenue streams	Geissdoerfer et al. (2022); Pasqualotto et al. (2023) Tura et al. (2019)
Technical	New technologies, new technological opportunity	Geissdoerfer et al. (2022); Tura et al. (2019)
Organizational	Corporate responsibility, company strategy and goals, strengthening company brand	Geissdoerfer et al. (2022); Tura et al. (2019)
Barriers		
Institutional	Lack of legislative and governmental support, lack of sustainable procurement, ineffective policies, lack of standards and guidelines, overlapping regulation, lack of CE know-how of political decision makers	De Jesus and Mendoca. (2018); Geissdoerfer et al. (2022); Vermunt et al. (2019); Tura et al. (2019)
Market	Low virgin material prices, market uncertainty, unclear customer demand, competition with linear system	De Jesus and Mendoca. (2018); Geissdoerfer et al. (2022); Vermunt et al. (2019); Tura et al. (2019)
Supply chain	Lack of partners, low availability of materials, high dependence on external parties, lack of knowledge exchange and collaboration, lack of support network	Vermunt et al. (2019); Tura et al. (2019)
Social	Lack of social awareness	Tura et al. (2019)
Financial	High costs, high risk, purchasing power, unclear business case	De Jesus and Mendoca. (2018); Geissdoerfer et al. (2022); Guldmann and Huulgaard. (2020); Vermunt et al. (2019); Tura et al. (2019)
Technical	Technical trade-offs, lack of technology, lack of technical capability	Geissdoerfer et al. (2022); Tura et al. (2019)
Organizational	Administrative burden, complex management system, lack of internal competencies or knowledge, lack of management support, conflict with business culture	Geissdoerfer et al. (2022); Guldmann and Huulgaard (2020); Vermunt et al. (2019); Tura et al. (2019)

3.4 Conceptual model

This research investigates how external drivers and barriers influence businesses in offshore wind in the transition to CE, with a particular focus on Denmark and the Netherlands. The conceptual model for this study is formed by integration of the 10R-Framework by Potting et al (2017) and the categories of the external drivers and barriers (Tura et al., 2019; Vermunt et al., 2019 & Lopez et al., 2019). Figure 4 represents this conceptual model, including the interaction between the drivers, barriers and CE strategies. The CE strategies are formed by R0-Refuse, R1-Rethink, R2-Reduce, R3-Reuse, R4-Repair, R5-Refurbish, R6-Remanufacture, R7-Repurpose, R8-Recylce and R9-Recover. The strategies follow a hierarchical order indicating R0 to R9 decreases in CE impact. This implies that R9-recycling is linked to the highest environmental pressure within a circular economy (Potting et al., 2017). Incineration and landfilling are not included in the conceptual model as these strategies link to a linear economy. The drivers and barriers are formed by the institutional, market and supply chain factors. The positive sign indicate a stimulating effect on the CE strategies and the minus sign highlights an hindering effect on the CE strategies. Overall, the conceptual model guides the analysis of the research and is referred recurringly in the upcoming chapters.

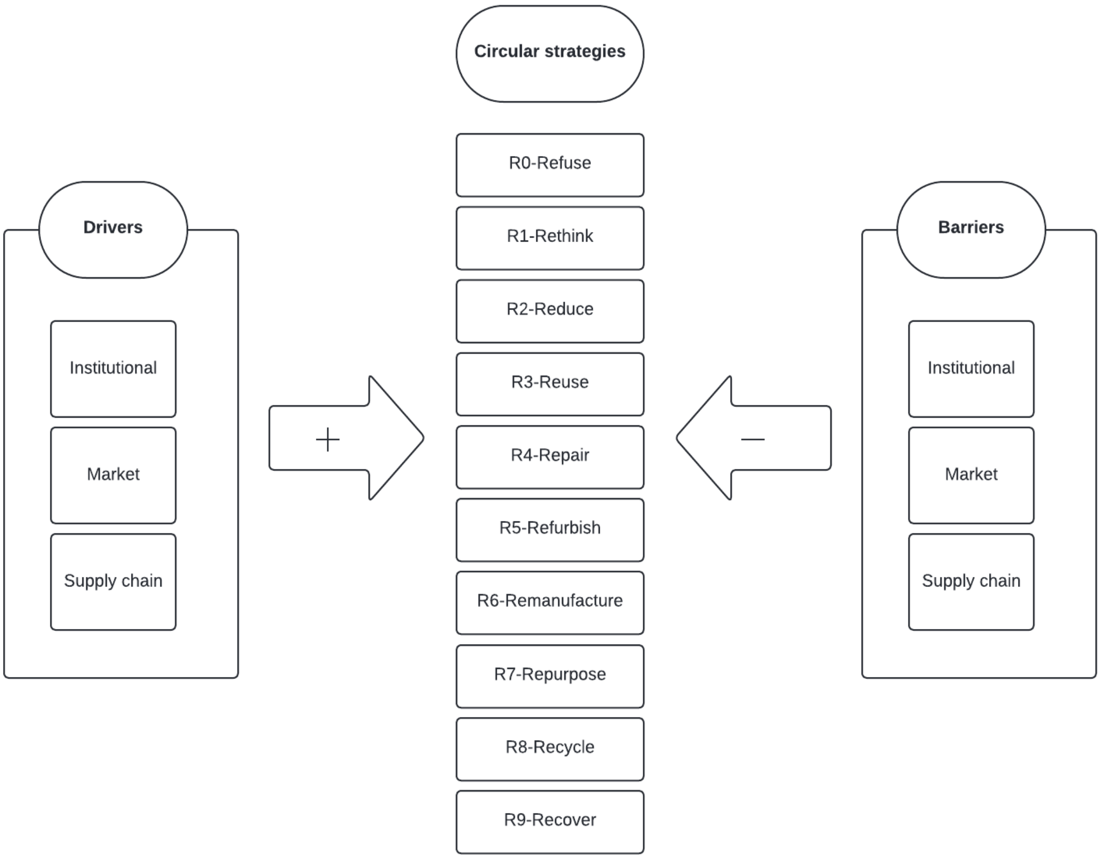

Figure 4: Conceptual model of the drivers and barriers influencing CE strategies

4. Methods

4.1 Research design

This research focused on how CE performance of offshore wind organizations are influenced external factors, with a particular focus on the Netherlands and Denmark. In order to meet the research objective, semi-structured interviews with stakeholders from both countries fitted the study's timeframe. This semi-structured approach allowed for a flexible approach and in-depth exploration of complex phenomena (Yin, 2018). The conceptual model, including the predetermined drivers, barriers and CE strategies, were used as a set up for the interview guide. Thereby associated with a systematic yet adaptable type of questioning (Bryman, 2016). The interview guide can be viewed in Annex IV. The interviews placed a strong emphasis on the external factors influencing a CE transition. Concepts related to institutional, market, and supply chain factors were explained at the beginning of each interview to ensure participants' understanding, enhancing the relevance of their responses (Clark et al., 2021). This also accounted for the holistic concept of a CE transition, including the hierarchical order of CE strategies. During the interviews, emphasis was put on a CE transition and the semi-structured approach provided sufficient opportunities to dive into specific CE strategies. Interviews were recorded, transcribed, and systematically coded, ensuring reliability and validity in the analysis (Bryman, 2016; Clark et al., 2021).

4.2 Sampling strategy

This research involved interviews with twenty-one experts from the offshore wind industry, including 10 Danish and 11 Dutch stakeholders. The participants represented a diverse range of organizations: governmental institutions (G1, G2), developers (D1, D2, D3), component suppliers (S1, S2, S3), transportation and installation companies (I-1, I-2), consultancy firms (C1, C2, C3, C4), ports (P1, P2), a recycling firm (Rec-1), and an original equipment manufacturer (O1). A diverse and large sample aligned to ensure a comprehensive perspective and representation of both cases (Clark et al., 2021).
Purposive sampling was conducted since the study required to select a specific target group of information reach stakeholders (Palinkas, 2015). The LinkedIn Sales Navigator tool supported the identification of experts for this research. It facilitated identifying experts from both countries and enabled using keywords as "circularity" and "sustainability" to narrow the target group. This targeted approach secured reliable and insightful responses (Bryman, 2016). References to the stakeholders are denoted by acronyms (Appendix III), maintaining confidentiality while providing clarity in the analysis.

4.3 Data analysis

Before coding the interviews, an AI-based transcription program (Cockatoo) was used to transcribe the recorded audios. These transcripts were coded used the tool *Atlas.ti*. The recordings and generated transcripts were verified, ensuring that the transcripts accurately reflected the actual interviews. Design of the codes were based on the predetermined codes of Table 1. The analysis was based on the conceptual model of Figure 4, linking the codes to one of the main external CE drivers or barriers. Descriptive coding was used for identifying and distinguishing institutional, market and supply chain factors. For instance, a quotation linked to institutional drivers could relate to 'the influence of tenders'. While not all codes corelated to a CE strategy, numerous quotations were given a code in case these referred to rethink, reduce, repair, refurbish or recycle. Thereafter, thematic analysis was used to explore the interaction between CE strategies and external factors. This helped in the cross-case analysis of how drivers and barriers affect the CE contribution of the Dutch and Danish offshore wind industry.

4.4 Ethics

In advance of the interview, an informed consent form has been send by mail. All interviewees were first asked if they were okay with a recording of the interview. The essence of this informed consent form was discussed after start of the recording and accordance to this form were conveyed orally. The recordings and transcripts were safely stored, and a file of the transcripts has been shared with the supervisor. All recordings will be deleted following the completion of the research. The interviewees were informed when a quote of the interview was used in the Results chapter, which provided the opportunity for revising or rejecting the quotation.

5. Results

The data in this chapter is aimed to answer how external factors influence the offshore wind industry to become more circular for the context of Denmark and the Netherlands. The conceptual model of Figure 4 is used throughout this chapter, which represents the interaction of the external factors and the CE-strategies of the 10R-framework. The drivers and barriers were formed by institutional, market, and supply chain factors (Vermunt et al., 2019; Tura et al., 2019). The aim of this chapter is to present the differences of the offshore wind CE performance of the Netherlands and Denmark.

5.1 Institutional drivers

The main institutional drivers that emerged during the interviews are tender criteria, alternative tender criteria, governmental grants and the impact of a landfill ban.

Tender criteria

Tenders are important government mechanisms that direct the design of OWFs as it sets the boundaries for every project (Verhees et al., 2015). All 21 interviewees highlighted institutions to be strongly influencing the procurement process of OWFs. Particularly, CE tender criteria was noted to promote a CE transition within offshore wind. Development and procurement of OWFs by the government were first strongly subsidized projects, which focused on lowest costs for producing energy (Verhees et al., 2015). Authorities were confident to stop subsidies for OWF development as costs of producing wind energy reduced and was lower than the market price of energy (idem)(G1, D1). The government knew that developers could compete on other aspects than price after a successful round of unsubsidized bids. Since then, non-priced tender criteria (e.g. environmental impact) could be integrated into upcoming tenders (Jansen et al., 2020) (G1). Recently, both The Netherlands and Denmark have included circular tender criteria in their latest offshore wind tenders (O1).

The Dutch tender Ijmuiden Ver was recurringly mentioned as a tender that introduced circular tender criteria (B1, C1, C2, C4, D1, D2, G1, G2, I-1, I-2, O1, P1, P2, R2, S2, S3). The Ijmuiden Ver tender is noted as the first Dutch offshore tender to integrate circular tender criteria. A developer from the Netherlands noted this and expressed they pushed this change (D2): "*In the Netherlands, we indeed see that they (circularity tender criteria) have taken on a role in IJmuiden Ver, and we have pushed quite hard for that. We have strongly encouraged this to happen because it is simply an extra trigger that stimulates the market to make more effort in a specific area.*" (D2). The tender particularly stimulated developers to become transparent on how they address circularity within the lifecycle of an OWF (Ijmuiden Ver Tender, 2024) (C1, D1, D2). The tender explains how developers can score points in order to be awarded for the project (Jansen et al., 2020). As circularity was noted as a new concept for tender criteria, the criterion acquired 10% of the total score (Ijmuiden Ver Tender, 2024) (G1, G2, D1, C1).

According to D1, the criteria included circularity with a holistic perspective, as highlighted: "*It actually started and forced everyone in the industry to start thinking about the same holistic, strategic approaches for circularity. For that, I deeply admire the Netherlands for doing this.*" (D1). A first aspect of the circular tender criterium was that developers were awarded for disclosing their impact in material reduction, critical material use, and the use of substitute materials (D1, R2, G2). Reduction of material impact was specifically encouraged through green steel, recyclable blades (D1, G2), limiting balsa and critical raw material use (R2, G1, G2). Including material reduction and substitute materials in the tender is clearly linked to strategy R2-Reduce as expressed in Figure 4. The tender also encouraged developers to stress how they will extend the lifetime of the main components of an OWF (D1). Thereby linked to the strategies Reuse, Repair, Refurbish, Remanufacture and Repurpose (R3 to R7 of Figure 4). In addition, developers were also encouraged to disclose the expected amount of materials to be recovered at the EoL stage (D1, G2), which links to strategy R8-Recycle.

The latest Danish tender also included circularity aspects as tender criteria (O1). According to O1, the Danish government incorporated circularity in two ways. First, developers were encouraged to document lifecycle assessments (LCA's) of the main components of the OWF (idem). Such LCA criteria for components incentives developers to cut emissions throughout the lifecycle of a windfarm (C2, D1, O1). It stimulates developers to substitute environmental polluting materials by low carbon alternatives (R2-Reduce) and also encourages extending the lifetime of components (2nd core CE theme) (C2, D1). The Ijmuiden Ver tender also included this as a criterium. Besides, the Danish tender also encouraged to install blades that can be recycled with a recovery rate more than 70% of the mass. This needed to be documented according to the EN 4555 standard and the ISO 14034 standard (O1). The incentive to substitute conventional fibre composite blades by recyclable blades helps the industry to focus on strategy R2-Reduce of the conceptual model (Figure 4).

The tender structures differ between the Netherlands and Denmark (O1, P2). As highlighted: "*There is no uniform approach across the world, not even across Europe. So, the government from the Netherlands has so far had the strongest incentive for a driven circular approach to wind farms*." (O1). It has been noted that Dutch tenders for OWFs stand out as it encourages developers to achieve the highest possible standards (D1, D2, O1). The Danish government differs from this approach as their tender structure rewards developers for meeting specific standards (O1). Besides the Netherlands and Denmark, tenders from Norway and France were also indicated as alternative examples to stimulate circularity (D2, R2). France authorities encourage developers to exceed minimum requirements, which promoted developers to introduce circular ideas (D2).

Landfill ban

Legislation that enforces an industry to think of circular alternatives helps in the CE transition. A national landfill ban has been highlighted as a strong governmental instrument to stimulate circularity (P1, R1, R2). As highlighted in Chapter 2.1, landfilling does not retain the value of materials and thereby stimulates a linear economy (Potting et al., 2017). Specifically for composite materials, the materials applied in blades, it is not allowed in the Netherlands to landfill these materials (P1, R1, R2). Although, a loophole allows the activity if costs of other end-of-life strategies exceed €205/ton (Beauson et al., 2022) (idem).

Currently Denmark has no legislation for a ban on landfilling composite materials. However, the lack of a landfill ban is argued to be a contested subject (P1, R1). Incineration of blades, which is considered to restore residual heat from burning the waste stream, is considered to be more environmental damaging as compared to landfilling (idem). Incineration exposes toxic chemicals and greenhouse gasses to the atmosphere. Also, when stored on a landfill within a controlled environment, it is argued that this does not pollute the environment (S3). Despite the absence of a strict landfill ban in Denmark, landfilling of offshore wind turbine blades has not occurred. According to B1, Danish developer Ørsted decommissioned one offshore wind farm and stores the blades until recycling technology advances.

Government grants

Governmental grants were highlighted to stimulate the circular transition of the offshore wind industry (C1, G2, R2, D1, P1). National and European financial support programs act as a government mechanism to stimulate the industry in the direction of CE (idem). Dutch funded research programs differ in focus as compared to the Danish funded research programs. In Denmark, funds are specifically designated for circular technologies that promote the recyclability of difficult-to-recycle materials (P1, R2). Most research projects within Denmark focus on recovering the waste stream of wind turbine blades (idem). The blades include layers of composite materials which are strengthened with an adhesive called an epoxy resin (Sakellariou, 2017). Particularly the properties of the resin type make the blades hard to decompose and recycle (idem).

Danish authorities have supported two innovative projects that focus on recovering the materials from blades. First project, called DecomBlades, focused on pyrolysis and used high temperatures to decompose the materials (R1, Rec-1, D1). While the project finished successfully and could produce new fibre composite blades at the end of the process, volumes have to become more significant to scale the technology to an economic viable solution (R1, Rec-1). Second project is formed by the CETEC project, which applied a different approach and uses chemically recycling to recover the fibre composites (D1). This technology dissolves blades in a chemical solution and is also showing promising results for recycling. As highlighted, both projects focus on strategy R8-Recycle. Both are technologies are also contested due to the consumed energy and needed chemicals (R2).

Dutch financial support is focussed to extend CE knowledge and helping the industry with developing EOL routes. The Netherlands is significantly represented in the project called EOLO Hubs, which is European project that aims to secure a circular downstream value chain. This project is aimed to reuse most of materials, and links to the strategies R3-Reuse, R5-Refurbish and R8-Recycle. A second Dutch funded project, called the Moonshot project, focused on how CE could be introduced within the Dutch offshore wind industry (C1). One of the outcomes of this project has been integrated within the latest tender since the project recommended to include circular tender criteria (C1, G2). This project focused on all aspects of circularity, thereby linking to R0-R9.

5.2 Institutional barriers

Lack of circular policies, laws and regulations

The institutional environment may also impede and hinder a CE transition for offshore wind. Inadequate policies, laws and regulation emerged as key institutional barriers for a CE transition (C1, C2, D1, D3, G1, O1, I-2, P1, Rec-1, R2, S1, S2, S3). Interviewee S3 perceived that governments do not dictate which components need to be refurbished or which materials need to be recovered through circular EOL strategies (S3). While decommissioning of the first pilot projects were small and required less challenges for material management, larger OWFs are expected to require more guidance from governments (Rec-1). Initial policies within offshore wind focused more on limiting costs and now also integrate CE within tenders, but a CE policy framework for offshore wind is currently lacking (D1, D3, I-2, S1).

A lack of political framework is particularly noted for the decommissioning of foundations (C1, C2, D1, G1, O1, I-2, P1, R1, S1). Two interviewees (C1, P1) mentioned that decommissioning is currently governed by the OSPAR agreement, which requires full removal of offshore structures after expiration of the permit. This agreement is designed for the offshore oil and gas industry, thereby outdated and inadequate as a policy for offshore wind (idem). A Dutch interviewee argued that full removal contradicts nature conservation laws, as marine life has established surround these underwater structures (C1). As highlighted: "*We need legislation that adapts to new situations. The legislation should quickly adjust regarding these foundations. Leave the lower part, say 2-3 meters, and remove the other part in such a way that preserves the ecology.*" (C1). The benefits of leaving structures within the sea were questioned by a Danish interviewee, which noted a lack of supporting data for both the ecological and long-term benefits (P1). A contradicting argument to leaving monopile structures at the seabed is that full removal contributes to CE, because significant kilotons of steel can be recycled (D1, O1, S2). This indirectly reduces pressure for virgin material input and mining iron ores, which is noted to be connected to significant biodiversity loss (D1, O1). The lack of a political framework is perceived as an ideological and political dilemma, which balances environmental impacts at sea against resource extraction in the global South (D1). Currently, the method of decommissioning involves cutting the steel monopile at seabed level, which leaves significant amount of steel behind (B1). Interviewees advocated for a vibro-piling technology, which enables seabed removal for 100% of the materials (I-2, S1, S2). A final consideration is that ecological conditions can widely vary between OWFs and are site specific to geological conditions (D1, O1). Overall, this debate highlights a need for policy to assists upcoming decommissioning as environmental and CE perspectives collide.

Lack of governmental knowledge and experience

A lack of governmental knowledge and experience was highlighted as an institutional barrier for the CE transition in wind (C4, D2, G2, R1). Circularity is a new topic within the industry, recently introduced as tender criteria (G1, G2, D2). Dutch government officials struggled to establish a baseline for CE performance in the industry, resulting in the absence of circular performance indicators (G2, C4). As noted: "*In the beginning, certain circularity standards had to be met, but no one knew exactly how that worked or how it was structured, and during the course of that tender they (the government) said, well, just leave it for now, so we would already appreciate it if you could at least indicate what is currently happening in circularity at your side*" (C4). Circularity within the tender shifted from strong norms to requesting more transparent variables (C4, G2). Governments noted that stringent CE criteria might adversely impact the bidding process and potentially hinder the achievement of offshore wind targets (G1, G2, D2). Minimum requirements are anticipated to be incorporated at a later stage, but this process is expected to require additional time (G2). As noted: "*As a minimum standard for circularity, we are currently gathering information from the sector. Unfortunately, there is a considerable waiting period before the permit becomes irrevocable, followed by an additional 18 months. Nevertheless, we can take necessary steps to establish a new minimum standard once this information is gathered.*" (G2).

Additionally, integrating CE tender criteria requires significant market understanding (R1, D2). Actor D2 recognized the importance to balance between a CE request and market knowledge. As noted: "*It is a very powerful instrument, but it is not an easy instrument, so as a government you also need to have a lot of knowledge about the status of the market and what you can ask to use it properly, because otherwise you either destroy the market or partly destroy the development of circularity.*" (D2).

Lack of subsidies

Subsidies for the CE transition were also noted to hinder the CE transition. Both Dutch and Danish authorities do not support the development of OWFs with governmental subsidies (G1, D1). This challenges developers to implement recyclable blades as these come with a price premium (O1, D1, G1). G1 noted: "*We would like to rollout the offshore wind farms in a rapid pace. And this is a bit at odds with emerging innovations, which simplify circularity*." (G1). The recyclable blades are currently not affordable for all developers within the industry, so the Dutch government awaits to mandate these blade types to the point these become affordable (idem). Besides a lack of financial support in the bidding process, organizations can apply for funding to develop, research, or upscale technologies (R2). While Danish authorities have provided substantial support for developing circular recycling technologies of composite blades, R2 reported difficulties in securing research subsidies for this.

EU regulation

The European Union has set a long-goal to become fully circular by 2050 (Fetting, 2020). In order to reach this goal, it is argued that regulation of the EU should better steer the industry (B1, Rec-1, R1, R2, G1, P1, O1). One the one hand, individual tenders do drive change, but a high-level CE policy approach or strong European agreement is expected to have more significant impact (R1). A high level agreement on European level such as the Paris Agreement would stimulate a change towards a circular economy (idem). As highlighted: "*So there has been a big push for renewables and then things happen very quickly. Actually, if we could do the same with circularity and sustainability at the same level, as a really top political decision and agenda, then things would be much faster.*" (R1). The European commission did present European plans related to CE (C1), e.g. the EU's 2020 Circular Economy Action Plan. However, policies for circularity are currently less prioritized than policies for the renewable energy transition (R1). This is therefore seen as an impeding factor for the CE transition of offshore wind.

While EU regulation is noted as an institutional barrier, stakeholders also highlighted the positive contributions of the European commission. The EU Critical Raw Materials Act is aimed to regulate supply chain bottlenecks and reliance on countries outside for critical raw materials (B1, P1). A European target has been set for recycling rare earth elements (REEs), which are highly concentrated in the electric equipment of nacelles (O1, P1). As highlighted: "*In the nacelle there are components with these rare earth materials. But there is, obviously there is market for it. And as far as I understand, the EU is trying to regulate this so these components stay in Europe for recycling.*" (P1). Thereby, the EU has a big interest in reducing reliance on other countries and strategy R8-Recycle is used to address this. In addition, the EU has largely been involved in funding the transition to lower carbon steel, which are involved in supply steel plates for towers sections and monopile foundations (S2, G2). EU funding stimulates strategy R2-Reduce and R8-Recycle since green steel relies on scrap materials and renewable energy (O1, P1) (Figure 4).

Lack of standardized measuring criteria for circularity

The evaluation of circular performance of developers and suppliers is a critical aspect of incorporating circularity into tenders (R1, R2). It is noted that there is no homogenous and accepted way of evaluating circular performance in offshore wind tenders (R1, R2, C3). Using Ijmuiden Ver as an example, this tender is based upon qualitative measurement criteria where developers had to disclose a number of circular strategies (R2). As developers can indicate whether they will fulfil the requirements of the qualitative criteria, there is no quantitative indication of which developer has designed the most circular wind farm (R2). As noted, the circular performance of developers can be interpreted in many different ways and there is no standardized method for evaluating this (R1). It has been expressed that developing a standardized measuring criteria for circularity could be as challenging as designing a standardized LCA methodology for offshore wind (R1).

Summary

Tender criteria for OWFs differ for Denmark and the Netherlands. Dutch tender approach is more holistically and focused on almost all CE-strategies (R2 to R8). Lack of a political framework for decommissioning, lack of governmental offshore CE experience and lack of standard measuring criteria applied for both countries. Danish governmental CE grants for offshore wind focus more on circular EOL strategies, whereas Dutch grants support more policy decision making. Dutch composite landfill ban contributes to CE, which does not apply for Denmark. So, from an institutional perspective, Dutch institutions have a higher impact on the CE transition of offshore wind.

5.3 Market drivers

Business opportunities

Developments within technology create new business opportunities, which drive the market of offshore wind to become more circular (C4, D3, S2, I-1). In the Netherlands, there is a high incentive for monopile suppliers to receive back monopile foundations at EOL stage. A new recycling factory is being built in the port of Rotterdam, which can processes old monopiles into smaller steel pieces (Van Beers et al., 2024) (S2). As noted: *"In that factory, we clean the old piles and cut them into pieces exactly as large as our steel factory needs. Then they go back, and because we supply those raw materials back to the steel factory, we also gain the right to green steel."* (S2). Significant volumes of foundations, measured in kilotons, are anticipated to be recycled by 2040 (Figure 6, Annex V). Development of this factory redesigns the downstream supply chain, thereby linked to the strategies R1-Rethink, R2-Reduce, and R8-Recylce.

In addition, decommissioning stage of OWFs also creates opportunities for T&I companies to extend the lifetime of old and smaller vessels (I-1). Since older vessels miss space and cranes for transportation of heavy turbines and monopiles, these would otherwise not be used (idem). As noted: "*The decommissioning phase may actually be an extension of lifetime for many of the original installation vessels, as it's not likely that you would hire a modern new built installation vessel from 2025 to decommission a project that was installed in 2010.*" (I-1). This business opportunity links to strategy R3-Reuse (Figure 4). Also, the industry transition to become more sustainable stimulated OEMs to invest in circular technologies, which resulted in successfully producing blades that can be recycled for a 100% (O1)(R2-Reduce, R8-Recycle).

Corporate social responsibility

Individual corporate beliefs which link to corporate social responsibility (CSR) also help to drive the market to contribute to a CE transition (D1, D2, D3, C3, C4, G1, I-1, I-2, Rec-1, R2). Some developers have set even higher CE performance standards, without a stimuli of government incentives (G1, R2). R2 mentioned that a Dutch-based developer is not willing to use coal-fired steel for the components of a wind turbine. Another example is that a developer stimulates its supply chain to use recycled content as this contributes to both CE and the net zero target (D1). As noted: "*We aren't living in a world where everything is abundant, where we can get everything for basically no price and where everything is* *available all the time. I think that has really become one of our main drivers for adopting more circular practices.*" (D1). The positive influence of CSR in practice has also been linked to the first decommissioned offshore wind farm of Denmark (B1). The developer perceived it harmful to incinerate wind turbine blades or landfill them (idem). The decision to store the blades and postpone for development of advanced technology is a way how CSR could contribute to CE.

Permit extension and life time extension incentives

Operators of OWFs lease the seabed during the operational period of the wind farms. These permits are generally linked to the lifetime of OWFs, which include 25 years (Jensen, 2018; Winkler, 2021). There is a significant market incentive to extend the permits if the OWFs still deliver sufficient energy security (D1, C1, G1, R1, B1, C2, S2, O1). For both Danish and Dutch OWFs there is the possibility to request an extension of the permit. After a full checkup of an OWF, it can be determined which components need to be repaired and which need to be changed (O1). As noted: "*I'm quite sure that the earlier wind farms can also be extended with smart operation and maintenance strategies and exchange of components. I see this as a higher probability as compared to taking the stuff down and putting it up.*" (O1). In the Netherlands it is important that agreements are made with the operator Tennet TSO B.V., which carries responsibility for maintenance of the substation (G1) (Figure 1). As highlighted by O1, repairing and exchanging components is expected to extend the lifetime for an additional 5 years. Permit duration increased over the years (G1, O1). In Denmark the contract is currently set at 30 years while Dutch contracts involve a duration of 35 years with opportunity to extend for 5 additional years (Afry, 2024) (G1, O1).

For the OWFs that will be decommissioned, significant amount of components still have a value, which can be retained (O1, D2, D3, S3, P2, R2, I-1). A baseline assessment secures which components can still be valuable and used in other offshore or onshore wind farms (S2, S3). Thereby, multiple components or entire assets can be resold and directly reused in other European countries (C1), which is connected to strategy R3-Reuse (Figure 4). There are also opportunities to replace multiple component and keep materials within a loop through strategy R5-Refurbish (S3, C1, P1). According to P1, the technology to refurbish blades is very well developed and not difficult to apply. The only requirement is to have a large warehouse of about 70 m long which provides the space to refurbish the blades (P1). Refurbishment possibilities can also be applied to the nacelle or equipment within the nacelle (idem).

Lifetime extension opportunities also arise through repurposing opportunities (R7-Repurpose, Figure 4). Particularly the blade components are technological feasible to use for other applications (R1, R2). Examples that have been provided within the interviews is the development of a bike shed, a playground and sound barriers (idem). Both the Netherlands and Denmark has experienced architect bureaus that are able to use blades within the design of other applications (C1). However, the opportunities for repurposing wind turbine blades are contested since it has not yet been applied for large volumes (P2). Also, none of the interviewees could verify if repurposing of offshore wind blades could be applied on a large scale decommissioning volume of OWFs from the Netherlands or Denmark.

5.4 Market barriers

Inflation

The effects of inflation on the CE performance of offshore wind are marked as contested, since it could have both a positive as negative effects for the industry (B1, C1, C4, D1, D2, D3, G1, I-1, I-2, O1, P1, R1, Rec-1, S1, S3). Significant increases in costs put pressure on the business case of OWF development. For development of an OWF, significant prices for virgin materials mean high costs for the business case (O1, D2, D3). It has been expected that developers will limit extra efforts in the circular design aspects in case costs rise significantly (O1). The circular design technologies that are now available for the design of OWFs are recyclable blades and low-carbon steel towers. These options are more expensive than the conventional components (D1, O1). As highlighted: *"I believe that any factor that increases costs makes it more difficult to progress. This is because fewer projects will be economically feasible, leading to fewer opportunities to implement these solutions. Consequently, the limited use of these technologies in fewer projects will hinder their widespread adoption." (D3).* It is also highlighted that developers deal with short- and long-term effects of inflation (D2). The short-term effect is that the business case is under pressure, which causes to limit initiatives related to sustainability (idem). The long-term vision is different, as noted: "*In the long term, we are convinced that these (circular initiatives) are no extras and are just as necessary as a cable between the turbines*." (D2). Additionally, at times materials are scarce and high in price, decommissioning an OWF could be more profitable than requesting for a permit extension (C1). On the other hand, It is argued that rising energy prices stimulate developers to request for a lifetime extension of the OWFs (R1, B1, D2, P1, Rec-1, C1, D1, C4, S1). Higher energy prices stimulate developers to invest more in O&M, which is sometimes neglected during low market prices (Rec-1).

Costs

Associated costs of circular initiatives were also associated as a market barrier (R1, R2, G1, O1). From a design perspective, it is more costly to include circularity as circular blades come with a price premium (O1). The costs are a critical barrier to do specific circular investments according to O1, particularly in case there is no strong governmental incentive. Costs can also be higher since CE technologies must be accredited by certification bodies (D3). Related to closing the loop of blades, costs of virgin materials for the design of new blades is currently lower than the costs of recycled content (R2). As highlighted: *"At the end of the day, when you have to pay more money than you originally thought to dismantle your wind farm, then circularity becomes a lower priority."* (R2). Also, the Dutch and Danish downstream value chain is currently not stimulated by the government to recover materials at high recovery rates (G1, Rec-1). This causes it to be cheaper to incinerate or landfill blades than recycling them. The market barrier of costs is mostly connected with the strategies R2-reduce and R8-recycle (Figure 4).

Lack of investment security

Despite the high costs of investing in CE technologies, it has been noted that CE is also considered with a lack of investment security (C1, D3, O1, Rec-1, S2). Difficulty lies in investment decision making related to upscaling circular technologies (e.g. recyclable blades) due to low market demand and limited tenders with circular design criteria (O1). A market wide circular agreement is suggest to address CE related investment insecurities (idem). Additionally, there is insufficient investment security to scale up circular end-of-life recycling technologies (Rec-1), as decommissioning occurs in small volumes and is project-based, complicating production line calculations (C1, Rec-1, S2). As noted: "*If you're talking about large quantities (of blades), you could really build a business model and set up a production process for a specific product.*" (C1). Investments of upscaling these technologies is also discouraged due to a limited off-taker market (Rec-1).

5.5 Supply chain drivers

Alliances

An alliance form a partnership between stakeholders that operate within the same branch of the supply chain (Tura et al., 2019). Organizations work on an arranged objective (idem), which can indirectly drive a CE change (D1, R1). Related to this, the International Energy Agency initiated an international alliance to collectively develop a standardized LCA methodology for the offshore wind industry (R1). Also, the organization Carbon Trust initiated such an alliance (Wind Sustainability JIP), which arranged working groups to standardize offshore wind LCA's (D1). In total, 12 global developers are affiliated with this alliance (idem). Such alliances link to CE as reducing the carbon footprint is inherently linked to circular design initiatives (D1, R1).

Partnerships and knowledge exchange

Other type of partnerships also help in the CE transition for the wind industry. These are more linked to close collaboration within their own supply chain (Geissdoerfer et al., 2020). Consortiums and arrangements with value chain partners emerged as two driving factors for the CE transition in offshore wind (C1, D2, O1, R2, S2). Two Dutch consortiums help the CE transition which are EOLO Hubs and Decom Cockpit (C1, S2). EOLO Hubs is a value chain wide partnership throughout Europe of consultancy organizations, industry organizations and research groups (C1, R2). It aims to build a policy hub, an industrial hub and a knowledge hub (C1). In total four Dutch organizations are involved in this consortium, whereas one Danish organization is affiliated. Another consortium is called Decom Cockpit (S2), which includes four Dutch organizations and aims to collectively recover all assets from an OWF. Partnerships within company's supply chain also arrange memorandum of understanding (MOU) with steel suppliers to secure green steel (D1, S2, O1). While these inter-organizational partnerships do contribute to CE, CE knowledge spillovers from such partnerships are regarded as limited (C1).

Also, organizations within Denmark stimulate a CE transition through various partnerships. A value chain wide partnership is formed by the CETEC project where multiple organizations help in development of a circular downstream value chain for composite blades (D1). The suppliers of wind turbines have also partnered up with steel suppliers to secure the supply of carbon reduced steel (O1). A Danish developer also partnered up with steel suppliers to reach a carbon reduced supply chain, and noted: "*We have a strong driver to reduce our use of virgin steel and increase our use of scrap steel in our own supply chain. We need to design the downstream value chain differently from steel than what it looks like today.*" (D1).

Innovations in the steel industry

Many European steel suppliers invest to lower their carbon footprint, which helps the offshore wind value chain to become circular (B1, O1, D2, G1, C3, S2, P2). Many steel suppliers have invested an innovative way of producing steel, the electric arc furnace, which uses electricity to generate heat and produce steel (S2, B1). Swedish steel producers were highlighted as the most promising contributors as these can use an electricity mix that is based on hydrogen energy (D2, G1, R3). As noted, an electric arc furnaces help in reaching reduced virgin material usage as it can produce steel using between 50% to 100% scrap materials (S2). This transition in the steel industry contributes to circularity of the offshore wind industry as the innovative recycling techniques reduces the virgin material usage and it also contributes in emission reduction. R3 highlighted that the emissions of circular steel could be as low as 0.2 tons of CO2 per ton steel when compared to a worldwide average of 2 tons of CO2 per ton steel. Both Vestas and Siemens Gamesa, two OEM's of offshore wind turbines and based in Denmark, now offer the option of wind turbines with carbon reduced steel (O1). In addition, the national energy mix is important to consider in calculating the impact in case there is no direct integration with sustainable energy sources (e.g. wind power or hydropower) (R3).

5.6 Supply chain barriers

Lack of downstream supply chain

The downstream supply chain for recycling permanent magnets and wind turbine blades is currently not on scale (P2, R2, Rec-1). Focusing on permanent magnets, both the Netherlands and Denmark have not invested in the technology to recycle these components (P2, R2). On a European scale, it has been highlighted that four recycling plants have been established (Rec-1). Particular rare earth elements (REE's) are aimed to be recycled. It is important to note permanent magnets are not used within all turbine types (Jensen, 2018). Turbines that produce energy using drive mechanisms, require per MW approximately 500 kg of permanent magnets, which include one third of its mass to REEs (Gielen and Lyons, 2022). Also, the mass per MW of REEs is about 10 times higher in direct drivetrains than in gearbox-generator systems (O1). First turbines with this technology were installed from 2011 onwards and are expected to be decommissioned in 15 years, which is main reason for a lacking downstream supply chain of REE recycling facilities (idem). The downstream value chain of fibre composite blades is also very uncertain. Recycling technologies are currently not economically viable, specifically with significant low decommissioning volumes (Rec-1). On the contrary, C4 noted interests from industries such as car manufacturers in recycled content of fibre materials, but this also requires significant volumes. Another pressing challenge for downstream value chains is that ports may prioritize installation of new OWFs over facilitating decommissioning activities (P2). Recycling or refurbishing requires significant volumes to be laid down, which is economically not attractive in ports and may cause hard-to-recycle components to be incinerated (P2, C4).

Lack of standardization

A lack of standardization within the supply chain also acts as a supply chain barrier for a CE transition in offshore wind (C3, C4, D3, I-1, I-2, R2, S1). Technological development increased the size of OWFs (C3, C4, D3, R2). Old offshore turbines (from OWF Egmond aan Zee) have a capacity of 3 MW, whereas OEM's have now successfully developed turbines with a capacity of 15 MW (O1) (Annex I). OEM's from Denmark are developing wind turbine blades that can reach up to 115 meter in length for 15MW turbines. The smart O&M strategies become challenging since older wind turbine components are out of production, which challenging repairing or exchanging components (C3, C4). The significant large turbine sections is also challenging for T&I companies. Transportation vehicles on land as well as vessels on sea have to adapt to the significant increase of turbine sections or components (C3, I-1, I-2). The steel equipment that is used for fastening components on deck of an installation vessel is particularly made fit for purpose (I-2). Thereby making it challenging to reuse steel equipment repetitively (I-2). In addition, blade compositions has changed throughout the decades (Rec-1, R2). A lack of standardization within the composition, particularly variations in epoxy resins, were noted to be challenging for recovering these materials (idem).

6. Discussion

This study helped to fill the gap of how the transition to a circular economy for offshore wind is influenced by drivers and barriers (Kramer, 2023). This study linked these factors to the cases of the Netherlands and Denmark and the interaction to the 10R-Framework by Potting et al. (2017). Linking the drivers and barriers to this framework brought new insights in the interaction between external factors and the transition to CE. The results underscore that the institutional, market, and supply chain factors influence the landscape for businesses in the Netherlands and Denmark in a CE transition both positively and negatively.

6.1 Interpretation of the results

The institutional factor and its interaction with the theory and conceptual model is discussed first. Integration of CE tender criteria has been noted in literature as a form to stimulate CE development (Mendoza et al., 2022). The government of both countries aimed to stimulate CE through the procurement process of OWFs. Both the Netherlands and Denmark stimulated substitution and resource reduction, thereby linked to strategy R2-Reduce (Potting et al., 2017). However, the tender of the Netherlands also stimulated developers to disclose potential lifetime extension strategies and CE EOL strategies. Additional CE strategies link to a holistic CE perspective (Reike et al., 2018). This underscores the importance of integrating multiple CE strategies across the lifecycle stages of an OWF to incentivize a CE impact throughout a projects lifetime.

Literature also identified legislation related to waste and material management as a significant institutional driver (Geissdoerfer et al., 2022). The Netherlands has implemented a landfill ban for composite materials, a regulation not yet adopted by Denmark. The practice of landfilling materials is associated with a linear economy (Potting et al., 2017), suggesting the Netherlands' ban on composite waste as a crucial step towards waste management regulation. Beyond legislation, governments can also promote a CE transition through supportive funds and subsidy policies (Tura et al., 2019). This research highlighted that support programs for stimulating a CE transition can differ in focus. Dutch funded projects primarily concentrate on acquiring knowledge of decommissioning routes and policy trajectories, whereas in Denmark, the emphasis in on development of closed loop recycling technologies. The varying focus of support programs underscores the challenge for a comparative analysis between the two countries.

This research highlighted that institutions can also impede a CE transition (Geissdoerfer et al., 2022). Currently, there is no governmental experience with decommissioning large OWFs. This, along with a misaligned regulation for decommissioning OWFs underscore the urgency of institutions being more involved at EOL stage. The absence of a targeted policy is expressed in literature as an institutional barrier (Vermunt et al., 2019). According to Topham et al. (2019) there is no focus on sustainability when developers remove the full structure. This research nuanced the environmental impact of full removal of OWFs and highlighted that leaving significant ktons of materials in situ reduces the recovery rate. Nevertheless, this research aligns with Topman et al. (2019) and notes that CE decommissioning policy is inadequate. Additionally, this research underscored that governments struggled with CE integration in the procurement process as it is a new topic within the sector. Limited subsidies for CE waste management initiatives has also emerged as an institutional barrier and linked to a lack of government support (Tura et al., 2019).

This research emphasized how economic market conditions stimulate organizations in a CE transition. Market opportunities emerge in both countries, though their CE impacts differ contextually. For instance, the recycling challenges of blades stimulated OEMs to innovate and design recyclable blades. This underscored that Danish business opportunities focus on material substitution (R2-Reduce) and enhancing recyclability (R8-Recyle). Furthermore, long-term customer and supplier satisfaction can drive a CE transition (Geissdoerfer et al., 2022). Numerous suppliers signed MOU's to secure this long term satisfaction with customers and suppliers and guarantees demand and supply for carbon reduced steel. This consolidated a strong market incentive to redesign the Dutch monopile supply chain, aligning with CE strategies R1-Rethink, R2-Reduce and R8-Recycle (Morseletto, 2020). It appears that the market incentive of long term satisfaction narrowly overlaps with the supply chain driver of partnerships. Innovations such as the development of the electric arc furnace secures a reduced input of virgin steel and stimulates developers, OEM's or other suppliers to secure this supply. It appears that market segments from both countries transition to a circular supply chain of steel. This guarantee of a supply chain transition through partnerships is noted as a supply chain driver (Pasqualotto et al., 2023).

The CE impact of market opportunities appears to be more linked to corporate performance than a national CE performance, which can be examined with the case of circular blades. While Danish organizations facilitate the blade production, these have yet to be implemented in Danish OWFs (Kramer and Beauson, 2023). This indicates that while CE technologies facilitate a transition for specific projects, their CE development does not necessarily translate to national CE performance. It is argued that extra substantiation is needed. However, it is also interpreted that suppliers could have a substantial impact, viewed from an EOL perspective (Velenturf et al., 2021). Danish OEMs are better positioned for refurbishing or remanufacturing turbines (Mendoza et al., 2022), whereas Dutch suppliers focus on closed-loop recycling for monopile structures. CE performance of market segments could be nuanced and impact could be evaluated to CE material flows. Overall, the CE impact of varying market segments could not be generalized to a country's CE performance.

Market conditions also drive CE transitions through permit extension of an OWF. As permits for initial OWFs expire in the coming years (Winkler et al., 2022), this research highlights that smart O&M strategies can extend their lifespan by approximately five years. Contracts for energy supply have also shifted from 20 to 25 years (Jensen, 2018) to current contracts ranging between 30 and 40 years. Thereby, designed lifetime is currently longer than mentioned in previous studies, which has to be accounted for in upcoming studies. An explanation for this could be the fast pacing development of the industry. In Denmark, current permits are set at 30 years, whereas contracts in the Netherlands are set at 35 years with the option for 5 additional years (Afry, 2024). Linking these outcomes to the theory, it implies that the Netherlands has a strong incentive to use assets for a longer period (Potting et al., 2017).

Lifetime extension strategies, including direct reuse, refurbishing, remanufacturing, and repurposing (Morseletto, 2020), introduce uncertainty regarding volumes for recycling (Kramer et al., 2024). Limited volumes and uncertainty create a barrier for upscaling recycling facilities (Beauson et al., 2022). This research also substantiated this as current volumes of blades and permanent magnets are insignificant to develop economic viable recycling facilities. The market barrier of market uncertainty emerged as evident in this research (De Jesus and Mendoca., 2018; Vermunt et al., 2019). While research stressed significant volumes of waste by 2030 (Winkler, 2022; Mendoza et al., 2022), this research indicated that expected volumes are too marginal to alleviate the business case for recycling blades and permanent magnets. The insignificant waste streams are noted as unexpected finding of the research. This research expects a constant decommissioning volume to be reached at 2040, based upon projections of Annex V. However, the research did align with literature that supported a lack of volumes impeding a CE transition (Vermunt et al., 2019). Inflation, CE-related costs, and investment insecurities further exacerbate the uncertainty for a CE transition. The external financial pressure on the industry is also expressed in literature as significant (Afry, 2024) and impedes the scaling of CE technologies.

6.2 Limitations

The study aimed to provide insights how organizations were externally influenced in a CE transition by drivers and barriers, with a particular focus on Denmark and the Netherlands. The use of a broad research scope aimed to support the analysis and focused on the entire offshore wind value chain. CE integration within this research mostly focused on the lifecycles design, operation, and EOL phase. Thereby, material use is directly linked to the asset, but creates a risk to overlook CE integration within the transport and installation branch. The two experts involved in this branch noted some CE drivers and barriers, but also acknowledged that their perspective is generally overlooked within the CE narrative of the entire industry. Additionally, the research also lacked a CE transition perspective of the cabling industry. Unfortunately it was not succeeded to involve cabling experts within the research and industry-wide experts expressed their limited knowledge. Given these limitations, this research may not be representative for the entire value chain and therefore cannot be generalized to the broader scope of the offshore wind value chain. Further research is suggested to also integrate the CE drivers and barriers for the CE transition of these branches.

The attention to an industry-wide perspective is arguably prone to shortcomings. This research represented the perspective of developers, ports, installation companies, suppliers, consultancies, governmental organizations, research institutes, an OEM, a recycling firm and a branch organization. Overall a significant representation is made for organizations from both countries, but it lacked to provide a full industry-wide perspective of both countries. Insights from cable suppliers, additional installation companies and Danish governmental authorities were missing in this research. Particularly, the missing Danish governmental perspective is noted as unfortunate. A lack of response could be attributed to the scheduled opening of the 6 GW auction, which indicates heightened activity for the Danish policy officials. Although all Danish stakeholders provided insights about Danish institutional CE impact, the perspective of Danish policy officials would have enriched the study. Another fallback of an industry-wide perspective is the argument whether the industries represent how a country performs related to CE. Country performance is arguably better measured in evaluating the integration of CE initiatives within upcoming projects or by reviewing the CE routes of upcoming decommissioning projects.

Identification of the barriers and drivers were based upon previous literature reviews. It is argued that drivers and barriers noted within offshore wind literature would allow for a stronger and more valid interpretation of the results. Current interpretation is limited since the results are linked to literature from general literature reviews of CE drivers and barriers. Although, it is noted that the identified drivers and barriers did correlate with the emerged drivers and barriers from literature.

This research narrowed the CE factors to the institutional, market and supply chain factors. Technological development was excluded in this research since this factor was linked to the internal technological capabilities of organizations (Vermunt et al., 2019). However, it is argued that technology can drive a CE transition of organizations through technological development occurring outside of organizations. For instance, technological development of robotics, drones or artificial intelligence could enable a CE transition. Therefore missing 'technology' as an external CE factor underscores a limited overview of all drivers and barriers influencing the landscape of the offshore wind value chain. While technological innovations were underscored as a supply chain driver (e.g. innovations in the steel industry), additional research is required to provide insights into the missing elements of technological development.

The varying market segments of the Netherlands and Denmark also limited this research, particularly for a country comparison. This research argues that each market segments is characterized by individual supply chains, including varying materials and differing CE challenges. Besides, the CE impact of the market segments are more related to corporate performance than a country's CE performance. The differences in institutional environment provided stronger insights for a country comparison. However, the magnitude of the CE tender criteria is yet unclear since awarded developers have a long period for disclosing their CE strategies. While varying contexts of the institutional, market and supply chain factors are arguably not reliable for a country comparison, the insights of this research did provide valuable knowledge for the value chains of both countries. Thereby, the factors do provide a better understanding of a CE transition in offshore wind. A country comparison on CE performance and offshore wind could be determined through evaluation of material flow streams and linking these to the varying CE routes.

Another limitation is that numerous experts underscored the high potential for recycling OWFs, which implies this as an impactful CE strategy. Some stakeholders underscored direct resell as the highest CE option for decommissioning, but expressed to recycle unsold components. When direct resell is not managed, other strategies (e.g. refurbishment, repurpose) would retain more value of the materials. This underscores that the hierarchical order requires more attention throughout the offshore wind value chain.

6.3 Recommendations

It is recommended to design an European-wide decommissioning policy since the current decommissioning policy is based on old agreements. Given that all countries with offshore wind farms will eventually decommission the structures, it is essential to have an adequate EU decommissioning policy for OWFs. A new policy framework has to guide the removal of materials and should focus on maximizing resource recovery while limiting the environmental impact and aligning with EU's nature restoration law. It is also important that the policy takes into account the varying environmental conditions as these greatly vary between offshore wind projects.

National authorities should also better steer the CE transition by designing a CE roadmap specific to the offshore wind industry including numerous CE targets. This plan should aim to support the long-term European goal of becoming circular by 2050. It is recommended to gradually increase the weight of CE criteria in tenders, which assist in reaching CE project development. Governments should also be more involved at a wind farms' EOL stage. It is recommended to include specific CE targets for EOL routes of OWFs. These must align with the hierarchical order of the CE strategies R3 to R9, in order to ensure low environmental impact. Moreover, the policy plan could also include targets for virgin material reduction and recyclability for upcoming OWFs, which should focus on CE design initiatives (e.g. carbon reduced towers and circular blades). The design and decommissioning targets help in evaluating the CE projections. Such insights provide information about the offshore wind's position of a CE transition. Areas that require additional attention can be targeted with CE policies or governmental incentives. Additionally, it is recommended that policy makers consider financial support in order to reach integration of CE technologies. It is expected that this alleviates the financial pressure for offshore wind projects.

This research can serve as a foundation for future research. This research highlighted that CE drivers and barriers are particular relevant for understanding CE transitions within market segments of offshore wind. Future research could build upon the conceptual model and add technological development as an external factor. For a more thorough understanding of entire value chain it is also important to include the CE impact of the cabling industry. Additionally, this study reveals that CE is gradually integrated into upcoming OWFs and circular EOL routes have yet to occur, which restricted a CE country comparison. It is recommended to research upcoming circular EOL routes and development of implementing CE initiatives in order to compare different countries. Reached focused on comparing countries can be extended to a cross country comparison including multiple European countries. A comparative research between multiple European countries, such as Germany, Belgium, and the UK, would provide a broader understanding of CE transitions in the offshore wind sector.

7. Conclusion

OWFs use significant volumes of materials and their lifecycle is limited, which presses the need for the industry to optimize material use and contribute to a circular economy. There is a pressing need to understand how a CE transition within offshore wind is influenced. Therefore, this study aimed to investigate how external drivers and barriers influence businesses in offshore wind in the transition to CE, with a particular focus on Denmark and the Netherlands. A holistic model of drivers, barriers and CE strategies assisted in the attempt of a comparative analysis of these countries.

The potential CE impact of the institutional environment is highlighted as most significant. Particularly the impact of tender criteria is highlighted as an influential factor for the industry to become circular. The Dutch tender is noted to have the strongest potential to stimulate development of circular wind farms since it stimulated resource reduction, material substitution, lifetime extension and circular recycling routes. Furthermore, a landfill ban and governmental support stimulates a CE transition, but were less influential. Following this, the most influential institutional barriers were formed by an inadequate policy framework for decommissioning and a limited governmental CE experience.

The most influential market drivers were formed by new business opportunities as well as opportunities for permit and lifetime extension. Suppliers from Denmark diversify and develop carbon reduced steel towers and circular blades with the aim to reduce and recycle materials. A Dutch business opportunity focused on rethinking the downstream supply chain of steel components, which caused to rethink the supply chain and helps to reduce and recycle materials. Requesting and extending the operational lifetime of an OWF can be done for old offshore wind farms, but outcomes of this are not yet present. Additionally, it is highlighted that offshore wind permits have developed throughout the years, which now account for 30 years in Denmark and 35 years with opportunity for 5 additional years within the Netherlands. The market barriers emerged in this research were formed by a lack of investment security, inflation and costs. However, this research highlights that these barriers influence the markets of offshore wind indifferently.

Innovations within the steel industry, alliances, partnerships and knowledge exchange were identified as the key supply chain drivers. Steel suppliers are gradually transforming to a carbon reduced steel supply chain, which is fuelled by electricity and steel scrap. Organizations from both countries partner up with their suppliers to offset steel components and secure low carbon steel. In addition, various knowledge programs support CE knowledge exchange throughout the supply chain. The supply chain barriers were formed by a lack of standardization and a lack of downstream supply chain.

Overall, the institutional, market and supply chain factors influence a CE transition for offshore wind, which slightly differ between industries markets segments and the Netherlands and Denmark. The research induces a stronger CE performance by the Netherlands due to tender criteria and a different permit structure. The final impact of this is yet unclear and there is also great uncertainty about circular routes for upcoming decommissioned OWFs. It is argued that a valid country comparison is currently limited. Nevertheless, the insights of how the environments of the institution, the market and supply chain influences a CE transition in offshore wind greatly supports knowledge creation for practitioners and policy officials.

References

4 C Offshore, 2024. https://www.4coffshore.com/. (Accessed 26 June 2024).

AFRY Netherlands BV. (2024). [Offshore Wind Energy Market Study – Implications for Tenders IJmuiden Ver Gamma and Nederwiek I]. AFRY. https://rvo.nl/sites/default/files/2024-05/Offshore-Wind-Energy-Market-Study.pdf

Beauson, J., Laurent, A., Rudolph, D., & Jensen, J. P. (2022). The complex end-of-life of wind turbine blades: A review of the European context. *Renewable & Sustainable Energy Reviews*, *155*, 111847. https://doi.org/10.1016/j.rser.2021.111847

Bertram, C., Riahi, K., Hilaire, J., Bosetti, V., Drouet, L., Fricko, O., Malik, A., Nogueira, L. P., Van Der Zwaan, B., Van Ruijven, B., Van Vuuren, D., Weitzel, M., Longa, F. D., De Boer, H., Emmerling, J., Fosse, F., Fragkiadakis, K., Harmsen, M., Keramidas, K., . . . Luderer, G. (2021b). Energy system developments and investments in the decisive decade for the Paris Agreement goals. *Environmental Research Letters*, 16(7), 074020. https://doi.org/10.1088/1748-9326/ac09ae

Blomsma, F., Pieroni, M., Kravchenko, M., Pigosso, D. C., Hildenbrand, J., Kristinsdottir, A. R., ... & Li, J. (2019). Developing a circular strategies framework for manufacturing companies to support circular economyoriented innovation. *Journal of Cleaner Production*, 241, 118271. https://doi.org/10.1016/j.jclepro.2019.118271.

Bocken, N., Short, S. W., Rana, P., & Evans, S. (2014). A literature and practice review to develop Sustainable Business Model Archetypes. *Journal of Cleaner Production*, 65, 42–56. https://doi.org/10.1016/j.jclepro.2013.11.039

Boulding, K.E. (1966). The economics of the coming spaceship earth. In: *Jarrett, H*. (Ed.), Environmental Quality Issues in a Growing Economy. Johns Hopkins University Press, pp. 3–14. http://arachnid.biosci.utexas.edu/courses/THOC/Readings/Boulding_SpaceshipEarth.pdf

Bryman, A. (2016). *Social research methods*. Oxford university press.

Clark, T., Foster, L., Bryman, A., & Sloan, L. (2021). *Bryman's social research methods*. Oxford University Press.

Conejo, A. N., Birat, J., & Dutta, A. (2020b). A review of the current environmental challenges of the steel industry and its value chain. *Journal of Environmental Management*, *259*, 109782. https://doi.org/10.1016/j.jenvman.2019.109782

Corvellec, H., & Stål, H. (2017). Evidencing the waste effect of Product-Service Systems (PSSS). *Journal of Cleaner Production*, *145*, 14–24. https://doi.org/10.1016/j.jclepro.2017.01.033

Dau, L. A., Li, J., Lyles, M. A., & Chacar, A. S. (2022). Informal institutions and the international strategy of MNEs: Effects of institutional effectiveness, convergence, and distance. *Journal Of International Business Studies*, *53*(6), 1257–1281. https://doi.org/10.1057/s41267-022-00543-5

Dedecca, J. G., Hakvoort, R. A., & Ortt, J. R. (2016). Market strategies for offshore wind in Europe: A development and diffusion perspective. *Renewable & Sustainable Energy Reviews*, *66*, 286–296. https://doi.org/10.1016/j.rser.2016.08.007

De Jesus, A., & Mendonça, S. (n.d.). Lost in transition? Drivers and barriers in the eco-innovation Road to the Circular Economy. *Ecological Economics*, *145*, 75–89. https://doi.org/10.1016/j.ecolecon.2017.08.001

Diani, M., Picone, N., Gentilini, L., Jensen, J. P., Angius, A., & Colledani, M. (2022). Disassembly of large Composite-Rich installations. *In Springer eBooks* (pp. 37–60). https://doi.org/10.1007/978-3-031-22352-5_3

Ellen MacArthur Foundation, Towards the circular economy Vol. 1: an economic and business rationale for an accelerated transition (2013).

Eisenhardt, K. M. (1989). Building Theories from Case Study Research. *The Academy of Management Review*, *14*(4), 532–550. https://doi.org/10.2307/258557

European Commission. (2023). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: European Wind Power Action Plan* (COM(2023) 669 final). Brussels.

Fennell, P. S., Driver, J., Bataille, C., & Davis, S. J. (2022). Cement and Steel — Nine steps to Net zero. *Nature, 603(7902), 574–577. https://doi.org/10.1038/d41586-022-00758-4*

Fetting, C. (2020). "The European Green Deal", ESDN Report, December 2020, ESDN Office, Vienna.

Geissdoerfer, M., Morioka, S. N., De Carvalho, M. M., & Evans, S. (2018). Business models and supply chains for the circular economy. *Journal of Cleaner Production*, *190*, 712–721. https://doi.org/10.1016/j.jclepro.2018.04.159

Geissdoerfer, M., De Pádua Pieroni, M., Pigosso, D. C. A., & Soufani, K. (2020). Circular Business Models: a review. *Journal of Cleaner Production*, *277*, 123741. https://doi.org/10.1016/j.jclepro.2020.123741

George, D. A., Lin, B. C. A., & Chen, Y. (2015). A circular economy model of economic growth. Environmental modelling & software, 73, 60-63. https://doi.org/10.1016/j.envsoft.2015.06.014

Gielen, D. and M. Lyons (2022), Critical materials for the energy transition: Lithium, International Renewable Energy Agency, Abu Dhabi.

Goyal, S., Esposito, M., & Kapoor, A. (2018). Circular economy business models in developing economies: lessons from India on reduce, recycle, and re-use paradigms. Thunderbird International Business Review, 60(5), 729-740. https://doi.org/10.1002/tie.21883.

Guldmann, E., & Huulgaard, R. D. (2020). Barriers to Circular Business model Innovation: A multiple-case study. *Journal of Cleaner Production*, 243, 118160. https://doi.org/10.1016/j.jclepro.2019.118160

Hunziker, S., & Blankenagel, M. (2021). *Research design in business and management: A Practical Guide for Students and Researchers. Springer Nature.*

Jansen, M., Staffell, I., Kitzing, L., Quoilin, S., Wiggelinkhuizen, E., Bulder, B., Riepin, I., & Müsgens, F. (2020). Offshore wind competitiveness in mature markets without subsidy. *Nature Energy*, *5*(8), 614–622. https://doi.org/10.1038/s41560-020-0661-2

Jensen, J. P. (2018). Evaluating the environmental impacts of recycling wind turbines. *Wind Energy*, *22*(2), 316–326. https://doi.org/10.1002/we.2287

Johansen, K. (2021). Blowing in the wind: A brief history of wind energy and wind power technologies in Denmark. *Energy Policy*, *152*, 112139. https://doi.org/10.1016/j.enpol.2021.112139

Karnøe, P., Kirkegaard, J. K., & Caliskan, K. (2022). Introducing the lens of markets-in-the-making to transition studies: The case of the Danish wind power market engagement. *Environmental Innovation and Societal Transitions*, 44, 79–91. https://doi.org/10.1016/j.eist.2022.05.003

Knol, E. & Coolen, E. (2019). Employment analysis (2019-2023) of various fields of activities in the Dutch offshore wind sector.

King, A.M., Burgess, S.C., Ijomah, W., Mcmahon, C.A., King, A.M., 2006. Reducing waste: repair, recondition, remanufacture or recycle? Sustain. Dev. 14, 257–267. https://dx.doi.org/10.1002/sd.271

Kirchherr, J., Reike, D., & Hekkert, M. P. (2017). Conceptualizing the Circular Economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kramer, K. J., & Beauson, J. (2023). Review existing strategies to improve circularity, sustainability and resilience of wind turbine blades – A comparison of research and industrial initiatives in Europe. *IOP Conference Series. Materials Science And Engineering*, *1293*(1), 012039. https://doi.org/10.1088/1757-899x/1293/1/012039

Kramer, K., & Schmidt, M. (2023). Circular Supply Chain Management in the Wind Energy Industry – A Systematic Literature review. In *Lecture notes in mechanical engineering (pp. 85–93).* https://doi.org/10.1007/978-3-031-28839-5_10

Kramer, K. J., Abrahamsen, A. B., Beauson, J., Hansen, U. E., Clausen, N., Velenturf, A. P., & Schmidt, M. (2024). Quantifying circular economy pathways of decommissioned onshore wind turbines: The case of Denmark and Germany. *Sustainable Production and Consumption*. https://doi.org/10.1016/j.spc.2024.06.022

Lahti, T., Wincent, J., Parida, V., 2018. A definition and theoretical review of the circular economy, value creation, and sustainable business models: where are we now and where should research move in the future? *Sustainability* 10 (8), 2799.

Lakshmanan, P., Sun, R., & Liang, J. (2021). Electrical collection systems for offshore wind farms — a review. CSEE Journal of Power and Energy Systems. https://doi.org/10.17775/cseejpes.2020.05050

Lewandowski, M. (2016). Designing the Business models for Circular Economy—Towards the Conceptual Framework. Sustainability, 8(1), 43. https://doi.org/10.3390/su8010043

Lopez, F. D., Bastein, T., & Tukker, A. (2019). Business model innovation for resource-efficiency, circularity and cleaner production: What 143 cases tell us. *Ecological Economics*, *155*, 20–35. https://doi.org/10.1016/j.ecolecon.2018.03.009

Lin, L., Lacal-Arántegui, R., Wieczorek, A., Negro, S. O., Harmsen, R., Heimeriks, G., & Hekkert, M. P. (2012). A Systemic Assessment of the European Offshore Wind Innovation. Insights from the Netherlands, Denmark, Germany and the United Kingdom". *JRC Scientific and Policy reports. https://doi.org/10.2790/58937*

Liu, X., Yang, T., Pei, J., Liao, H., & Pohl, E. A. (2019). Replacement and inventory control for a multi-customer product service system with decreasing replacement costs. *European Journal of Operational Research*, *273*(2), 561–574. https://doi.org/10.1016/j.ejor.2018.08.029

Mendoza, J. M. F., Gallego-Schmid, A., Velenturf, A. P., Jensen, P. D., & Ibarra, D. (2022). Circular Economy Business Models and Technology Management Strategies in the wind Industry: sustainability potential, industrial challenges and opportunities. *Renewable & Sustainable Energy Reviews*, *163*, 112523. https://doi.org/10.1016/j.rser.2022.112523

Mont, O. (2002). Drivers and barriers for shifting towards more service-oriented businesses: Analysis of the PSS field and contributions from Sweden. The Journal of sustainable product Design, 2(3), 89-103.

Morseletto, P. (2020). Targets for a circular economy. *Resources, Conservation And Recycling*, *153*, 104553. https://doi.org/10.1016/j.resconrec.2019.104553

Nancy M. P. Bocken, Ingrid de Pauw, Conny Bakker & Bram van der Grinten (2016) Product design and business model strategies for a circular economy, *Journal of Industrial and Production Engineering*, 33:5, 308-320, DOI: 10.1080/21681015.2016.1172124

Nasir, M. H. A., Genovese, A., Acquaye, A. A., Koh, S., & Yamoah, F. (2017). Comparing linear and circular supply chains: A case study from the construction industry. *International Journal of Production Economics*, 183, 443–457.

Oh, K., Nam, W., Ryu, M. S., Kim, J., & Epureanu, B. I. (2018). A Review of Foundations of Offshore Wind Energy Convertors: Current status and Future Perspectives. *Renewable & Sustainable Energy Reviews*, *88*, 16–36. https://doi.org/10.1016/j.rser.2018.02.005

Palinkas, L. A., Horwitz, S. M., Green, C. A., Wisdom, J. P., Duan, N., & Hoagwood, K. (2013). Purposeful sampling for qualitative data collection and analysis in mixed method implementation research. *Administration and Policy in Mental Health and Mental Health Services Research*, *42*(5), 533–544. https://doi.org/10.1007/s10488-013-0528-y

Prahinski, C., & Kocabasoglu, C. (2006). Empirical research opportunities in reverse supply chains. *Omega*, *34*(6), 519–532. https://doi.org/10.1016/j.omega.2005.01.003

Reike D., Vermeulen, W.J.V., Witjes, S. (2018). *The circular economy: New or Refurbished as CE 3.0? – Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resources Retention Options.* Resources, Conservation and Recycling, 135, 246-264. Available at: http://doi.org/10.1016/j.resconrec.2017.08.027

Reim, W., Parida, V., & Örtqvist, D. (2015). Product–Service Systems (PSS) Business Models and Tactics – A Systematic Literature review. *Journal of Cleaner Production*, *97*, 61–75. https://doi.org/10.1016/j.jclepro.2014.07.003

Ricardo Energy & Enviroment. (2016). *Briefing Paper: Refurbished & Remanufactured wind turbines*. https://www.gov.wales/sites/default/files/publications/2019-09/briefing-paper-refurbished-remanufactured-wind-turbines.pdf

Rli. Circular Economy: From Wish to Practice [‘Circulaire Economie: Van Wens Naar Uitvoering’]; Raad voor de Leefomgeving en Infrastructuur: Den Haag, The Netherlands, 2015.

Rodrigues, S., Restrepo, C., Katsouris, G., Pinto, R. T., Soleimanzadeh, M., Bosman, P., & Bauer, P. (2016). A Multi-Objective optimization framework for offshore wind farm layouts and electric infrastructures. *Energies*, 9(3), 216. https://doi.org/10.3390/en9030216

Rüdiger, Mogens, 2019a. From import dependence to self-sufficiency in Denmark, 1945– 2000. Energy Pol. 125, 82–89. https://doi.org/10.1016/j.enpol.2018.10.050.

Sakellariou, N. (2017). Current and potential decommissioning scenarios for end-of-life composite wind blades. Energy Systems, 9(4), 981–1023. https://doi.org/10.1007/s12667-017-0245-9

Sánchez, S., López-Gutiérrez, J., Negro, V., & Esteban, M. D. (2019). Foundations in Offshore Wind farms: Evolution, characteristics and range of use. Analysis of main dimensional parameters in monopile foundations. *Journal of Marine Science and Engineering*, *7*(12), 441. https://doi.org/10.3390/jmse7120441

Sunday, K., & Brennan, F. (2021). A review of offshore wind monopiles structural design achievements and challenges. *Ocean Engineering*, *235*, 109409. https://doi.org/10.1016/j.oceaneng.2021.109409

Topham, E., Gonzalez, E., McMillan, D., & João, E. (2019). Challenges of decommissioning offshore wind farms: Overview of the European experience. *Journal Of Physics. Conference Series*, *1222*(1), 012035. https://doi.org/10.1088/1742-6596/1222/1/012035

Tripathi, S., & Petro, G. (2011). Evolving green procurement and sustainable supply chain practices in the organizations: a framework to align functional strategy implementation to organization's corporate social responsibility (CSR) objectives. *Management Convergence*, *1*(1), 24-32.

Tukker, A. (2015). Product Services for a Resource-efficient and Circular Economy – a review. *Journal of Cleaner Production*, *97*, 76–91. https://doi.org/10.1016/j.jclepro.2013.11.049

Urban, F., & Nordensvärd, J. (2023). *Handbook on Climate Change and Technology*. Elgar Handbooks

UN. Paris Agreement; UN: New York, NY, USA, 2015.

Van Beers, F., Rauber, S., Dillinger, Sif, Reinicke, M., Wernet, J., & Geurts, S. (2024). Green deal between Sif and Dillinger will make monopiles fully circular. In *Press Release*. https://sif-group.com/en/investor-relations/download/c5a19254-3384-4ac8-8b5c-9138e89daed8/20240516pr-sif-dillinger-greendealwillmakemonopilesfullycircular.pdf

Van Der Loos, H. A., Negro, S. O., & Hekkert, M. P. (2020). Low-carbon lock-in? Exploring transformative innovation policy and offshore wind energy pathways in the Netherlands. *Energy Research & Social Science*, 69, 101640. https://doi.org/10.1016/j.erss.2020.101640

Van Der Loos, A., Normann, H. E., Hanson, J., & Hekkert, M. P. (2021). The co-evolution of innovation systems and context: Offshore wind in Norway and the Netherlands. *Renewable & Sustainable Energy Reviews*, *138*, 110513. https://doi.org/10.1016/j.rser.2020.110513

Velenturf, A. P. (2021). A framework and baseline for the integration of a sustainable circular economy in offshore wind. *Energies*, *14*(17), 5540. https://doi.org/10.3390/en14175540

Verhees, B., Raven, R., Kern, F., & Smith, A. (2015). The role of Policy in shielding, nurturing and enabling Offshore wind in the Netherlands (1973–2013). *Renewable & Sustainable Energy Reviews*, *47*, 816–829. https://doi.org/10.1016/j.rser.2015.02.036

Vermunt, D., Negro, S. O., Verweij, P., Kuppens, D., & Hekkert, M. P. (2019). Exploring barriers to implementing different circular business models. *Journal of Cleaner Production*, 222, 891–902. https://doi.org/10.1016/j.jclepro.2019.03.052

Vrontisi, Z., Fragkiadakis, K., Kannavou, M., & Capros, P. (2020). Energy system transition and macroeconomic impacts of a European decarbonization action towards a below 2 C climate stabilization. *Climatic Change*, *162*, 1857-1875.

Wesseling, J., Lechtenböhmer, S., Åhman, M., Nilsson, L. J., Worrell, E., & Coenen, L. (2017). The transition of energy intensive processing industries towards deep decarbonization: Characteristics and implications for future research. *Renewable & Sustainable Energy Reviews, 79, 1303–1313. https://doi.org/10.1016/j.rser.2017.05.156*

Winans, K. S., Kendall, A., & Deng, H. (2017). The history and current applications of the Circular Economy concept. *Renewable & Sustainable Energy Reviews*, 68, 825–833. https://doi.org/10.1016/j.rser.2016.09.123

WindEurope (2024). Product | WindEurope. WindEurope. https://windeurope.org/intelligence-platform/product/european-offshore-wind-farms-map-public/

Winkler, L., Kilic, O. A., & Veldman, J. (2022). Collaboration in the offshore wind farm decommissioning supply chain. *Renewable & Sustainable Energy Reviews*, *167*, 112797. https://doi.org/10.1016/j.rser.2022.112797

Witjes, S., & Lozano, R. (2016). Towards a more Circular Economy: Proposing a framework linking sustainable public procurement and sustainable business models. *Resources, Conservation And Recycling*, *112*, 37–44. https://doi.org/10.1016/j.resconrec.2016.04.015

Yin, R. K. (2018). *Case Study Research and Applications: Design and Methods* (6th ed.). Thousand Oaks, CA: Sage.

Annex

I. Offshore wind farms in the Netherlands

Table 2: Offshore wind farm projects of the Netherlands (Adapted from Díaz & Soares, 2020 & 4C Offshore, 2024)

Location	Year	Installed Capacity (MW)	Number of Turbines	Foundation type
Lely (decommissioned in 2022)	1994	2	4	Monopile
Irene Vorrink (decommissioned in 2022)	1997	16,8	28	Monopile
Egmond aan Zee	2007	108	36	Monopile
Prinses Amalia	2008	120	60	Monopile
Eneco Luchterduinen	2015	129	43	Monopile
Westermeerwind	2016	144	48	Monopile
Gemini	2017	600	150	Monopile
Borssele I-II	2020	752	94	Monopile
Borssele III-IV	2021	731	77	Monopile
Borssele V	2021	19	2	Monopile
Friesland	2021	380	89	Monopile
Hollandse Kust Noord V	2023	759	69	Monopile
Hollandse Kust Zuid I-IV	2024	1530	139	Monopile
Windplan Blauw	2024	132	24	Monopile
Hollandse Kust West VI	Planned for 2026	760		Monopile
Hollandse Kust West VII	Planned for 2027	760		Monopile
Ijmuiden Ver Alpha	Planned for 2029	2000		Monopile
Ijmuiden Ver Beta	Planned for 2029	2000		Monopile

II. Offshore wind farms in Denmark

Table 3: Offshore wind projects of Denmark (Adapted from Díaz & Soares, 2020 & 4C Offshore, 2024)

Location	Year	Installed Capacity (MW)	Number of Turbines	Foundation type
Vindeby	1991	5	11	Gravity-base
Tuno Knob	1995	5	10	Gravity-base
Middelgrunden	2001	40	20	Gravity-base
Horns Rev I	2002	160	80	Monopile
Frederikshavn	2003	7,6	4	Monopile
Ronland	2003	17,2	8	High rise pile cap
Nysted	2003	166	72	Gravity-base
Samso	2003	23	10	Monopile
Horns Rev II	2009	209	91	Monopile
Sprogo	2009	21	7	Gravity-base
Avedore Holme	2009	10,8	3	Gravity-base
Rodsand II	2010	207	90	Gravity-base
Anholt	2013	400	111	Monopile
Nissum Bredning Vind	2018	28	4	Jacket
Horns Rev III	2019	406	49	Monopile
Kriegers Flak	2021	605	72	Monopile

III. Interview overview

Table 4: Overview of conducted interviews

Type of organization	Abbreviation	Expertise interview participant	Country
Developer	D1	Circularity	Dk
Developer	D2	Business	NL
Developer	D3	Business	Dk
OEM	O1	Circularity	Dk
Installation company	I-1	Sustainability	Global
Installation company	I-2	Business	Global
Supplier of a component	S1	Sustainability	Dk
Supplier of a component	S2	Business	NL
Supplier of a component	S3	Business	NL
Governmental Agency	G1	Government	NL
Governmental Agency	G2	Government	NL
Recycling company	Rec-1	Business	Dk
Consultancy company	C1	Circularity	NL
Consultancy company	C2	Consultancy	Dk
Consultancy company	C3	Consultancy	Dk
Consultancy company	C4	Consultancy	NL
Branche Organization	B1	Business	NL
Research institute	R1	Materials	Dk
Research institute	R2	Materials	NL
Port	P1	Business	DK
Port	P2	Business	NL

IV. Interview Guide

Introductory questions

- Could you shortly introduce yourself?
- Could you elaborate on your understanding about the concept of a circular economy?

Institutional Drivers

- How do you perceive the national government steers the offshore wind industry to become more circular?
- How do you view the influence of tenders?
    - How do you perceive CE criteria within tenders of the Netherlands/Denmark?
    - Which CE strategies stimulated the industry?
- What is the influence of other governmental regulations?
- How do you view that legislation steers the offshore wind to become circular?
- Are there other forms how your government stimulates a CE transition?

Institutional Barriers

- How do you perceive the national government may hinder the offshore wind industry in the CE transition?
- How do you perceive governmental has sufficient CE knowledge?
- Are there policies or legislation hindering the CE transition?

Market Drivers

- How do you perceive economic market conditions drive the CE transition?
- Do you perceive high probability for lifetime extension strategies?
    - How are permit extension requests organized in the Netherlands/Denmark?
- Which innovations within the value chain drive the market to CE?
    - How do these drive change?

Market Barriers

- How do you perceive economic market conditions may hinder the CE transition?
    - What are the main financial hurdles for a CE transition in wind?

Supply chain Drivers and Barriers

- How do you perceive that partnerships stimulate the CE transition?
- Do you think knowledge exchange within the supply chain is sufficient?
    - Do you perceive CE engagement can be better?
- How do you perceive the supply chain development contributes to a CE?
- How is the downstream supply chain currently organized in the Netherland/Denmark?
    - Do you perceive supply chain bottlenecks?

Concluding question

What would be you prioritize as most pressing in the CE transition of offshore wind?

V. Overview of decommissioning market for monopile foundations

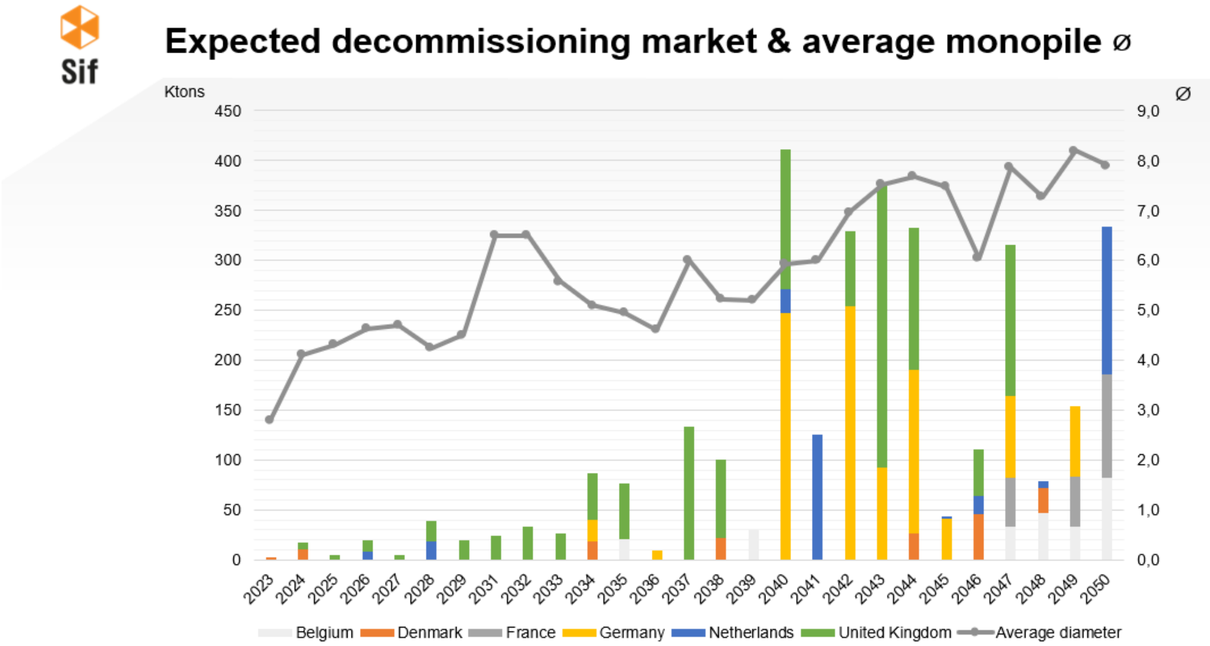

Figure 5: Volume decommissioning projection for monopile foundations (Target markets: Belgium, Denmark, France, Germany, Netherlands and UK), provided by SIF group.