Stagnating development of offshore wind energy in the North Sea

Towards interventions addressing the challenges of offshore wind development in the North Sea

CoSEM Master Thesis

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By

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to obtain the degree of Master of Science
in Complex Systems Engineering and Management
at the Delft University of Technology,
to be defended publicly on June 5, 2025.

Student number: 4727045
Project duration: November 1, 2025 – April 14, 2025
Thesis committee: Ir. M.W. Ludema, TU Delft (first supervisor)
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Summary

Offshore wind energy in the North Sea is poised for unprecedented growth, with European ambitions targeting 166 GW of capacity by 2030 and 500 GW by 2050. Achieving these targets requires high installation rates (on the order of several large turbines per day) and massive infrastructure upscaling. The North Sea is the cornerstone of this expansion, already hosting over 75% of Europe's offshore turbines and expected to supply roughly half of all offshore wind capacity by mid-century. However, recent developments indicate that offshore wind build-out is not keeping pace with ambitions. Despite rapid growth, the industry now faces signs of stagnation due to multifaceted challenges. Macroeconomic shocks have driven up costs, such as the rising Levelized Cost of Energy (LCOE), further widening the gap between offshore wind and other renewable technologies like solar PV and onshore wind. Supply chain bottlenecks are straining the value chain, and developers encounter difficulties in securing investments amid uncertainty. Projects have even been canceled, marking the first downward revisions of 2030 capacity forecasts since targets were introduced. Existing literature has typically focused on individual hurdles—technical, financial, or logistical—without providing a holistic view of the full development ecosystem. As a result, there is a need for a comprehensive analysis that provides structured insight into how challenges interconnect and lead to stagnation. In response, this thesis investigates why offshore wind development in the North Sea is slowing and how this stagnation can be overcome. The central research question is: How have current challenges in North Sea offshore wind development led to stagnating growth, and what are the underlying causes of these challenges? Four sub-questions guide the inquiry, examining: (1) how offshore wind development can be categorized and how it has evolved in the North Sea; (2) what current challenges exist and what the root causes are; (3) how these challenges interact and can lead to stagnation; and (4) how current interventions address these challenges, and which actors are involved. The study adopts an exploratory, qualitative research approach that combines desk research, semi-structured interviews, literature analysis, and systems thinking tools. The historical and systemic character of offshore wind development is captured through S-curve theory, which distinguishes three development phases: innovation, market adaptation, and market stabilization. To structure the analysis, offshore wind development is categorized into three key aspects: (i) the offshore wind value chain, which includes planning, permitting, manufacturing, installation, O&M, and decommissioning (Shafiee et al., 2016); (ii) the financial structure, covering revenue mechanisms, equity-debt configurations, and risk allocation; and (iii) the global supply network, capturing international dependencies on raw materials and components. These aspects are used to track historical trends, identify stagnation points, and build an integrated view of systemic development challenges. Stakeholder interviews and literature confirm that protracted permitting processes, grid infrastructure lags, rising CAPEX, and global supply dependency are converging into system-wide bottlenecks. Two core tools—Current Reality Tree (CRT)and Causal Loop Diagrams (CLD) —were used to identify root causes and model systemic feedback loops that reinforce stagnation. The results show that offshore wind development in the North Sea has indeed transitioned into a slower growth phase, consistent with the upper plateau of the S-curve. In the value chain, industrial processes have matured, yet challenges such as port congestion, turbine installation bottlenecks, and skilled labor shortages persist, resulting in delays and increased costs. The financial structure of projects has shifted from feed-in tariffs to competitive auctions such as Contracts for Difference (CfDs). While this shift increased cost-efficiency, it also introduced greater exposure to market volatility, particularly in an era of inflation and high interest rates. Meanwhile, the global supply network—responsible for components like turbines, cables, and rare earth metals—has become more vulnerable. A limited pool of global suppliers means that disruptions (e.g., in Asia or the US) ripple into North Sea projects, affecting costs and delivery timelines. The CRT analysis identifies several root causes: first, a fragmented governance system, where each North Sea country uses differing permitting

regimes, creating delays and uncertainty. Second, a shift from policy-driven to market-based support structures, which, while beneficial for competition, undermines project bankability in volatile markets. Third, uncoordinated value chain scaling, where infrastructure, logistics capacity, and workforce development are not growing in sync with offshore wind targets, causing systemic strain. These root causes underlie and perpetuate visible surface-level issues. The CLD visualizes the interconnected feedback loops that sustain stagnation. For instance, high capital costs and limited financial incentives delay projects, eroding developer confidence and leading to underinvestment in ports, vessels, and grid infrastructure, which in turn raises costs—a vicious cycle. Similarly, developers sourcing cheaper international components to cut costs can reduce local industrial development, thereby increasing dependency and long-term vulnerability (Špicar, 2014). The CLD highlights how reinforcing loops initially fueled growth but are now countered by balancing loops tied to resource and governance limitations, marking a systemic plateau in deployment momentum. In the discussion and conclusion, the thesis underscores that North Sea offshore wind has reached a strategic inflection point. Current interventions—such as streamlined permitting procedures, auction design reforms, and supply chain incentives—have helped but remain fragmented, insufficient, and reactive. Many initiatives focus on symptoms rather than structural bottlenecks. For example, grid delays are often tackled at the national level, without cross-border infrastructure alignment; auction schemes are revised to improve pricing but do not address investor exposure to inflation and long-term uncertainty. To overcome stagnation, the thesis proposes a suite of systemic interventions directly tied to the CRT's identified root causes. These include: (1) harmonizing permitting and environmental regulations across the North Sea to reduce bureaucratic delays; (2) accelerating investment in grid expansion and port upgrades to ensure that infrastructure matches deployment goals; (3) introducing stabilized revenue frameworks such as inflation-indexed CfDs to restore investor confidence and (4) strengthening domestic supply chains through local manufacturing, workforce training, and innovation support, to reduce global dependency and boost resilience. Additionally, the thesis calls for enhanced EU and regional coordination—a meta-level intervention to align timelines, funding, and infrastructure across borders. Together, these actions aim to transform current self-reinforcing stagnation loops into growth-enabling dynamics. By aligning permitting, financing, infrastructure, and supply capacity, policymakers and industry actors can shift toward a virtuous cycle of accelerated deployment. In conclusion, the thesis asserts that meeting Europe's offshore wind ambitions will require coordinated, cross-sectoral action to remove structural barriers and build systemic resilience. Only then can the North Sea fulfill its role as the backbone of Europe's green energy future.

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1. Introduction

This chapter introduces the context, problem statement, and outline of the thesis. The chapter covers the growing demand for offshore wind energy, the North Sea's pivotal role in achieving ambitious capacity targets, and the need for research in the challenges that may hinder these targets.

1.1. North Sea Powerhouse

Geopolitical developments are forcing Europe to become independent of Russian gas, which three years ago represented approximately 1,500 TWh of Europe's energy balance. In addition, decarbonization and electrification will greatly increase electricity requirements in the years to come. Offshore wind is expected to be an important part of the solution to cover the potential lack of energy. Hence, current developments are accelerating political measures to achieve the green transition and have led to increased country ambitions. The ambitions for offshore wind in Europe (EU&UK) are quite extensive. Figure 1 gives an overview of these ambitions and the needed upscaling. To reach the goal of 166GW installed by 2030, 22GW of capacity needs to be installed each year, more than half of the total current offshore installed capacity. This average annual growth needs to be sustained until 2040, when it needs to be 11GW per year towards 2050. In 2050, the goal is to have 500GW installed capacity, almost 15 times that of the current 34GW installed. In 2023, the largest offshore wind park under construction was Sofia near the coast of the UK, with a capacity of 1.4 GW (100 times 14MW turbines). This means that if the target of 500GW is to be achieved in 2050, roughly 332 Sofias need to be developed with a total of 33 thousand 14MW turbines (WFO, 2024). This translates into an installation rate of 3.5 14MW turbines per day beginning now, not considering that offshore wind turbines are decommissioned after roughly 25 years.

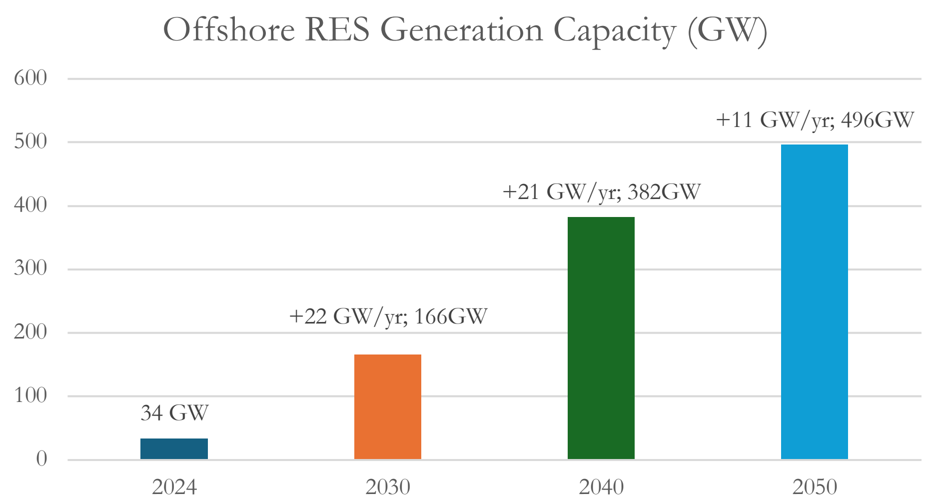
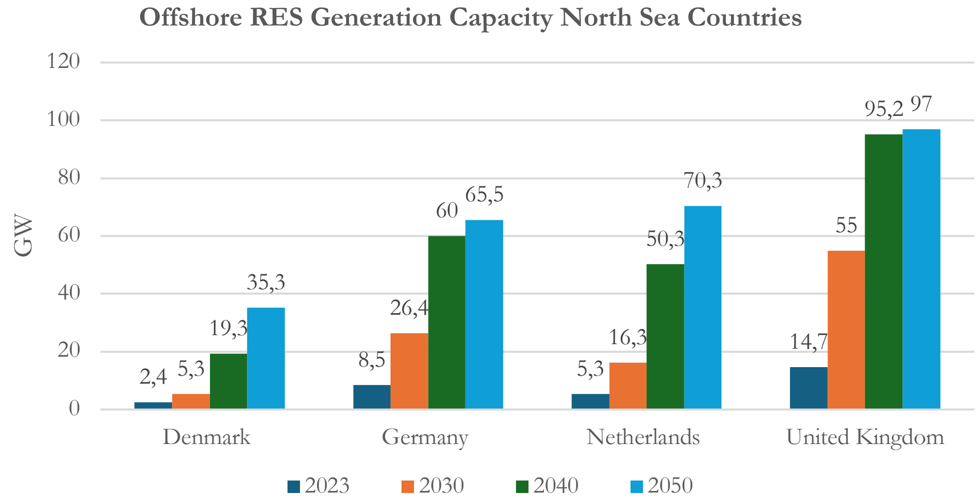


Figure 1: Adapted from ENTSO-E. (2024). TYNDP 2024 Sea-Basin ONDP Report: TEN-E Offshore Priority Corridor: Northern Seas Offshore Grids. Retrieved from https://www.entsoe.eu/outlooks/offshore-hub/tyndp-ondp/

With lots of shallow waters and high wind speeds, the Northern Sea has huge potential for offshore wind and can fulfill a large amount of the European Offshore wind capacity targets. Today, more than 75% of Europe's offshore wind turbines are in the North Sea. New players such as Ireland, Spain, Portugal, Italy, Greece, Poland, and the Baltic States are now entering the offshore wind market. However, the North Sea will still host 80% of all installations over the next five years and will still make up 50% of Europe's total offshore wind capacity by 2050 (WindEurope, 2022). Figure 2 shows the offshore wind development of Denmark, Germany, the Netherlands, and the United Kingdom, the four countries with the most planned capacity by 2050 in the North Sea. The pace of offshore wind development will be significant in these countries, especially until 2040.



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1.2 Problem statement

For this ambition, significant acceleration is needed in the installation and infrastructure of offshore wind energy. While renewable energy sources (RES) have been widely deployed in recent years in Europe, the fast outlay of offshore wind energy in the North Sea shows obstacles. The amount of wind energy in the North Sea has expanded rapidly, but the value chain is showing signs of stagnation due to various challenges. Macroeconomic events led to a sharp rise in the levelized cost of energy (LCOE) of offshore wind energy, widening the gap with renewable energy counterparts such as solar PV and onshore wind even more (Weiss et al., 2024). Suppliers are challenged with continuous bottlenecks and difficulties in signing off on investments, given some continued uncertainties on the pace of buildout. The industry faces significant challenges along the steps of the value chain, a complex network involving government, manufacturers, logistics providers, developers, and service companies (Shafiee, 2015). The challenges cause the development of offshore wind to stagnate in the North Sea and hinder its goals in the future energy mix of Europe. Figure 3 shows the cumulative installed offshore wind capacity of Denmark, Germany, The Netherlands, and the United Kingdom. Whilst offshore wind in the North Sea has rapidly expanded in the past years, it is not certain that that pace of upscaling the value chain can be realized to reach the targets for 2030 and after. Some wind projects are being canceled in the North Sea, lowering the expected installed capacity by 2030 for the first time since the goals were set (Hurtado, 2023).

Existing literature tends to focus on critical components of offshore wind development, but the current multi-faceted challenges require a more comprehensively overview of the effects. These studies focus on technical aspects or logistical hurdles without offering a holistic view of the entire development of wind energy and its value chain (Shields, 2021; Eckardt & Stenzel, 2023). A comprehensive analysis that provides a structured overview of the causes of the challenges, how they interconnect, and how they contribute to stagnation is needed to be able to develop robust interventions for the offshore wind industry's sustainable development in the North Sea.

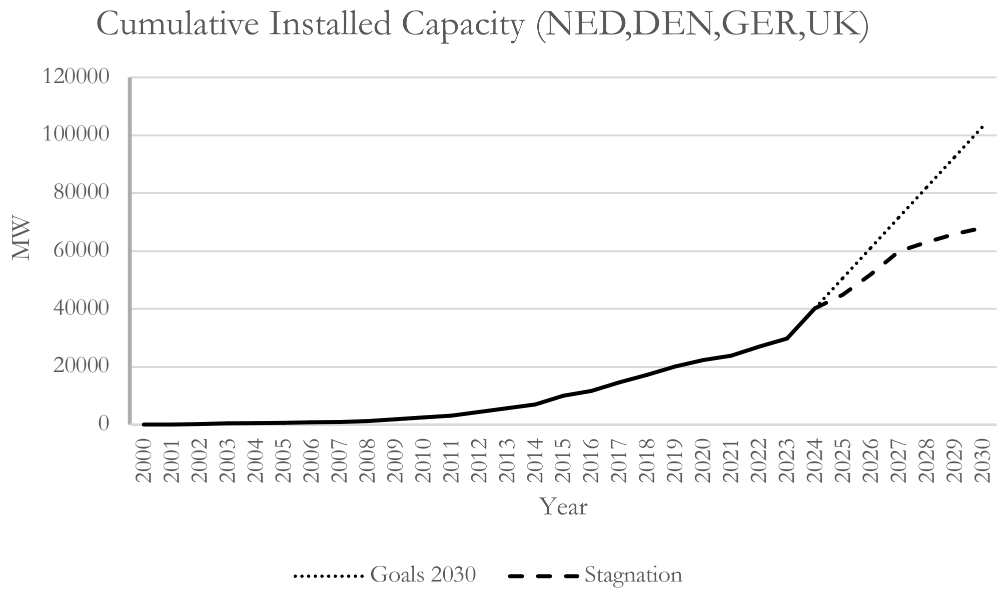
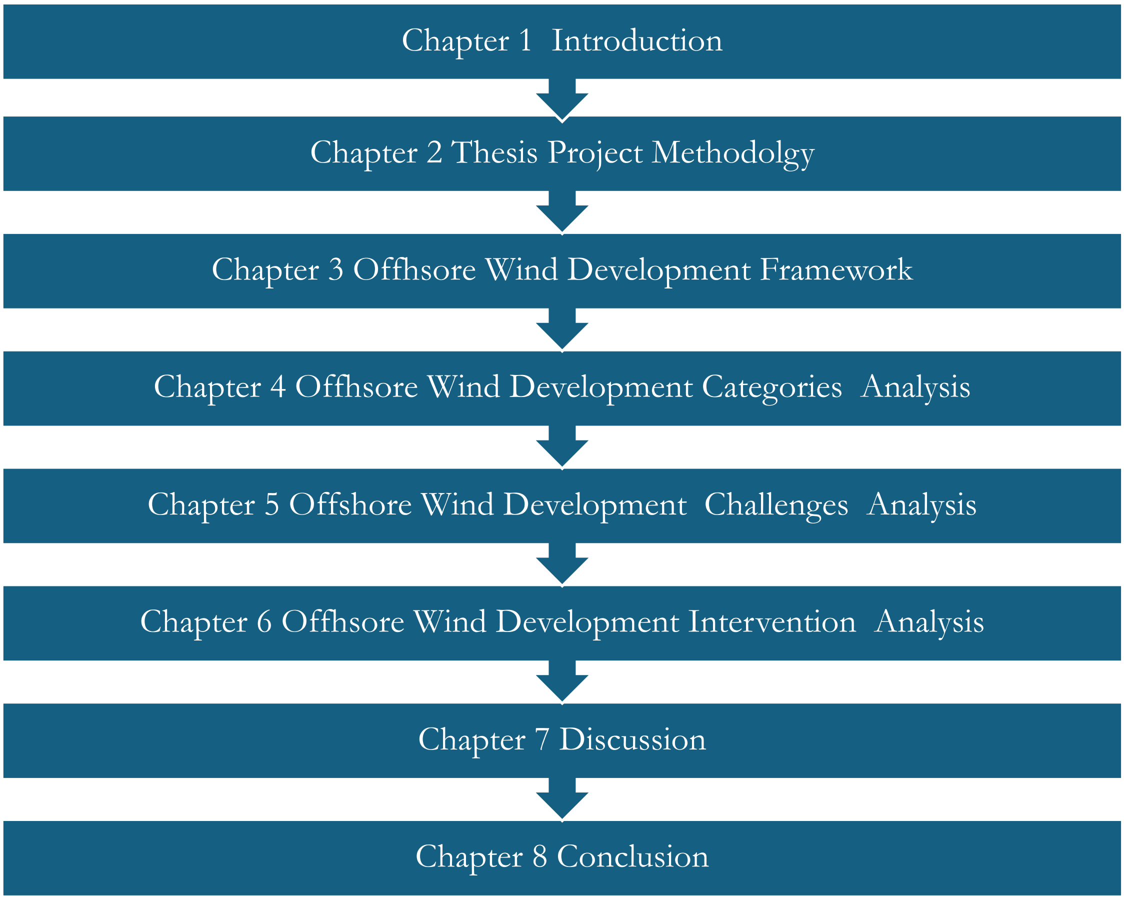


Figure 3: Cumulative installed capacity of offshore wind and outlook

1.3. Outline of the report

The outline of the paper is as follows. In Chapter 2 the thesis project methodology will be covered. This chapter will cover the research questions, the research approach and methods and tools used for answering the questions. The scope, deliverables and relevance of the research will be described at the end of the chapter. Hereafter will Chapter 3 provide a framework for understanding offshore wind development by dividing its growth in the history into three phases and categorizing development into three aspects. Chapter 4 will use this framework to analyze the offshore wind development in the North Sea over time to its current form. Chapter 5 covers the challenges using the categories of offshore wind development and how they can lead to stagnation. The chapter will further explore the underlying causes of these challenges using the historical analysis of the previous by means of a Current Reality Tree. A Causal Loop Diagram will be made for analyzing the interconnectedness of the challenges and their effect on the stagnation of development. In Chapter 6, intervention will be covered for these challenges and evaluated and where there might remain a gap for self-proposed interventions. Chapter 7 will have a discu.sion on the found results and will evaluate these results against the research questions of the thesis. Chapter 8 the thesis will be concluded, and recommendations will be given. A conceptual overview can be seen on the following page


Chapter 1 Introduction
Chapter 2 Thesis Project Methodolgy
Chapter 3 Offhsore Wind Development Framework
Chapter 4 Offhsore Wind Development Categories Analysis
Chapter 5 Offshore Wind Development Challenges Analysis
Chapter 6 Offhsore Wind Development Intervention Analysis
Chapter 7 Discussion
Chapter 8 Conclusion

2. Thesis Project Methodology

This section outlines the research questions and methodology guiding this research, which aims to understand the stagnation of offshore wind development in the North Sea. It further will describe the approach of the research, the methods use tools used, the scope of the research and its deliverables. At the end its relevance towards different field of society is given.

2.1. Research Questions

The main research question is as follows:

How do challenges in offshore wind development in the North Sea lead to stagnating growth, and what interventions can address these challenges?

To address this question, the study is guided by the following sub-questions:

1. How can offshore wind development be categorized and how did these offshore wind development in the North Sea change over time?
2. What are the current challenges in offshore wind development in the North Sea and what are the underlying causes of these challenges?
3. How do these challenges affect the offshore wind development in the North Sea, and how can they lead to stagnation?
4. How do current interventions address these challenges, and which actors are responsible?

2.2. Research Approach

The study adopts an exploratory, qualitative approach that progresses through four interlinked sub-questions. Exploratory research is well-suited for investigating complex and evolving systems such as offshore wind development and create a better understanding of a subject. Each stage builds on the previous one, creating a cumulative understanding of offshore wind development, its current challenges, and how interventions respond to them. The research uses a combination of desk research, interviews, literature review, and systems thinking tools to develop insights that are both historically grounded and forward-looking. Rather than testing a fixed hypothesis, the study aims to uncover and structure the challenges that have emerged in this sector, understand how they relate to one another, and evaluate how current interventions attempt to address them. The North Sea serves as the focal point for this investigation, given its central role in Europe's offshore wind ambitions. The study spans from the early stages of offshore wind development up to current efforts aiming for rapid expansion by 2030. This approach allows for a systemic analysis that considers both historical developments and present-day dynamics.

2.3. Research Methods

To answer the first sub-question— *How can offshore wind development be categorized and how did offshore wind development in the North Sea change over time?* —the study begins by categorizing the offshore wind sector into distinct yet interconnected aspects. These include the evolution of the value chain, its financial structure, and global supply network. Through extensive desk research and application of S-curve theory, the development of these aspects is traced over time to understand how the sector matured across different phases. This categorization will serve as theoretical framework for the rest of the research. The S-curve provides a dynamic lens to capture this evolution, highlighting periods of acceleration, stagnation, and transition. This historical perspective not only contextualizes the current state of offshore wind but also sets the stage for identifying why certain issues have emerged or persisted.

Building on the categorization framework, the second sub-question asks: *What are the current challenges in offshore win development in the North Sea and what are the underlying causes of these challenges?* To address this, the study integrates findings from academic articles and industry reports with insights gathered through semi-structured interviews with industry stakeholders. See appendix A and B for the process of how the interviews and literature where conducted. These sources help surface a range of ongoing challenges—ranging from permitting delays and supply chain bottlenecks to policy fragmentation and technological uncertainties. However, rather than stopping at the identification of surface-level issues, the study applies the Current Reality Tree (CRT) to uncover the root causes behind these challenges. As the previous section investigated the historical development of offshore wind in the North Sea, this section will use that information to find the underlying causes of stagnation. The CRT tool organizes problems into a logical flow, revealing how systemic issues contribute to stagnation. This step creates a deeper understanding of the nature of these challenges, revealing not only what is going wrong, but also why. The theory behind the CRT will be discussed in the next subsection.

The third sub-question— *How do these challenges affect the offshore wind development in the North Sea, and how can they lead to stagnation?* —moves from identifying causes to understanding how they interact. As the different aspects of offshore wind development have some overlap the challenges in these aspects do so as well. Recognizing that many of the challenges are interrelated, this phase of the research applies systems thinking to map their interconnectedness. Using the Causal Loop Diagram (CLD), the study visualizes how different challenges reinforce or amplify one another through feedback loops. For instance, delays in grid connection may affect investor confidence, which in turn may lead to underinvestment and further slowdowns in project deployment. The CLD is developed through a combination of insights from earlier stages, literature analysis, and interview feedback, and is modeled using Vensim software. This model provides a systemic view of how stagnation may emerge and persist, offering a powerful tool to explore leverage points within the system. The theory behind CLD will be discussed

Finally, the fourth sub-question— *how do current interventions address these challenges, and which actors are responsible?* —examines how existing policies, strategies, and initiatives respond to the challenges identified. Desk research is conducted to analyze European policies, and these are compared to the perspectives of interviewees. These interventions are then compared to the systemic challenges revealed in the CRT and CLD to determine their effectiveness and relevance. This phase identifies where efforts are aligned with root causes and where gaps remain. The evaluation highlights both strengths and shortcomings of current interventions, offering guidance on where self-proposed interventions might address these challenges and which actors should then be made responsible.

2.4. Research Tools

Current Reality Tree Tool

The Current Reality Tree (CRT**)** method from Goldratt's Theory of Constraints provides a complementary tool for identifying root causes of stagnation in offshore wind development. By mapping the cause-and-effect relationships between symptoms and underlying root causes, the CRT method reveals systemic core problems that hinder development (Dettmer, 1997; Dettmer, 1998; Scheinkopf, 1999). A CRT is not only a static tool but also offers a dynamic approach to tracking symptoms over time. By establishing a clear starting position, it outlines how various problems accumulate and interact as the system evolves. This dynamic perspective helps visualize how some initial undesirable effects may evolve into broader system stagnation.

Causal Diagram Tool

A causal loop diagram (CLD) is a critical tool within system dynamics that can effectively analyze the complex interplay of factors impacting a system. Causal loop diagrams serve as a framework to visualize and communicate the complex, interconnected dynamics of systems. They function similarly to sentences, constructed by linking critical variables and defining the causal relationships among them. By combining multiple loops, a coherent narrative emerges, clarifying the structure and behavior underlying specific problems or issues (Tip, 2011).

Drawing insights from the methodologies presented in Sterman's Business Dynamics (Sterman, 2000) and Špicar's work on system archetypes (Špicar, 2014), this section highlights the role of CLDs in mapping the intricate web of challenges in the offshore wind industry. System dynamics, as defined by Sterman (2000), is a powerful approach that emphasizes the interconnections between variables, reinforcing and balancing feedback loops, and the long-term behavior of complex systems. In the context of offshore wind development, the use of CLDs helps to visualize feedback mechanisms that shape industry development. Based on a thorough review of Haraldsson's work (2004) on systems thinking and causal loop diagrams, this analysis incorporates foundational principles to enrich the understanding of offshore wind stagnation dynamics. According to Haraldsson (2004), Causal Loop Diagrams serve as powerful tools for explicitly mapping and visualizing the dynamic interrelationships within complex systems, facilitating holistic rather than linear problem-solving approaches. CLDs thus allow stakeholders to clearly discern how various system components influence each other through feedback loops and causal links.

System dynamics is particularly suited to offshore wind development due to its inherent dynamic complexity. As Sterman (2000) highlights, dynamic complexity arises when systems are characterized by feedback loops, time delays, and non-linear behavior. Offshore wind development reflects this complexity, with numerous interdependencies across technical, economic, and policy dimensions. For example, investments in offshore wind capacity may boost growth, but delays in port expansion, transmission grid integration, or environmental permitting may counteract this growth. Recognizing these complex interactions is essential to identifying effective strategies.

A causal loop diagram typically includes the following elements:

1. Variables: These represent factors affecting offshore wind development, such as investment, supply chain capacity, grid integration, and policy support.
2. Arrows (causal links): Indicate the direction of influence between variables.
3. Positive (+) and Negative (-) Signs: Show reinforcing (positive feedback) or balancing (negative feedback) effects.

Drawing on system archetypes described by Špicar (2014), common patterns such as "Limits to Growth" and "Growth and Underinvestment" are particularly relevant to offshore wind development.

Example 1: Limits to Growth Archetype

1. Reinforcing Loop: Initial investment in offshore wind leads to greater capacity expansion, improved technology, and increased investment attractiveness, further accelerating growth.
2. Balancing Loop: As capacity increases, grid congestion, environmental concerns, and supply chain constraints act as limiting factors, slowing the growth rate.

Example 2: Growth and Underinvestment Archetype

1. Reinforcing Loop: Increased investment drives turbine deployment and boosts industry growth.
2. Balancing Loop: If investments in infrastructure (e.g., port facilities or grid upgrades) lag, these constraints suppress the growth potential.

3. Time Delays: A critical challenge arises due to the slow response time for infrastructure expansion. Delays between identifying the need for capacity expansion and its completion often result in bottlenecks, ultimately constraining offshore wind development (Špicar, 2014).

Causal Loop Diagrams (CLDs) provide a valuable tool for understanding and analyzing the dynamic behavior that contributes to this stagnation. According to Haraldsson (2004), CLDs are particularly effective for illustrating non-linear feedback mechanisms, which are a key factor in the development pattern described by the S-curve. Non-linear behaviors often result in exponential growth, rapid decline, or the characteristic S-curve trajectory observed in complex systems. By mapping reinforcing and balancing loops, CLDs can reveal how various interdependent factors influence each other over time, ultimately contributing to stagnating growth patterns. As these loops drive accelerated growth, they align with the upward trajectory of the S-curve. Conversely, balancing loops emerge when limiting factors, such as supply chain bottlenecks, policy delays, and resource constraints, begin to slow growth. This balancing feedback create resistance to continued expansion, aligning with the stagnation phase seen in the S-curve model. As Haraldsson (2004) emphasizes, delays are a key factor in CLDs that contribute to non-linear behavior. For instance, workforce shortages may initially have minimal impact on growth but become increasingly influential as project volumes increase, eventually becoming a dominant balancing loop that limits further progress. Similarly, regulatory changes may create a time-lagged feedback effect, where actions intended to accelerate development inadvertently create stagnation in the long term. This delayed feedback dynamic is a typical feature of systems modeled using CLDs. Integrating CLDs into offshore wind research offers a powerful method to capture the complexity of the sector's development. It not only complements the insights derived from the S-curve but also enhances the understanding of non-linear behaviors that drive stagnation, providing a comprehensive view of the factors influencing offshore wind deployment. By applying a causal loop diagram to offshore wind development, the interplay of reinforcing and balancing feedback loops becomes clearer. This enables better identification of leverage points — areas where interventions can mitigate limiting factors. The use of a CLD grounded in system dynamics theory provides an effective framework for analyzing the multifaceted challenges of offshore wind development. The combination of CLDs and CRT offers a comprehensive analytical framework, ensuring that both systemic complexity and underlying constraints are addressed in offshore wind development strategies.

2.5. Scope and Deliverables

The scope of this research is geographically focused on the North Sea, specifically the offshore wind development in Denmark, Germany, the Netherlands, and the United Kingdom. These countries are key players in the European offshore wind landscape and will be central to achieving the EU's 2030 renewable energy goals. The study is forward-looking, aiming to address challenges relevant to the near-term horizon, up to 2030. However, its findings are grounded in historical development to understand the roots of current stagnation.The research delivers several interrelated outputs: a categorization and historical mapping of offshore wind development in the North Sea; a structured analysis of current challenges and their systemic causes using the Current Reality Tree; a systems map of stagnation using a Causal Loop Diagram; and a critical assessment of existing interventions and remaining gaps. Together, these deliverables form an analytical framework that can support future policymaking, strategy development, and academic inquiry into offshore wind development in the North Sea and beyond.

2.6. Research Relevance

This thesis aligns with the CoSEM program and the Energy track by addressing the multi-faceted challenges of offshore wind development in the North Sea through a holistic, stakeholder-informed analysis of the entire value chain. It bridges gaps in existing research by integrating an up-to-date analysis of the different aspects of stagnation and uses of different stakeholder perspectives by using a system thinking approach for making the causal loop diagram. By considering socio-technical complexities and offering insights for systemic interventions, the thesis embodies CoSEM's mission to design innovative, interdisciplinary solutions for the energy sector's pressing challenges. In a broader scientific context, this research fills a notable gap by providing an integrated and current analysis of offshore wind energy development. Previous studies have often focused on individual technical or logistical aspects, whereas this thesis offers a comprehensive view of the offshore wind value chain—from planning and design through installation, operation, and maintenance—highlighting the critical bottlenecks within these processes. The integral approach generates new insights beneficial to both scientific research and practical application, particularly by identifying systemic constraints and their underlying causes through systems thinking methodologies, such as causal loop diagrams. Furthermore, offshore wind energy is essential for achieving climate targets and establishing a sustainable energy supply. Therefore, insights gained from this research contribute directly to the energy transition discourse and enrich scientific debates on scaling sustainable energy systems within a complex global context.

3. Offshore Wind Framework

This section provides the theoretical foundation necessary for the framework that will be used for understanding the complexities of offshore wind development. The section covers the S-curve model to illustrate offshore wind's growth trajectory over time during the different phases of the curve, explores these historical phases of offshore wind development, and examines the value chain activities and its financial aspects. Additionally, global supply network with the role of key players, such as China, are discussed. Together, these insights provide a comprehensive backdrop for understanding the challenges and within the offshore wind sector.

3.1. S-Curve Model Theory

Different developments have shaped the growth of offshore wind energy in the North Sea. To analyze this development structurally. Offshore wind development is divided into different growth phases in its history by using S-Curve Model Theory. The development of offshore wind energy in the North Sea can be analyzed using the S-curve of technological diffusion, as introduced by Rogers (1962) and further developed by Ortt and Schoormans (2004). This model suggests that technological innovation does not penetrate the market in a single smooth motion but follows distinct phases of development and adoption. Ortt and Schoormans (2004) demonstrate that the classical S-curve is often preceded by two early phases: the innovation phase and the market adaptation phase, which precede the market stabilization phase. This extended model is relevant for offshore wind energy, as this sector has undergone a long and complex development process, involving technological, economic, and policy-related factors (Dedecca et al., 2016). Figure 4 shows the S-curve with the 3 different phases of wind energy growth. A key argument for this classification is the prolonged experimental period before the commercial application of offshore wind technology as shown in Figure 3 by the relative few installations in the early years. The first initiatives were small-scale demonstration projects characterized by significant technical

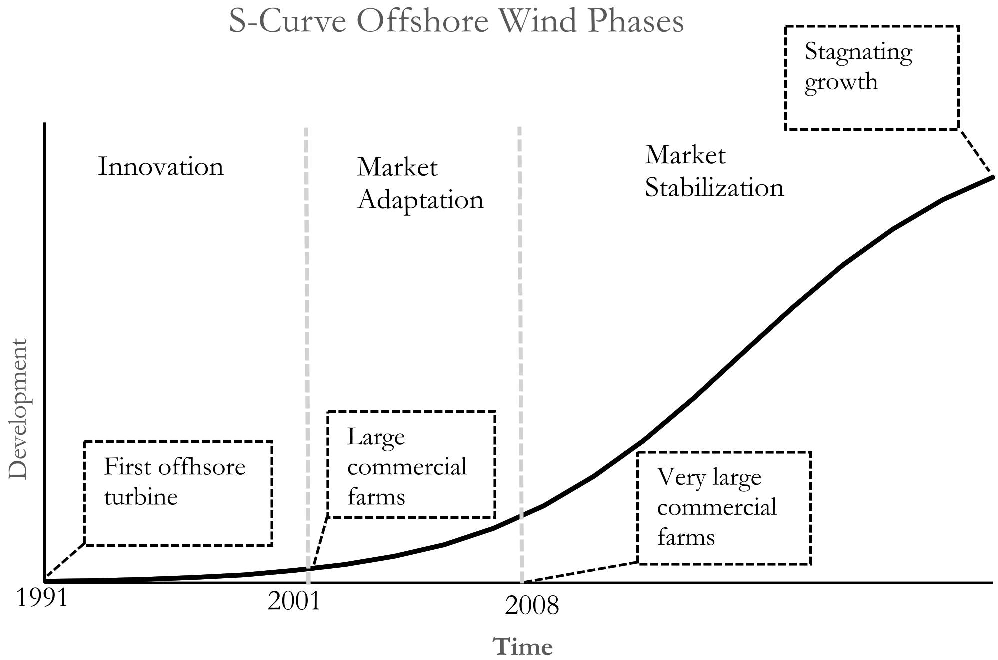


Figure 4: S-Curve Offshore Wind Adapted from Dedecca, J. G., Hakvoort, R. A., & Ortt, J. R. (2016). Market strategies for offshore wind in Europe: A development and diffusion perspective. Renewable and Sustainable Energy Reviews, 66, 286-296.

uncertainties (Barthelmie, 1998; Wieczorek et al., 2013). This was followed by a phase in which different technological concepts and market solutions competed with one another, characteristic of the market adaptation phase (Rodrigues et al., 2015). Only in a later stage did the market stabilize, with the standardization of technologies and the emergence of a limited number of dominant market players (Markard & Petersen, 2009). Moreover, offshore wind energy development is distinct due to its strong dependence on policy interventions. Unlike many other energy technologies, the scaling up of offshore wind was heavily influenced by government support in the form of subsidies, regulations, and investment mechanisms (Kemp & Volpi, 2008; European Commission, 2011). This structural support helped bridge the gap from the experimental phase to a mature industry. Considering these arguments, it becomes clear why the classification into innovation, market adaptation, and market stabilization is an appropriate framework for analyzing the development of offshore wind energy in the North Sea over time. To further investigate how offshore wind development evolved, this study examines how the offshore wind development can be categorized into different aspects.

3.2. Offshore Wind Development Categories

Offshore wind development in the North Sea has progressed through distinct S-curve phases of innovation, market adaptation, and market stabilization. Understanding why growth stagnates requires a holistic look at the system. This section will provide the argumentation of the categorization of offshore wind into different aspects. Three interdependent aspects are especially critical in the theoretical framework for analyzing this development: (1) the offshore wind value chain, (2) the financial structure of projects, and (3) the global supply network. Each of these dimensions influences the trajectory of offshore wind through its phases – and each can become a source of bottlenecks or slow-down if not managed properly. Below each aspect in turn is examined, with academic evidence underscoring their importance with a focus on the North Sea context.

3.2.1. Offshore Wind Value Chain

The offshore wind value chain encompasses the full life cycle of a wind farm – from site planning and permitting, through turbine and foundation manufacturing, installation at sea, grid connection, operation & maintenance (O&M), and eventually decommissioning The value chain provides a structured way to analyze key activities required to develop and maintain offshore wind farms and allows for a more detailed understanding of shifts in technological advancements, policy changes, and economic feasibility across different periods of development. The offshore wind value chain can be divided into five key phases, each contributing to the overall development and financial feasibility of a wind farm (Shafiee et al., 2016). By analyzing how these phases evolved in each stage of the S-curve, we can understand how offshore wind development in the North Sea changed over time:

1. **Pre-development and Consenting:** This phase include project management, feasibility studies, legal authorizations, and engineering activities. It generally occurs about five years before the installation phase and involves extensive planning and regulatory approvals to ensure technical and economic feasibility.
2. **Manufacturing:** This phase focuses on procuring wind turbines, foundations, power transmission systems, and monitoring systems. It represents a major component of capital expenditure (CAPEX) and determines the technological choices that influence long-term operational costs.
3. **Installation and Commissioning:** The I&C phase encompasses port-related activities, installation of components such as turbines and foundations, commissioning of electrical

systems, and insurance costs. This stage is critical as it involves logistical challenges, requiring specialized vessels and infrastructure.

4. **Operation and Maintenance:** O&M covers routine operational expenses, maintenance strategies (corrective and preventive), transmission charges, and insurance. Given the offshore environment, maintenance costs are significantly higher than for onshore wind farms due to access difficulties and harsh weather conditions.
5. **Decommissioning and Disposal:** This final phase involves dismantling offshore wind farms at the end of their operational lifespan, waste management, site clearance, and post-decommissioning monitoring. The costs associated with this phase depend on regulatory requirements and the level of material recyclability.

This chain involves a wide range of specialized actors (developers, engineering firms, turbine manufacturers, installation contractors, vessel operators, etc.), making offshore projects highly complex. Scholars note that the offshore wind value chain has multiple interlinked phases, and despite appearing sequential, each phase can influence the others (Dedecca et al., 2016). For example, design choices affect maintenance needs later, illustrating how tightly coupled the stages are. Accounting for the entire value chain is critical to understanding development and potential stagnation. Offshore wind is not just "onshore wind at sea" – deploying turbines offshore required developing new competencies and industries. Jacobsson & Karltorp (2013) emphasize that expanding offshore wind "is not a simple diversification by the onshore wind turbine industry to a new segment," but rather demands overcoming numerous technological and organizational obstacles. Such evolution shows why analyzing the value chain is vital: any weak link or lagging segment can lead to stagnation. Research has identified "project complexity" as a fundamental challenge – offshore wind farms involve more numerous and integrated components phases than onshore projects, requiring integration of many disciplines (mechanical, electrical, marine, etc.) (Dedecca et al., 2016). This complexity heightens the risk that challenges in one part (for example, a shortage of cable-lay vessels or delays in grid hookup) will slow the entire development. Overall, academic and industry literature strongly supports including the full value chain in any analysis of offshore wind development, as it captures the multi-stage, multi-actor nature of the sector and helps explain why scaling up can stagnate without coordinated growth across all links of the chain

3.2.2. Financial Structure of Offshore Wind Projects

The financial structure of offshore wind projects refers to how these capital-intensive projects are funded and financed – including the mix of equity investors, debt lenders, public subsidies or support mechanisms, and risk allocation among stakeholders. Offshore wind in the North Sea involves enormous up-front investments (often on the order of billions of euros per project). Simply put, if financing cannot be secured on acceptable terms, projects will not move forward – leading to stagnation even if the technology itself is ready. Academic studies underline that financing is "critical to offshore wind's success" and that failing to address key financial challenges could put deployment targets at risk (Hansen et al., 2024). Including the financial dimension in an offshore wind development analysis is therefore essential. As one recent study on offshore wind finance put it, capital is available globally but deploying it for offshore wind faces "grand challenges" that must be overcome to meet growth targets (Hansen et al., 2024). By integrating this aspect into the theoretical framework, we capture how the pace of offshore wind diffusion is tightly coupled to investment appetites, cost figures, and policy support – factors that can accelerate growth or lead to stagnation.

3.2.3. Global Supply Network

Offshore wind's rise in the North Sea has always been part of a global supply network. The industry's supply chain is geographically dispersed: wind turbine components, substations, cables, installation vessels, and even expertise often come from an international pool of suppliers and contractors. An important insight from recent research is that renewable energy sectors like offshore wind are increasingly globalized, with "lead firms appropriating value on a global scale" through complex supplier networks (Van der Loos et al., 2022). In practice, this means a developer (or lead firm) building a North Sea wind farm might source turbine blades from one country, foundations from another, electrical components globally, and specialized installation services from a handful of firms worldwide. Van der Loos et al. (2022), examining offshore wind projects in Europe, found that indeed developers mostly draw on the global market for key segments of the supply chain, except when specific policies (like local content rules) incentivize using local suppliers. This global interdependence brings both opportunities (access to the best technology and scale economies) and vulnerabilities (exposure to international bottlenecks and market dynamics). Understanding the global supply network is critical to explaining the rapid growth and stagnation in offshore wind deployment. Including the global supply network in the analytical framework highlights such systemic interdependencies across regions and sectors. For instance, a surge in offshore wind development in Asia or the US can tighten the global market for certain components or vessels, leading to delays or higher costs in Europe (and vice versa). Likewise, trade policies or international commodity price swings (steel, copper, rare earth magnets for turbines) feed into project economics. The literature points out that national strategies must therefore consider global dynamics. Van der Loos et al. (2022), show governments try to balance global efficiencies with local value creation (e.g. through local content rules). By citing this aspect, it is acknowledged that offshore wind is a globally interconnected industry, and its progress in any single region (like the North Sea) cannot be fully understood in isolation from global supply-side factors.

Offshore wind development in the North Sea has progressed through distinct S-curve phases of innovation, market adaptation, and market stabilization (Ortt & Schoormans, 2004; Rogers, 1962). Understanding why growth occasionally stalls require a holistic system view. Three interdependent aspects are particularly critical in a theoretical framework for analyzing this development: (1) the offshore wind value chain, (2) the financial structure of projects, and (3) the global supply network. Each of the three aspects above – value chain, financial structure, and global supply network – is individually crucial, but it is their interaction that truly defines the trajectory of offshore wind development. Stagnation or slowdowns occur due to a combination of issues across these dimensions. For example, a spike in global steel prices (supply network issue) can raise turbine costs, which then undermines project financial viability (finance issue) and forces developers to delay projects, causing a gap in the construction pipeline that idles parts of the value chain (value-chain issue). Because of such feedback, scholars stress the need for a systemic approach. Jacobsson & Karltorp (2013) identify multiple blockers in the European offshore wind innovation system and conclude that addressing them "requires coordination of interventions across policy domains and national boundaries". In summary, incorporating the offshore wind value chain, the financial structure, and the global supply network into the analysis provides a robust theoretical framework for a North Sea offshore wind thesis. These aspects are supported by academic literature as key determinants of how and why the industry has evolved through its S-curve phases. They can help explain both periods of rapid growth and periods of stagnation (when challenges in one or more of these dimensions constrained growth.

4. Offshore Wind Development Categories Analysis

This section will analyze offshore wind development in the North Sea with the use of the theoretical framework developed and using desk research for data collection. This section explores the development of offshore wind energy by first providing a background on offshore wind energy, outlining its benefits and key technological developments. Following this, the offshore wind value chain in the North Sea is examined and will be analyzing the current aspect of the value chain activities. A detailed financial assessment follows, highlighting capital and operational expenditures, financing mechanisms, risk management strategies, and cost reduction trends. Hereafter, a global supply network perspective is introduced, addressing the growing importance of international manufacturing and resource dependencies in offshore wind development. Finally, the section will describe the change of Offshore wind Development in the North Sea using the S-Curve and with a focus on four relevant wind energy producing countries (Denmark, United Kingdom, Germany and The Netherlands). The found information from the different aspects how the offshore wind development changed over time. By presenting a structured analysis of offshore wind energy development, this chapter provides a foundation for understanding the complexities of the industry. It sets the stage for subsequent discussions on challenges within the offshore wind value chain and the critical factors that influence its stagnation.

4.1. Background Offshore Wind Energy

Wind energy has a long-standing history, initially harnessed for practical tasks like water pumping on farms. With the evolution of renewable energy technologies, wind turbines have emerged as an essential source of electric power generation (Wee, 2012). To take advantage of abundant wind resources and reduce land-use impacts, many wind turbines are now located offshore. Offshore wind energy plays a crucial role in the transition to a sustainable energy system, offering a renewable and environmentally friendly solution to meet increasing energy demands and mitigate climate change (Hrouga & Bostel, 2021). Among various renewable energy sources, wind energy stands out for its efficiency and sustainability. It relies on natural, renewable wind resources and does not produce greenhouse gases, toxic emissions, or radioactive waste. This makes it a key contributor to reducing the greenhouse effect and addressing climate change. Additionally, wind energy production increases during winter months when wind speeds are stronger and more consistent, enhancing its reliability (Hrouga & Bostel, 2021). Figure 5 shows the different components of an offshore wind turbine (OWT) and the types of foundations they employ (Jiang, 2021). These turbines are organized into marine wind farms to streamline transportation, energy management, installation, and maintenance processes. Offshore wind farms (OWFs) are strategically developed in areas with strong, stable wind conditions, enabling them to generate more electricity compared to onshore installations (Soares-Ramos et al., 2020). The expansive offshore environment allows for larger wind farms and the deployment of larger turbines, which benefit from reduced turbulence and steadier wind speeds. This results in higher energy outputs and greater efficiency. Offshore locations also help mitigate the visual and acoustic impacts often associated with onshore wind farms, addressing common public concerns (Bilgili et al., 2011; Esteban et al., 2011). Offshore wind turbines are typically larger than their onshore counterparts due to the ability to construct and transport components at port facilities, facilitating the deployment of massive installations (Hrouga & Bostel, 2021).

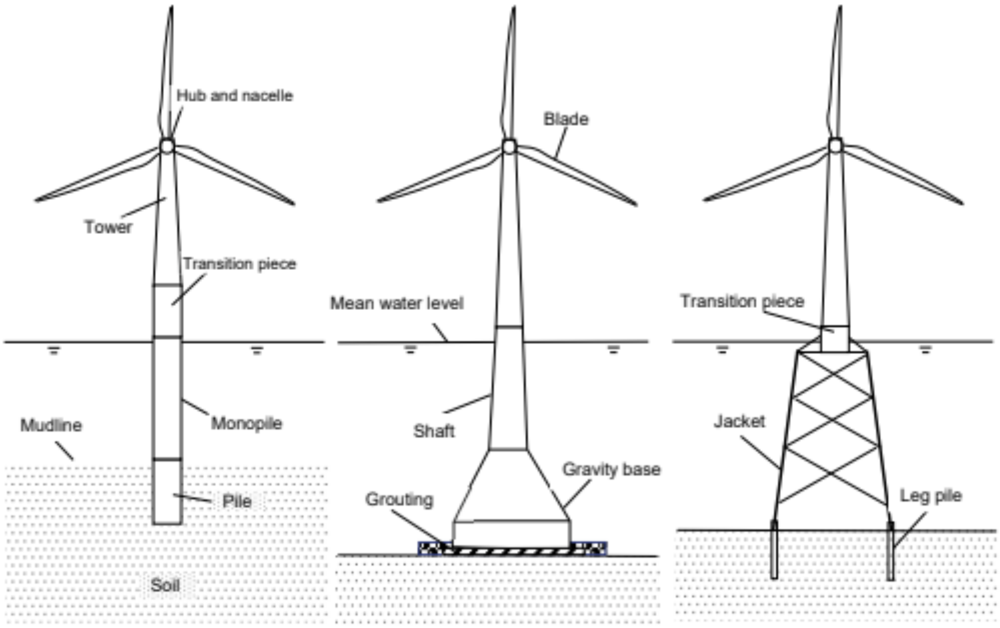


Figure 5: from Jiang, Z. (2021). Installation of offshore wind turbines: A technical review. Renewable and Sustainable Energy Reviews, 139, 110576

Historically, wind energy generation was connected to the electric grid with minimal impact, leading to less stringent grid requirements. As wind power installations have grown significantly—often contributing hundreds of megawatts—detailed grid stability analyses have become essential (Perveen et al., 2014). Wind energy conversion relies on both fixed-speed and variable-speed generators, with variable-speed systems preferred for maintaining steady output under varying wind conditions. Various generator types are employed, including double-fed induction generators (DFIGs), synchronous generators (SGs), and permanent magnet synchronous generators (PMSGs). DFIGs are particularly favored for their low cost, modularity, and compact design, despite requiring a more complex drivetrain and precise pitch control (Perveen et al., 2014). Transmission technologies are critical for integrating offshore wind energy into the broader power grid. Typically, 20 kV or 33 kV voltage levels are used for interconnecting individual turbines, with step-ups to 150 kV or 400 kV for grid transmission (Perveen et al., 2014).
High-voltage direct current (HVDC) systems are advantageous for large-scale wind farms, reducing transmission losses and minimizing grid impact (Kalair et al., 2016; Zhang et al., 2011).

4.2. Value Chain Analysis

This section will cover the current value chain activities in depth. The offshore wind industry in the North Sea has evolved into a structured and well-integrated energy sector with clearly defined value chain processes. The development of offshore wind farms involves multiple phases, each requiring collaboration among different stakeholders, including government agencies, manufacturers, developers, grid operators, service providers, and financial institutions. The key components of the offshore wind value chain—pre-development and consenting, manufacturing, installation and commissioning, operation and maintenance, and decommissioning and disposal—have become more specialized and efficient as the industry has matured.

Pre-Development and Consenting: The development of offshore wind projects begins with a rigorous pre-development and consenting phase, which includes several essential surveys and studies to ensure feasibility, minimize risks, and comply with environmental regulations. This phase is critical for identifying suitable sites, securing necessary permits, and mitigating risks that could impact project viability. A key component of this phase is environmental assessment.

Environmental surveys evaluate potential impacts on marine and bird species, including benthic, pelagic, ornithological, and marine mammals, ensuring that offshore wind farms do not significantly disrupt biodiversity (Umoh & Lemon, 2020). These studies are complemented by coastal process assessments, which analyze how offshore wind developments might influence sedimentation patterns and coastal erosion. Additionally, meteorological and oceanographic surveys collect essential data on wind patterns, wave heights, and ocean currents. This information is crucial for estimating energy yields and anticipating potential challenges during installation. Another fundamental aspect of pre-development is seabed analysis. Seabed surveys assess the composition and stability of the ocean floor to determine suitable locations for turbine foundations and cable routes. These surveys help mitigate technical uncertainties and inform the Front-End Engineering and Design (FEED) process, which establishes the fundamental engineering and construction concepts before contracts are awarded. Accurate seabed data is particularly important for determining the best foundation types, such as monopiles, jackets, or floating structures, depending on depth and soil conditions. To address potential social impacts, human impact studies are conducted. These studies examine visual, noise, and socio-economic effects on coastal communities and maritime industries, ensuring that offshore wind developments align with broader societal and economic objectives. Engagement with stakeholders, including fisheries, shipping industries, and local governments, is an integral part of this process, as it helps address concerns and integrate offshore wind farms into existing marine activities. Permitting is a critical step in the offshore wind development process, shaping how projects progress from concept to realization. The permitting process involves obtaining approvals from regulatory authorities, conducting environmental impact assessments (EIAs), and ensuring compliance with national and international frameworks. The REPowerEU plan introduced measures to streamline permitting, aiming to accelerate the deployment of renewable energy (WindEurope, 2022; Mahdi, 2023).
Countries like Germany and the Netherlands have adopted centralized permitting models where the government conducts pre-development studies and site assessments, reducing risks for developers (Kaldellis & Kapsali, 2013). In contrast, open-door permitting allows developers to propose sites, but this approach can lead to uncertainties and unforeseen conditions impacting project feasibility (Del Río & Kiefer, 2023). Permitting processes must balance energy development with environmental protection and stakeholder interests. Offshore wind farms operate within Exclusive Economic Zones (EEZs), governed by frameworks like the United Nations Convention on the Law of the Sea (UNCLOS) (Williamson, 2000). Additionally, the Maritime Spatial Planning (MSP) Directive guides EU Member States in designating areas for offshore wind while managing potential conflicts with fishing, shipping, and defense activities (Mahdi, 2023). To meet climate goals, there is a growing emphasis on simplifying permitting procedures. Initiatives by organizations like the International Marine Contractors Association (IMCA) aim to standardize permitting requirements, reducing administrative burdens and expediting approval. This shift toward streamlined permitting helps mitigates risks associated with project delays and improves investment certainty for developers. Despite these regulatory advancements, permitting remains a time-intensive process due to the need for compliance with maritime spatial planning regulations, environmental protection laws, and grid connection agreements (Mahdi, 2023). In many jurisdictions, permitting can precede or overlap with the tendering process. For example, governments may pre-permit offshore sites to reduce risks and attract competitive bids during tenders. The Netherlands, for example, follows a site-specific tendering system where the government pre-selects offshore wind zones and conducts preliminary environmental and technical assessments before awarding contracts (RES Legal, 2024). The United Kingdom employs seabed leasing rounds through The Crown Estate, combined with the Contracts for Difference (CfD) mechanism, which provides revenue stability for developers (United Kingdom Government, 2019). Germany transitioned from fixed feed-in tariffs to an auction-based allocation system to maintain cost efficiency while ensuring investment security (Vieira et al., 2019). The tender process

for offshore wind energy involves multiple stages, from pre-qualification to awarding development rights, each designed to ensure transparency, competitiveness, and efficiency (Berk, 2024).

1. **Pre-Tender Phase:** In the pre-tender phase, regulatory authorities identify and designate suitable offshore sites for wind farm development through spatial planning and environmental assessments. (Governments may conduct feasibility studies, grid connection assessments, and Environmental Impact Assessments (EIAs) to reduce uncertainty for developer. This phase ensures that site-specific risks are minimized, which is crucial for attracting qualified bidders (Jansen, 2020).
2. **Pre-Qualification Questionnaire (PQQ):** Developers participate in a Pre-Qualification Questionnaire (PQQ) process, where their financial stability, technical expertise, and experience are evaluated (Berk, 2024). This phase screens potential bidders to ensure they meet the minimum requirements for project execution.
3. **Invitation to Tender (ITT):** In the Invitation to Tender (ITT) phase, pre-qualified developers submit detailed bids. These bids often include technical proposals, financial offers, and plans for mitigating environmental impacts and ensuring local community benefits. In some jurisdictions, such as the UK, the ITT process may be split into two stages, with iterative bidding rounds to refine offers and ensure competitive pricing (Greve & Rocha, 2020).
4. **Bid Evaluation:** Bids are evaluated based on price and non-price criteria. Non-price criteria can include factors such as ecological sustainability, supply chain robustness, and social contributions (Berk, 2024). The increasing use of zero-subsidy bids and negative bids reflects a trend where developers compete not only on cost but also on the value, they add to the broader energy system (Jansen, 2020).
5. **Awarding the Contract:** The winning bidder is granted the rights to develop the offshore wind project and, in some cases, secure grid connection and government support schemes like Contracts for Differences (CfD) (Berk, 2024; Jansen, 2020). This phase may also involve signing agreements to lock in supply chain commitments and financing structures.
6. **Post-Tender Phase:** After the tender award, developers proceed with project execution, which involves securing final permits, financing, and supply contracts. Difficulties during this phase include managing supply chain risks, ensuring timely delivery of components, and coordinating with transmission system operators for grid connection (Greve & Rocha, 2020).

Manufacturing: Offshore wind turbines consist of several key components, each requiring advanced materials and precise engineering. Figure 7 shows the component breakdown of an offshore wind turbine (OWT). Rotor blades are designed to withstand extreme environmental forces while maintaining flexibility and durability. They are primarily constructed from composite materials such as fiberglass-reinforced plastic and carbon fiber-reinforced plastic, ensuring that blades remain lightweight yet strong enough to endure mechanical loads and environmental stress throughout their operational lifespan. The nacelle houses essential components such as the gearbox, generator, and control systems. To protect these critical elements, nacelles are manufactured using steel, aluminum, composites, and hybrid materials that offer the necessary strength and durability for offshore conditions. The tower, a structurally critical component, elevates the nacelle and rotor to optimal heights for wind capture. Towers are primarily made from rolled steel plates, concrete, and zinc coatings to ensure strength, fatigue resistance, and corrosion protection. The foundation provides stability to offshore wind turbines in challenging marine environments, enduring forces from waves, currents, and wind. The choice of foundation depends on site-specific factors such as water depth and seabed conditions. Monopiles are the most widely used foundation type in shallow waters due to their simplicity and cost-effectiveness (O'Kelly &

Arshad, 2016). Jacket foundations are preferred for deeper waters where monopiles become impractical, while gravity-based structures are used in areas with stable seabeds and shallow water conditions. Floating platforms represent an emerging technology for deep-water sites. These foundations are constructed using steel, concrete, and key metals such as chromium, manganese, molybdenum, nickel, and zinc, with zinc coatings playing a crucial role in corrosion resistance. Beyond the core turbine structure, the balance of plant components, including cables and substations, is vital for the transmission and distribution of electricity. Offshore wind farms rely on export cables and inter-array cables made from copper and aluminum, designed to handle high voltages ranging from 132 kV to 220 kV. These cables are insulated and reinforced to withstand water pressure, mechanical stress, and temperature fluctuations. Offshore substations collect power from multiple turbines and convert it to higher voltages before transmitting it to the onshore grid. These structures, fabricated primarily from steel, house electrical transformers, switchgear, and control systems. The transition piece, which connects the foundation to the tower, ensures structural stability and facilitates the installation and maintenance of auxiliary systems such as access platforms and corrosion protection. With the increasing deployment of larger turbines and taller towers, the demand for these materials is expected to rise significantly.

The manufacturing process for offshore wind components involves multiple stages, including pre-assembly and testing. Nacelles, rotors, and other critical components are often pre-assembled at port-side facilities to simplify offshore installation (Rodrigues et al., 2015). Each component undergoes rigorous testing before deployment, with nacelles tested for gearbox and generator functionality, blades examined for aerodynamic performance and structural integrity, and cables and transformers assessed for electrical performance under high loads. By ensuring high-quality standards and optimized logistics, the manufacturing sector continues to support the expansion and cost reduction of offshore wind energy in the North Sea region.

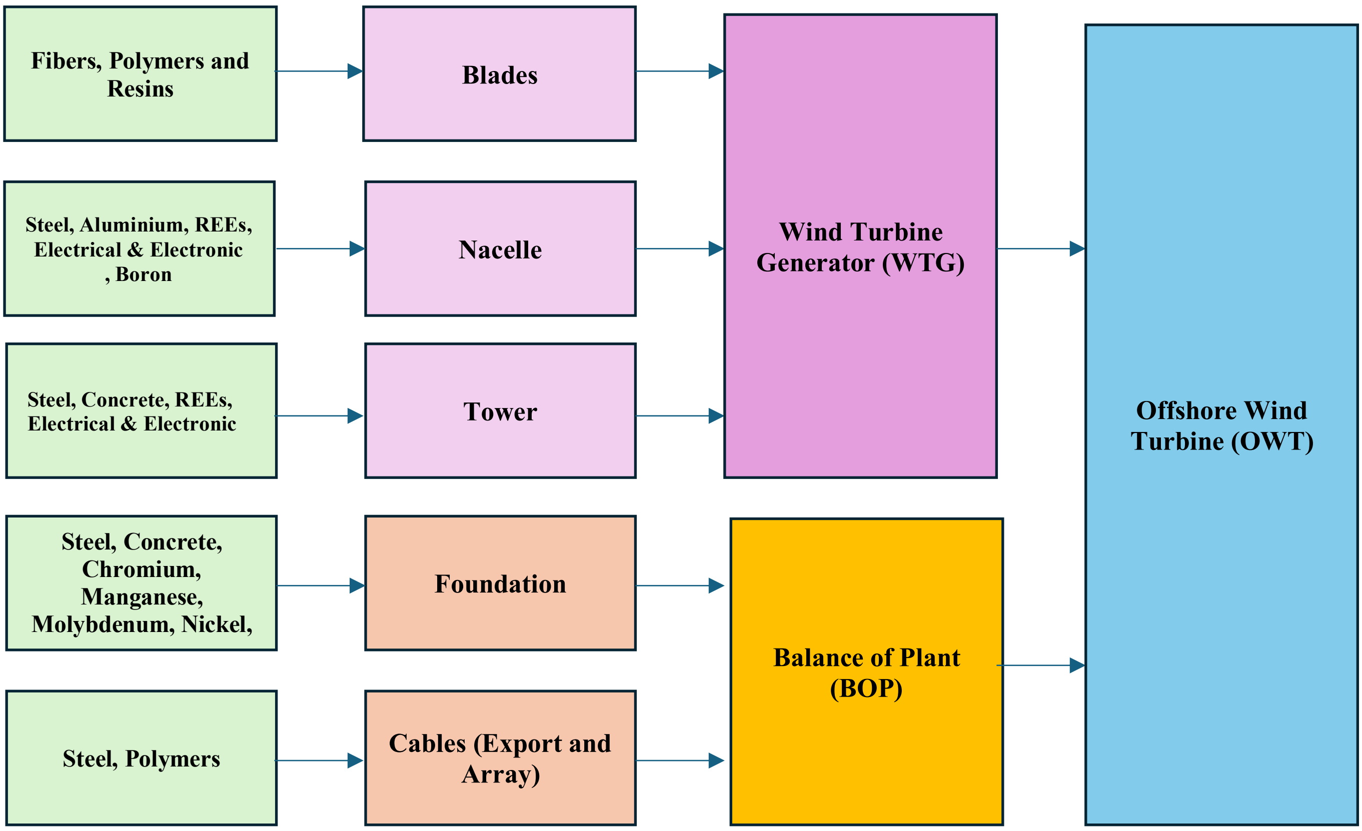


Figure 7: Component Breakdown OWT

Installation and Commissioning: The installation phase of offshore wind farms has benefited from major advancements in engineering and logistical innovations. Specialized installation vessels and floating cranes have improved deployment efficiency, allowing for faster construction in both shallow and deep waters (O'Kelly & Arshad, 2016). Offshore wind projects typically follow a multi-stage contracting approach, involving distinct procurement models for various project elements such as wind turbine generators, foundations, substations, and export cables. The contracting strategy significantly influences project timelines, costs, and risk allocation (Berk, 2024). Two main contracting strategies are commonly used in offshore wind projects:

1. **Multi-Contracting Approach:** Developers award separate contracts for each project component, such as turbine supply, foundation fabrication, and electrical infrastructure. This strategy provides greater control over costs and quality but requires strong project management to coordinate multiple contractors (Guillet, 2022).
2. **EPCI Contracting:** A single contractor manages multiple aspects of the project, reducing interface risks but increasing overall project costs due to higher contractor risk premiums (Industri, 2024).

The transportation of wind turbine components follows different logistical approaches depending on project requirements. The logistics of offshore wind installation involve specialized vessels that transport and install turbine components. Each vessel type has a distinct role in facilitating the transportation, installation, and construction processes necessary for offshore wind projects. Figure 8 illustrates the primary vessels used in OWT installation (Jiang, 2021). Tugboat (Figure 8a): Tugboats are essential for manoeuvring and towing other vessels or floating structures, such as barges and platforms, to and from the installation site. Their versatility and manoeuvrability make

Figure 8 from Jiang, Z. (2021). Installation of offshore wind turbines: A technical review. Renewable and Sustainable Energy Reviews, 139, 110576.

them crucial for positioning large components during the construction of offshore wind farms. Crane Barge (Figure 8b): Crane barges are equipped with heavy-duty cranes that facilitate the lifting and placement of components such as monopiles, towers, and nacelles. These vessels are particularly useful in shallow waters and for projects where other specialized vessels are not feasible. Heavy Lift Vessel (Figure 8c): Heavy lift vessels are designed for transporting and lifting massive components, including turbine blades, towers, and nacelles. Their high load capacity and stability make them indispensable for the large-scale installations typical of modern offshore wind farms. Jackup Barge (Figure 8d): Jackup barges feature extendable legs that can be lowered to the seabed, providing a stable platform for lifting and installation activities. They are commonly used for foundation installation and turbine assembly, offering stability even in rough sea conditions. Purpose-Built Jackup Vessel (Figure 8e): Purpose-built jackup vessels are specifically designed for offshore wind installations. Equipped with cranes and extendable legs for seabed stabilization, these vessels can transport and install entire wind turbine components efficiently. They are capable of operating in deeper waters and extending their operational windows due to their enhanced stability. Semisubmersible Construction Vessel (Figure 8f): Semisubmersible construction vessels are highy stable platforms that can partially submerge to provide a steady base for construction activities. These vessels are used for complex offshore tasks, including the installation of large turbines and substations. Their stability and capacity to handle heavy loads make them ideal for deep-water installations.

The selection of the appropriate vessel depends on factors such as water depth, seabed conditions, component size, and weather conditions. Each vessel type plays a critical role in ensuring the efficiency, safety, and success of offshore wind turbine installations. Advances in vessel design continue to enhance the ability to deploy larger turbines, improve installation timelines, and reduce overall project costs (Jiang, 2021). There are multiple strategies for installing an offshore wind turbine. One strategy involves shipping components from manufacturing facilities to a dedicated pre-assembly port, where turbines are partially assembled before transport to the wind farm site. This approach allows for greater flexibility in scheduling installations, as pre-assembled components can be quickly deployed when weather conditions permit (Scholz-Reiter et al., 2010). Another method involves transporting components directly from manufacturers to a staging area near the wind farm, where specialized construction vessels complete the assembly process offshore. This minimizes intermediate storage and handling, reducing logistical complexity. A third approach utilizes jack-up vessels that transport fully pre-assembled turbine components directly to the wind farm site. These vessels are equipped with cranes and stabilizing legs that anchor to the seabed, allowing installation operations to continue even in moderate sea conditions, thereby extending operational days per year (Scholz-Reiter et al., 2010). Weather constraints have historically been a major factor limiting the feasibility of offshore wind installation. Earlier estimates suggested that weather conditions restricted offshore construction to between 50% and 75% of the year in North Sea regions, leading to significant downtime and delays (Scholz-Reiter et al., 2010). However, advancements in installation techniques and predictive modeling have improved scheduling efficiency. Recent studies show that the use of larger jack-up vessels, dynamic positioning systems, and digital forecasting tools has significantly increased the number of operational days per year. Discrete Event Simulation (DES) models are now widely used to predict potential weather downtime and optimize installation schedules, accordingly, reducing overall project delays (Muhabie et al., 2016). The integration of real-time weather forecasting with logistical planning has further minimized risks, ensuring that vessels and personnel are deployed optimally. The installation phase includes several other key activities. Export cables are laid to connect offshore substations to the onshore grid, ensuring efficient power transmission. Array cables link individual turbines to each other and the offshore substation. Foundation installation is another critical step, with monopile being the most common solution to anchor turbines securely to the seabed (O'Kelly & Arshad, 2016). The construction port serves as a logistical hub, enabling the efficient storage and transport of turbine components and other infrastructure. Offshore substations are then installed to convert the electricity generated by the turbines before transmission to the grid. This is followed by the commissioning phase, which includes visual inspections, mechanical testing, and electrical system verification to confirm that the wind farm is fully operational (Scholz-Reiter et al., 2010). Advancements in offshore wind installation have led to increased efficiency, reduced costs, and more predictable deployment timelines. Improvements in vessel technology, logistics planning, and weather prediction models have significantly decreased downtime and enhanced overall project feasibility. These innovations have contributed to the growing competitiveness of offshore wind energy in the North Sea, supporting its role as a major renewable energy source (Muhabie et al., 2016).

Operation and Maintenance: The operations and maintenance (O&M) phase is critical for ensuring the long-term efficiency and profitability of offshore wind farms. Advancements in monitoring systems, predictive maintenance, and digital technologies have significantly improved operational reliability, reducing both maintenance costs and turbine downtime (Shafiee, 2015). After commissioning, wind farms enter the routine operational phase, where technician and equipment transfers become a key logistical challenge. Safe and efficient transportation to and from offshore turbines is essential for routine inspections, repairs, and emergency interventions. To support extended maintenance activities, offshore accommodation facilities are often used, allowing technicians to remain on-site for prolonged periods without returning to shore. A major challenge in O&M is the repair, refurbishment, and replacement of large components, such as gearboxes, generators, and rotor blades. These components experience the highest failure rates, leading to significant downtime if not managed proactively. Research by Umoh and Lemon (2020) highlights that generators and gearboxes account for the most downtime per failure, emphasizing the importance of preventive maintenance strategies. To mitigate these risks, routine and preventive maintenance programs are employed. Routine maintenance includes inspections, lubrication, and mechanical adjustments, reducing the likelihood of unexpected failures. Predictive maintenance, enabled by SCADA systems, condition-based monitoring, and AI-driven analytics, allows operators to detect early warning signs of potential failures, ensuring timely interventions before major breakdowns occur (Industri, 2024). The use of digital twins—virtual models of wind farms—has revolutionized O&M strategies by simulating turbine performance, optimizing energy production, and improving maintenance scheduling. These digital solutions complement the deployment of autonomous drones and robotics, which perform real-time inspections, reducing the need for human technicians in hazardous environments (Shafiee, 2015). Strategic O&M service hubs have been established in major offshore wind regions such as Esbjerg (Denmark) and Hull (United Kingdom). These hubs provide rapid-response capabilities for maintenance, ensuring minimal downtime. Floating service platforms and offshore operation centers further enhance logistical efficiency, allowing faster deployment of repair teams. Continuous performance monitoring ensures that wind farms maintain optimal efficiency, allowing operators to adjust power output, detect energy losses, and implement corrective actions. The combination of proactive maintenance strategies, advanced monitoring, and efficient logistical operations is crucial in minimizing turbine downtime and maximizing offshore wind energy output (Umoh & Lemon, 2020).

Decommissioning and Disposal: Decommissioning is the final phase of a wind farm's lifecycle and aims to restore the site to its original state as far as practicable. It involves project management, infrastructure removal, and post-decommissioning site monitoring, with strict adherence to environmental regulations to minimize risks to marine ecosystems (Department of Energy & Climate Change, 2011). The process requires substantial planning and logistical coordination due to the harsh offshore environment, site-specific conditions, and evolving regulatory frameworks (Topham & McMillan, 2017; Welstead et al., 2013).As the first generation of large-scale offshore wind farms approaches the end of their operational life, decommissioning strategies have gained importance. Between 2020 and 2030, decisions regarding lifetime extension, repowering, or full decommissioning will be needed for over 1,800 offshore wind turbines. This number will increase substantially, with nearly 20,000 offshore wind turbines reaching their end-of-life phase in Europe between 2030 and 2040 (Topham & McMillan, 2017). The decommissioning and disposal can be structured in the following phases:

1. **Planning**: Effective planning ensures the efficient scheduling of vessels, equipment, and personnel while minimizing costs and operational risks. The planning phase includes environmental impact assessments, risk mitigation strategies, and compliance with national and international regulations (Topham & McMillan, 2017; Welstead et al., 2013).
2. **Infrastructure Removal**:
    a. **Turbines and Foundations**: Wind turbines are dismantled and transported onshore for reuse, recycling, or disposal. Monopile foundations are typically cut 1–2 meters below the seabed, while gravity and suction bucket foundations can often be fully extracted (Kaiser & Snyder, 2012; Smyth et al., 2015).
    b. **Cables and Scour Protection**: Subsea cables are sometimes left in situ if buried adequately to prevent environmental disturbance. However, unburied sections are removed. Scour protection materials, such as rocks placed around turbine foundations to prevent seabed erosion, are typically left in place unless they pose risks to navigation or marine habitats (Topham & McMillan, 2017).
3. **Post-Decommissioning**: Following infrastructure removal, seabed clearance and site monitoring ensure minimal environmental impact and habitat recovery. Some jurisdictions require long-term monitoring programs to assess how marine ecosystems respond to wind farm decommissioning (Castle & Pryor, 2016).

Circular economy principles are increasingly shaping decommissioning strategies. In the Netherlands Extended Producer Responsibility (EPR) schemes require turbine manufacturers to take responsibility for end-of-life management, encouraging component recycling and repurposing (RES Legal, 2024). Research into sustainable materials for turbine blades continues, as composite blades remain a major challenge for recycling efforts.
Governments are also mandating financial security measures for decommissioning, requiring developers to submit decommissioning plans at the project approval stage. This ensures that sufficient financial resources are available for site restoration and waste management, mitigating risks of abandoned offshore infrastructure (Castle & Pryor, 2016).

4.3. Financial Structure Analysis

This subsection will cover a detailed financial assessment, highlighting capital and operational expenditures, financing mechanisms, risk management strategies, and cost reduction trends.

Value Chain CAPEX & OPEX
A thorough understanding of the types of costs is essential to evaluate the financial viability of offshore projects and identify areas for cost reduction. Figure 9 shows the distribution of cost per value chain activity.

Pre-Development and Consenting: The development of an offshore wind farm begins several years before construction and involves numerous preliminary activities to ensure technical and economic feasibility. The pre-development and consenting phase include costs related to:

1. **Project Management**: Administrative tasks such as pre-feasibility studies, financing, and subcontractor negotiations are essential. Project management typically constitutes around 3% of the total capital expenditure (CAPEX) (Shafiee et al., 2016).
2. **Legal Authorization**: Government or regulatory body authorization is required and varies by country. Legal authorization is estimated at approximately 0.13% of CAPEX (Howard, 2012).
3. **Surveys**: Site-specific surveys—covering environmental impact, coastal processes, seabed conditions, and metocean data—are essential for evaluating feasibility. Survey costs vary based on the installed capacity and location of the wind farm (Shafiee et al., 2016).
4. **Engineering**: After final approval, a multidisciplinary team is assembled for detailed design activities, including structural design, turbine layout, and grid connection. Engineering costs depend on project size and are often modeled as a function of installed capacity (Castro-Santos & Diaz-Casas, 2014).
5. **Contingencies**: Unpredictable expenses and allowances for equipment replacement due to catastrophic failure are covered by a contingency fund, typically around 10% of CAPEX (Howard, 2012).

Manufacturing: Production costs form a major portion of CAPEX in offshore wind projects, including the procurement of essential components. Figure 9 show the cost per WTG component.

1. **Wind Turbines**: Turbine costs are a function of the number, power rating, and transport requirements of turbines. Costs increase with larger turbines, but economies of scale help mitigate costs for high-capacity units (Shafiee et al., 2016).
2. **Support Structures** (around 20% of CAPEX): Foundation costs rise with water depth and seabed conditions, with the cost of support structures estimated to increase by about 2% per meter of additional water depth (Nielsen, 2003).
3. **Power Transmission Systems** (around 10% of CAPEX): Offshore projects require extensive transmission infrastructure, including inter-array and export cables, as well as substations. Transmission system costs are influenced by factors such as the number of turbines and the distance from shore (Dicorato et al., 2011; Myhr et al., 2014). Efficient transmission systems are critical for reducing energy losses and ensuring the financial success of offshore wind farms. For shorter distances, high-voltage alternating current (HVAC) systems are typically used, while longer distances require high-voltage direct current (HVDC) systems, which minimize energy losses during transmission. Emerging technologies like low-frequency alternating current (LFAC) are also showing promise as cost-effective solutions for medium- to long-distance energy transport (Lakshmanan et al., 2015; Ruddy et al., 2016).

4. **Monitoring Systems**: SCADA and condition monitoring systems are installed to track turbine performance in real-time, contributing to initial CAPEX but providing long-term benefits by optimizing maintenance (Tavner, 2013).

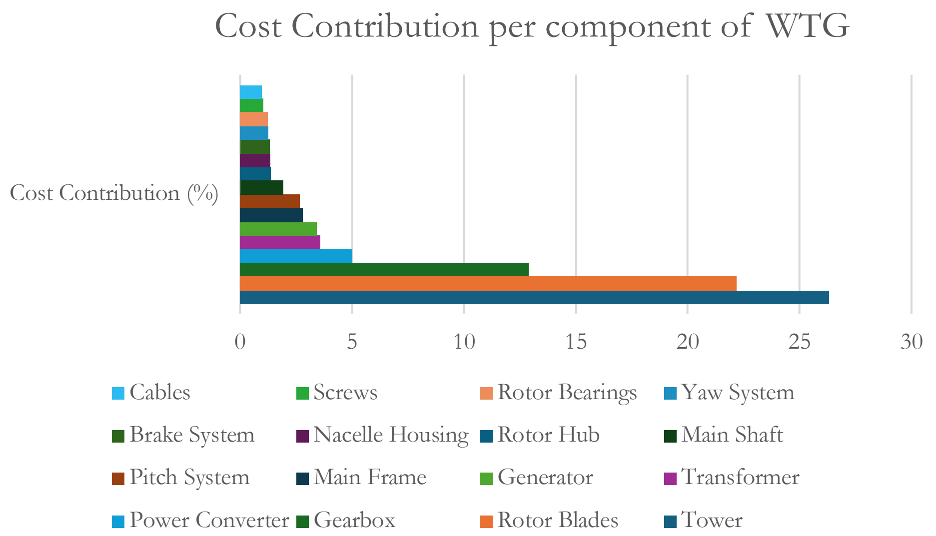


Figure 9 from Johnston, B., Foley, A., Doran, J., & Littler, T. (2020). Levelised cost of energy, a challenge for offshore wind. Renewable Energy, 160, 876-885.

Installation and Commissioning: Installation is a particularly cost-intensive phase, requiring specialized vessels and equipment. This phase includes:

1. **Port and Transportation Fees**: Ports play a crucial role in component pre-assembly and transportation, with fees for infrastructure and labor (Maples et al., 2013).
2. **Component Installation**: Installation costs vary by component (e.g., foundations, turbines, and electrical systems) and are highly influenced by offshore conditions. Specialized vessels and crews are required, particularly for deep-sea installations, which add significantly to the cost (Shafiee et al., 2016).
3. **Insurance**: Installation insurance is essential to cover risks associated with environmental and logistical challenges and is usually a small percentage of CAPEX.

Operation and Maintenance: O&M costs for offshore wind projects are considerably higher than for onshore projects due to limited accessibility and harsh environmental conditions. Key O&M cost drivers include:

1. Maintenance Logistics: Offshore maintenance requires specialized vessels, which are costly and often restricted by weather. These logistics represent around 26% of the project's lifetime costs (Shafiee et al., 2016).
2. Rental and Insurance: Seabed rentals and operational insurance are necessary for offshore sites. Rental costs are often tied to the wind farm's revenue, while insurance costs scale with installed capacity (Shafiee, 2015a).
3. Transmission Fees: Offshore projects pay annual transmission charges based on capacity, which covers the connection to the national grid (Howard, 2012).

Decommissioning and Disposal: At the end of a wind farm's operational life, decommissioning costs include dismantling, removing cables, and site clearance. These costs can be offset by the resale of recyclable materials, such as steel from turbine towers and copper from cables. Key decommissioning costs include:

1. Waste Management: Processed materials are transported to recycling facilities or landfills, with costs based on material weight (Department of Energy & Climate Change, 2011).
2. Post-Decommissioning Monitoring: Monitoring may be required after decommissioninto assess environmental impacts if components are left on-site (Shafiee et al., 2016).

Financing strategies and Risk management

Offshore wind energy development is capital-intensive, requiring substantial upfront investments across all project stages. These costs encompass turbine acquisition, foundation construction, electrical infrastructure, and long-term operation and maintenance. While initial capital expenditures for offshore wind projects exceed those of onshore installations, their economic feasibility is enhanced by higher capacity factors and fewer land-use conflicts. Offshore wind's ability to generate stable and higher outputs makes it a vital contributor to both energy security and economic growth, particularly in regions like Europe where policy support and technological advancements continue to drive progress (Green & Vasilakos, 2011; Hrouga & Bostel, 2021).

Financing Structures and Strategies:

Figure 10 illustrates a typical financing structure for an offshore wind energy project, showcasing the key financial flows and stakeholder relationships involved in developing and operating a large-scale wind farm with a capacity of 882 MW, comprising 60 turbines and a total project cost of approximately €2.9 billion. The diagram outlines the roles of lenders, equity investors, construction companies, O&M contractors, grid connection providers, and electricity offtakers, highlighting the complex financial and contractual framework that underpins such projects. The wind energy company sits at the center of this structure, acting as the project developer and financial coordinator. The company secures funding from two primary financial sources: debt financing from lenders and equity contributions from investors. Lenders provide around 75% of the total project cost, equating to approximately €2.2 billion. This debt finance is facilitated through loan agreements, and the company is obligated to repay this debt over time. Debt repayment follows the flow of revenue generated through electricity sales and other financial returns. Equity investors contribute approximately 25% of the project cost, amounting to around €0.7 billion. Key equity investors such as EDP Renewables, Engie, and UAB Ignitis Renewables provide capital under a shareholders' agreement. In return for their investment, these equity investors are entitled to dividend payments from the company as profits are realized. This equity injection is essential for covering initial development expenses and improving the project's financial stability to attract debt financing. The construction phase is managed through contracts with key construction firms such

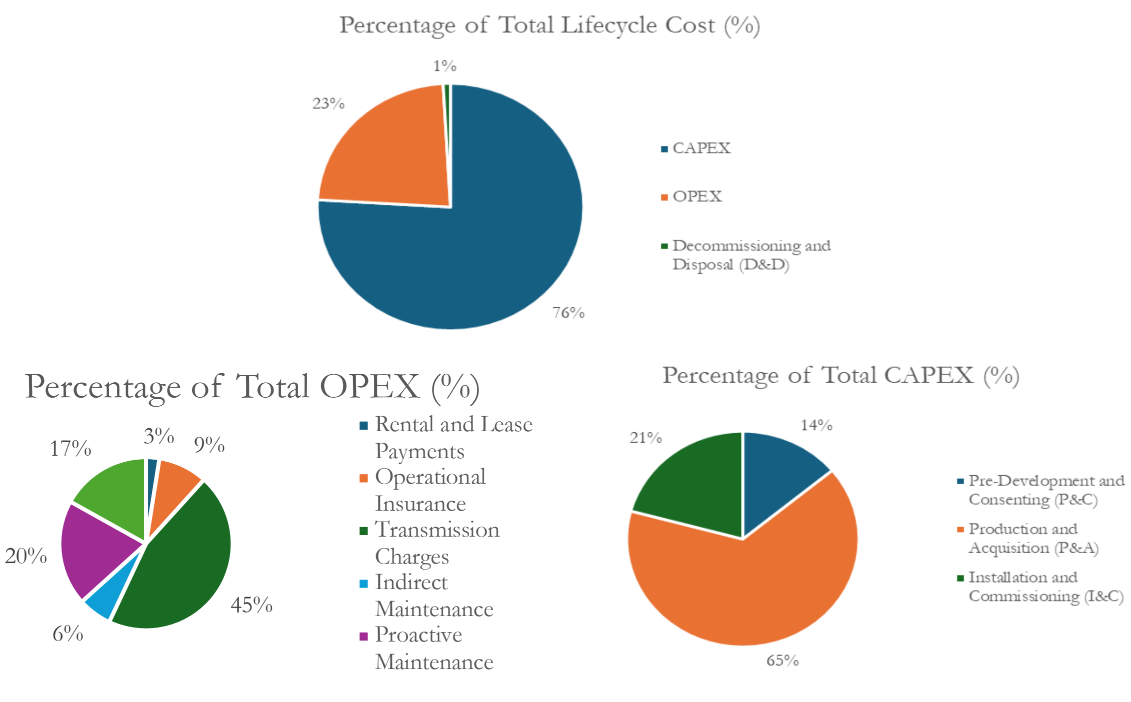


Figure 9 from Johnston, B., Foley, A., Doran, J., & Littler, T. (2020). Levelised cost of energy, a challenge for offshore wind. Renewable Energy, 160, 876-885 as Siemens Gamesa, DEME, and Boskalis. These firms are responsible for building the wind farm infrastructure, including the installation of turbines, foundations, and cables. The company enters a construction contract with these firms and provides payments for their services as milestones are met. Upon completion of the construction phase, the Wind Energy Company engages in ongoing operations and maintenance (O&M) activities, which are contracted to Siemens Gamesa. The O&M contractor is responsible for maintaining the turbines and ensuring optimal performance throughout the project's lifecycle. Payments for these services are made by the company to the O&M contractor under a service agreement. For electricity transmission, the company must secure a grid connection. This is achieved through an OFTO (Offshore Transmission Owner) tender process, where a separate entity takes ownership of the offshore grid connection assets. The company then pays this grid connection provider for access to the transmission system, enabling the flow of generated electricity to the onshore grid. Revenue generation is driven by power purchase agreements (PPAs) with major corporate offtakers such as Amazon and Google. These agreements guarantee the sale of the produced electricity at predetermined prices, ensuring stable cash flow for the company. The revenue from these agreements is crucial for financing debt repayment obligations, as well as generating returns for equity investors. This financing structure reflects the complexity of offshore wind development, where multiple stakeholders are involved in securing capital, managing construction risks, and ensuring long-term operational stability. The model emphasizes risk-sharing mechanisms, with lenders providing most of the capital but requiring secure repayment structures, while equity investors bear greater risk but gain higher potential returns through dividend distributions. By coordinating these financial flows effectively, offshore wind developers can mitigate risks, secure investment, and successfully deliver large-scale renewable energy projects.

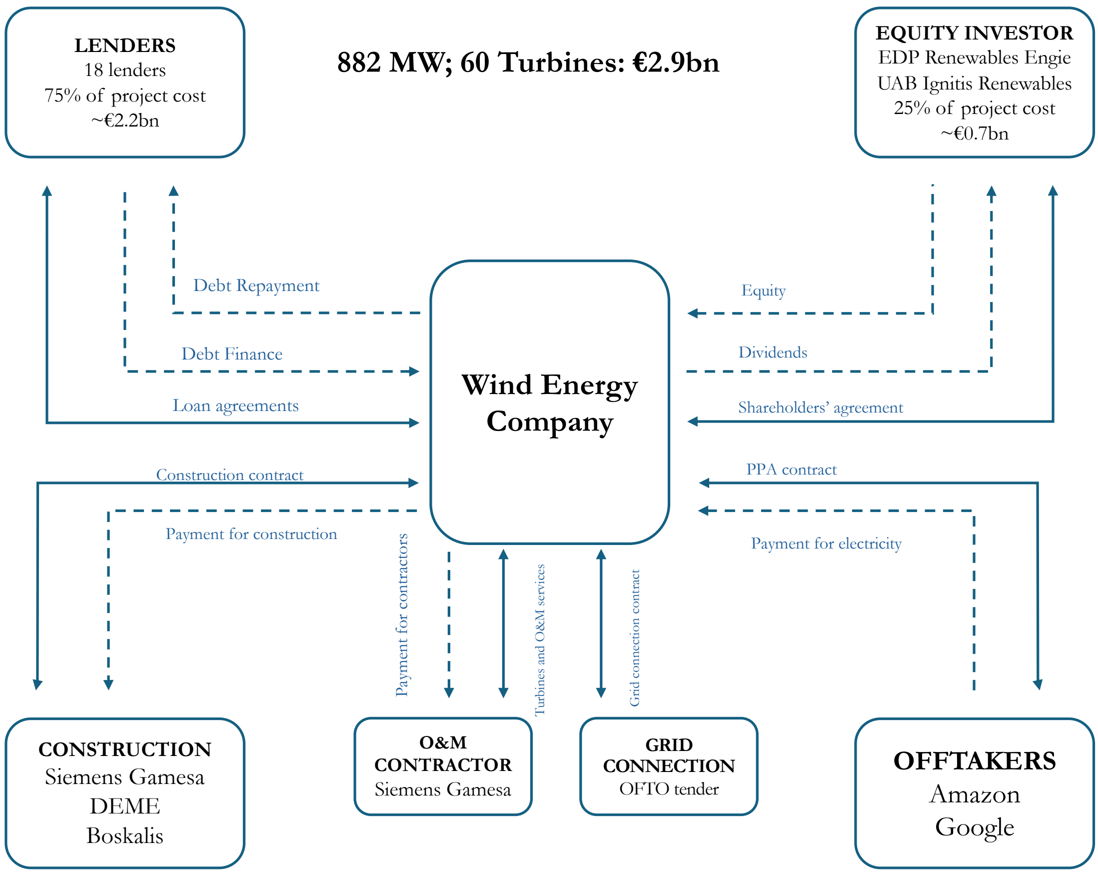


Figure 10 Example Financing Structure offshore wind farm from https://windeurope.org/intelligence-platform/product/financing-and-investment-trends-2022/

Financing offshore wind projects requires a structured combination of debt and equity financing to manage risks and ensure long-term financial viability. Projects are typically structured through standalone project companies, facilitating a financing model known as project finance. Under this approach, lenders rely on the project's cash flows for repayment rather than the balance sheets of equity investors, ensuring that risks are appropriately distributed while protecting lenders' interests. Equity financing, provided by sponsors and institutional investors, is most deployed during the early, high-risk stages of development, such as permitting and securing contracts. As projects transition into the construction and operational phases, debt financing, primarily supplied by commercial banks and institutional lenders, becomes the dominant financial instrument due to the presence of stable revenue streams. Extensive due diligence and well-defined contractual frameworks are required by lenders to mitigate risks and ensure project feasibility (Green Giraffe, 2019). The financing process is divided into three distinct phases. During the pre-development phase, project risks are at their highest, but this stage is also where significant value is created by securing permits and contracts. The construction phase introduces risks such as cost overruns, delays, and weather-related disruptions, which are managed through close project oversight, contingency budgets, and insurance mechanisms. Once operational, offshore wind farms generate stable revenues, which often enable project refinancing at lower interest rates, improving long-term profitability (Green Giraffe, 2019). Offshore wind energy has substantial potential, but it requires significant upfront and ongoing investment. The Levelized Cost of Energy (LCOE) is a useful metric for comparing the cost-effectiveness of offshore wind against other energy sources, aiding investors in evaluating financial viability. As the industry matures, understanding and managing these cost drivers—across development, production, installation, operation, and decommissioning—will be crucial for making offshore wind more cost-competitive and sustainable (Blanco, 2009; Shafiee et al., 2016).

Figure 11 shows the LCOE of different renewable energy sources over time. The financial outlook for offshore wind has improved substantially in recent years due to economies of scale, technological advancements, and financial optimization strategies. Between 2014 and 2023, the LCOE for offshore wind declined by over 40%, one of the most significant cost reductions in the renewable energy sector. This trend has been primarily driven by the upscaling of turbine sizes and wind farm capacities, allowing developers to maximize economic returns. By selecting the largest commercially available turbines at the time of financial close, project developers ensure higher energy yields and lower costs per megawatt-hour (Shields et al., 2021). Despite these cost reductions, offshore wind's LCOE remains higher than that of other renewable energy sources, such as solar PV and onshore wind, both of which continue to experience cost declines. However, this gap is narrowing, and offshore wind is becoming increasingly competitive, particularly in markets with strong policy support and favorable financing conditions (Johnston et al., 2020).

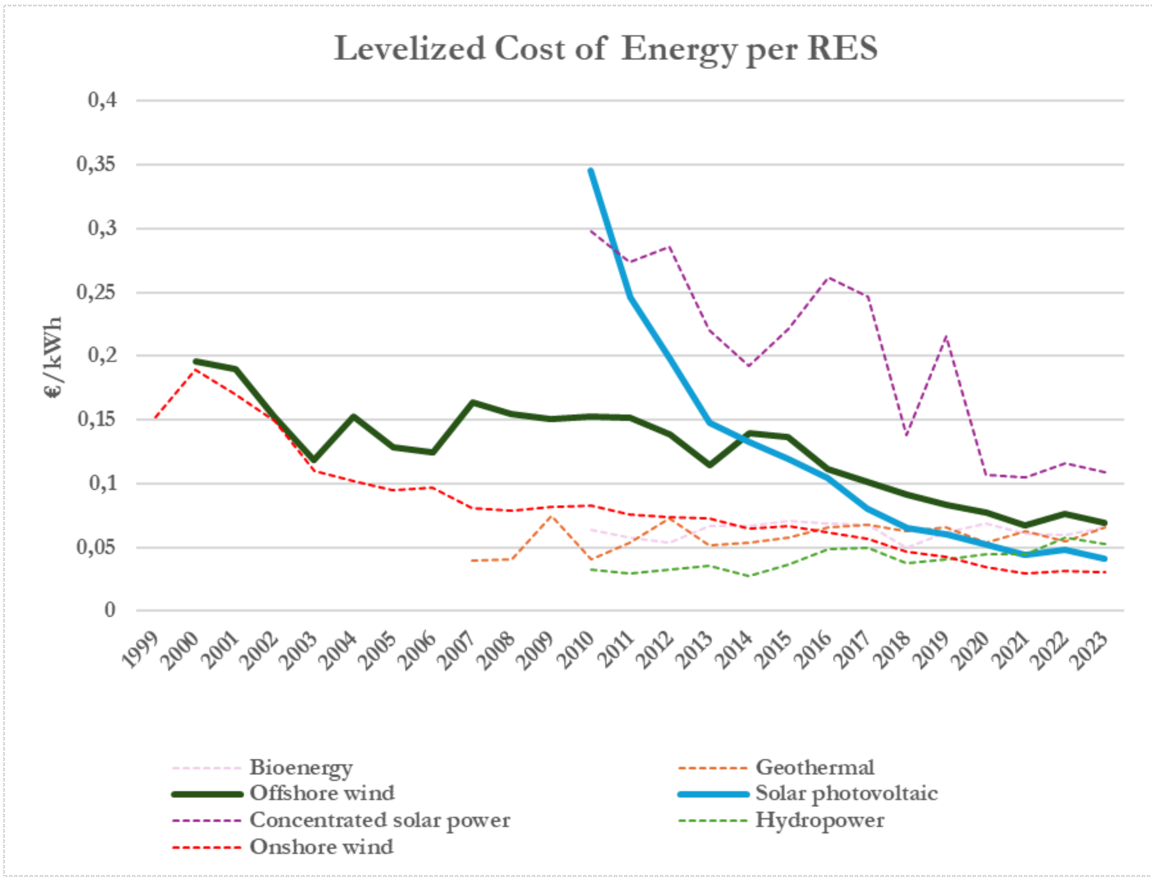


Figure 11 Adapted from IRENA (2024) – with minor processing by Our World in Data. "Bioenergy levelized cost of energy" [dataset]. IRENA, "Renewable Power Generation Costs" [original data].

Risk Management in Offshore Wind Financing:

Offshore wind project financing is associated with significant risks, given the scale and complexity of developments. Key risks include construction-related challenges such as cost overruns, logistical delays, and unpredictable weather conditions. Operational risks, including high maintenance costs, turbine downtime, and energy production variability, can further impact project economics. Additionally, market risks, such as fluctuating electricity prices and changing regulatory frameworks, introduce uncertainty into long-term financial planning. To mitigate these risks, stakeholders implement robust project management strategies, establish contingency reserves, secure insurance coverage, and utilize well-defined contractual agreements to allocate risks effectively. Lenders and investors closely monitor these risk mitigation measures to ensure project feasibility and safeguard financial returns (Green Giraffe, 2019). Despite these challenges, offshore wind energy presents significant economic and strategic benefits that justify its high upfront costs. Offshore wind contributes to energy security by diversifying the energy mix and reducing reliance on fossil fuels. Additionally, it plays a crucial role in job creation across the supply chain and fosters technological innovation, reinforcing its importance in achieving carbon neutrality goals (Hrouga & Bostel, 2021). In Europe, affordability remains a key consideration in energy policy, ensuring that renewable energy sources remain cost-competitive with fossil fuels. Offshore wind contributes to reducing long-term energy costs while strengthening the EU's economic position relative to other global markets, such as the United States and China. However, to maintain its competitive advantage, offshore wind must continue to lower its LCOE while sustaining high levels of reliability and performance (Wee, 2012; Johnston et al., 2020).

Cost Reduction Trends and Implications

Wind turbine and power plant upsizing have become key trends in offshore wind deployment, significantly influencing project economics and energy production. Between 2010 and 2019, the average turbine capacity installed in offshore wind farms grew from less than 3 MW to over 6 MW. Simultaneously, the typical size of offshore wind projects doubled, increasing from an average of 190 MW to nearly 400 MW. As offshore wind farms expand in scale and capacity, the number of turbines per farm has steadily increased and is expected to continue growing (Soares-Ramos, 2020). As seen in Figure 12 the number of turbines will relatively increase more over the coming years than the number of wind farms meaning that the number of turbines per farms will increase. This trend of upsizing is anticipated to continue as technology advances and economies of scale become more pronounced (Shields et al., 2021). Research by Shields et al. (2021) highlights that within a design range of 6–20 MW turbines and 250–2500 MW plant capacities, opting for larger turbines and plant sizes leads to significant economic advantages. Increasing turbine capacity to 20 MW and plant size to 2500 MW reduces the Levelized Cost of Energy (LCOE) by approximately 23.6%, from $69.8/MWh to $53.3/MWh. This reduction is attributed to several key factors:

1. Balance-of-System (BOS) Cost Reductions: BOS costs, which include expenses for cables, foundations, and substations, decrease by up to 29.2% as plant capacity increases. Larger projects benefit from economies of scale, optimizing logistics and infrastructure (Shields et al., 2021).
2. Operations and Maintenance (O&M) Savings: O&M costs decrease by approximately 36.7% with upsized turbines and plant capacities. Larger turbines reduce the need for frequent servicing and maintenance interventions compared to a greater number of smaller turbines, thereby lowering operational expenditures.
3. Annual Energy Production (AEP) Gains: Larger turbines capture more wind energy per installation, leading to a 5.8% increase in AEP, thereby enhancing overall project efficiency (Shields et al., 2021).

As offshore wind projects scale up, Balance-of-System (BOS) cost reductions are achieved across various infrastructure components, including array cables, export cables, monopiles, substations, and turbine installations. When plant sizes expand from 500 MW to 2500 MW, these cost categories see significant savings due to improved logistics, reduced duplication of infrastructure, and the more efficient deployment of installation vessels (Shields et al., 2021). Large-scale projects benefit from bulk procurement and optimized project execution strategies, which help lower the cost per megawatt installed. Larger turbines enhance energy production per megawatt of installed capacity, making them a more efficient investment. However, as turbine size and plant capacity increase, wake losses—reductions in energy output caused by turbines blocking wind flow to downstream turbines—can become more pronounced. Despite this, the overall gains in energy production from using larger turbines generally outweigh the negative effects of wake losses (Shields et al., 2021). Advanced wake loss mitigation strategies, such as optimized turbine spacing and yaw control technologies, continue to be developed to further improve energy yields. As offshore wind capacity expands, the financial landscape will increasingly favor large-scale projects with advanced cost-reduction strategies. The combination of declining CAPEX and OPEX, along with rising energy production efficiencies, will ensure that offshore wind remains a cornerstone of future energy systems.

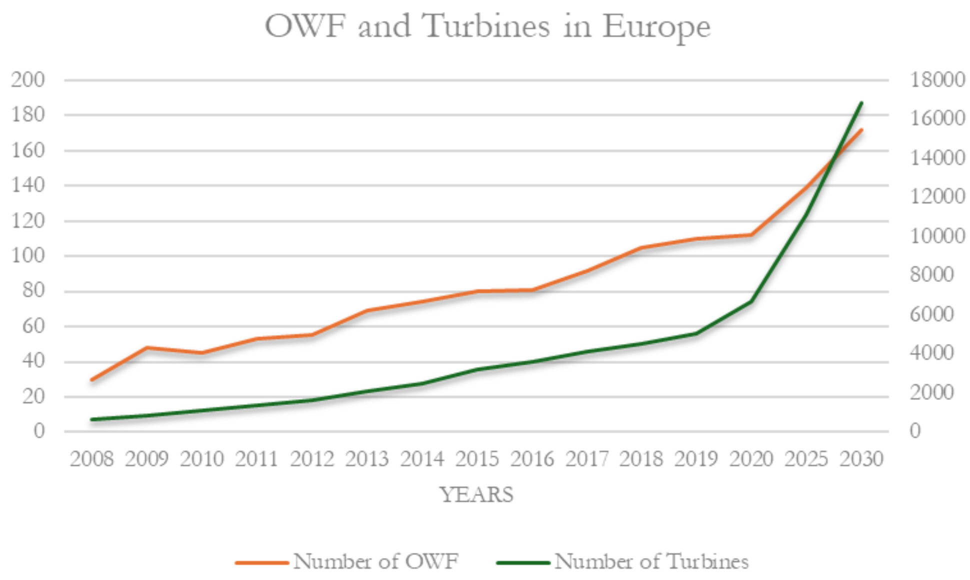


Figure 12: Adapted from Soares, C. G. (2020). Review of the status, technology and future trends of offshore wind farms. Ocean Engineering, 209, 107381.

The increasing scale of offshore wind turbines and power plants is driving a significant rise in material demand. Table 1 presents the projected annual material demand for various key materials in offshore wind energy development, highlighting the growth expected between 2020, 2030, and 2040 (Li et al., 2022). As turbines become larger and more powerful, the need for structural components, electrical systems, and rare earth elements (REEs) is expected to surge by 2040.

1. Steel and Concrete: The most substantial increase is projected for low-alloy steel, essential for towers and foundations, with demand growing from 3,496.2 kilotonnes (kt) in 2020 to 22,344.2 kt by 2040, marking a sixfold increase. Similarly, iron demand is expected to rise by 613%, reflecting the structural reinforcements required for taller towers and larger nacelles. Concrete usage is also projected to grow significantly, from 265.4 kt in 2020 to 2,316.7 kt in 2040, an 870% increase, due to the expansion of gravity-based and deep-water foundations (Li et al., 2022).
2. Rare Earth Elements (REEs) and Advanced Materials: The shift toward direct-drive turbines, which eliminate gearboxes in favor of permanent magnet generators, has intensified demand for REEs such as neodymium, dysprosium, and praseodymium. While their usage in offshore wind was relatively low in 2020, demand is projected to rise by 1027% for neodymium, 797% for dysprosium, and 1810% for praseodymium by 2040. These elements are critical for enhancing turbine efficiency and reliability, particularly in large-scale offshore installations (Li et al., 2022).
3. Key Metals: Essential metals such as copper, aluminum, and zinc will also see sharp increases in demand. Copper, used in electrical wiring and transmission cables, is expected to grow by 407% by 2040 as offshore wind farms scale up and expand further from shore. Aluminum, widely used in tower structures and nacelle components, is projected to increase by 359%, while zinc, essential for corrosion-resistant coatings, will rise by 416%. These materials play a pivotal role in ensuring structural integrity and long-term durability in the harsh marine environment (Li et al., 2022).
4. Rotor Blades and Composite Materials: As turbines increase in size, longer and more aerodynamic blades are required to capture more wind energy. This trend is reflected in the growing demand for polymers, glass fiber, and carbon fiber, which are used to construct lightweight yet durable rotor blades. Carbon fiber demand is projected to rise by 5403% by 2040, underscoring the industry's reliance on advanced composite materials to improve turbine performance while maintaining structural flexibility (Li et al., 2022).

The rapid increase in material consumption due to turbine and plant upsizing highlights the need for strategic supply chain planning, including resource diversification, recycling initiatives, and secure procurement strategies. As offshore wind capacity expands, ensuring a stable and sustainable supply of critical materials will be essential to maintaining cost reductions and meeting global renewable energy targets. These materials and components are supplied by an extensive network of companies operating in different countries. To fully understand offshore wind network this global supply network need to be further analysed.

Table 1: Adapted from Li, C., Cai, J., Zhang, S., & Guedes Soares, C. (2022). Material demand and supply chain analysis for offshore wind energy under different scenarios. Renewable and Sustainable Energy Reviews, 164, 112603

Material	**Component(s)**	**Annual Demand (2020) (kt)**	**Annual Demand (2030) (kt)**	**Annual Demand (2040) (kt)**	**Ratio to Current Demand (2040) (%)**
Iron	Tower, Nacelle	234.3	619.3	1436.3	613.0
High-Alloy Steel	Tower, Nacelle	179.3	430.5	911.7	508.5
Low-Alloy Steel	Tower, Foundation	3496.2	8883.8	22344.2	639.1
Concrete	Foundation	265.4	289.3	2316.7	872.9
Electrical & Electronics	Nacelle, Tower	8.8	17.7	49.3	560.3
Polymer	Blades	55.6	123.1	231.4	416.2
Resin	Blades	53.0	123.6	232.5	438.7
Glass Fiber	Blades	108.9	225.1	296.6	272.4
Carbon Fiber	Blades	5.1	52.3	275.6	5403.2
Neodymium	Nacelle	0.3	0.8	3.2	1027.3
Dysprosium	Nacelle	~0.0	0.1	0.3	797.9
Praseodymium	Nacelle	~0.0	0.1	0.5	1810.5
Terbium	Nacelle	~0.0	~0.0	0.1	1350.9
Copper	Nacelle, Cables	17.2	46.8	69.9	406.5
Aluminum	Nacelle, Tower	11.9	25.5	42.8	359.3
Chromium	Tower, Nacelle	5.9	13.5	26.5	448.7
Manganese	Tower, Nacelle	9.5	21.1	39.9	420.0
Molybdenum	Tower, Nacelle	1.2	2.7	5.3	444.4
Nickel	Tower, Nacelle	5.1	10.9	18.0	353.9
Zinc	Tower, Foundation	66.4	147.0	276.4	416.2
Boron	Nacelle	~0.0	~0.0	0.1	2675.9

4.4. Global Supply Network Analysis

4.4.1. Offshore Wind Component supply

The offshore wind industry is less fragmented than its onshore counterpart, with a concentrated number of key players dominating the global market. Leading developers such as Vattenfall, Ørsted (formerly Dong Energy), and E.ON drive offshore wind expansion, often collaborating with engineering firms, suppliers, and national governments to secure tenders. Europe remains the global leader in offshore wind development, with Denmark, Germany, and the Netherlands acting as major hubs for both offshore wind project deployment and supply chain activity (Hrouga & Bostel, 2021). The offshore wind supply chain in the North Sea has matured significantly, focusing on efficiency, local manufacturing, and supply chain resilience. Advances in wind turbine technology have led to larger turbines, with capacities exceeding 15 megawatts, improving energy production while reducing the number of turbines required per wind farm. The manufacturing sector is primarily dominated by European firms such as Siemens Gamesa and Vestas which have established production facilities across the region. Countries like Denmark, Germany, and the Netherlands have invested in local manufacturing hubs to strengthen supply chain security and reduce reliance on global logistics (WindEurope, 2022).

Europe possesses one of the world's most advanced manufacturing networks for offshore wind components, supported by an interconnected supply chain facilitated by the European Union Free Trade Agreement. This allows for streamlined movement of goods across borders, enhancing collaboration between different manufacturers. Germany, Spain, and Denmark play crucial roles in producing key wind turbine components such as blades, nacelles, and towers. France has recently expanded its role by developing blade and nacelle production facilities, while the Netherlands and Germany lead in the production of offshore wind foundations. The supply chain for offshore wind extends beyond turbines. Medium- and high-voltage cable production is concentrated in countries such as Italy, France, the UK, Poland, Norway, and Sweden, where companies specialize in both offshore wind interconnectors and subsea power transmission for other industries, such as oil and gas electrification. A significant portion of these manufacturing facilities is in port cities, ensuring streamlined transportation by sea and reducing logistical bottlenecks.

The construction of the Beatrice offshore wind farm in the UK provides an example of the complexity of offshore wind supply chain coordination. The project required contributions from ten suppliers and six contractors for its major components. Siemens Gamesa produced blades in Hull, UK, while nacelles were assembled in Cuxhaven, Germany. Foundations were sourced from multiple companies, including BiFab in Scotland, EEW in Germany, and Sif in the Netherlands. Smulders contributed upper sections of jackets from Belgium, while final assembly took place in Newcastle. The project's supply chain was further supported by the Port of Nigg in Scotland, which functioned as a primary marshalling hub, demonstrating the critical role of ports in offshore wind logistics (WindEurope 2022). Figure 13 highlights the detailed location of manufacturing bases, emphasizing the interconnectedness of European manufacturers and the pivotal role of port facilities in ensuring efficient assembly and deployment.

As the offshore wind sector expands, the demand for specialized materials and manufacturing capabilities will continue to increase. The supply chain's ability to scale up production while maintaining cost efficiency will be a determining factor in achieving ambitious offshore wind capacity targets.

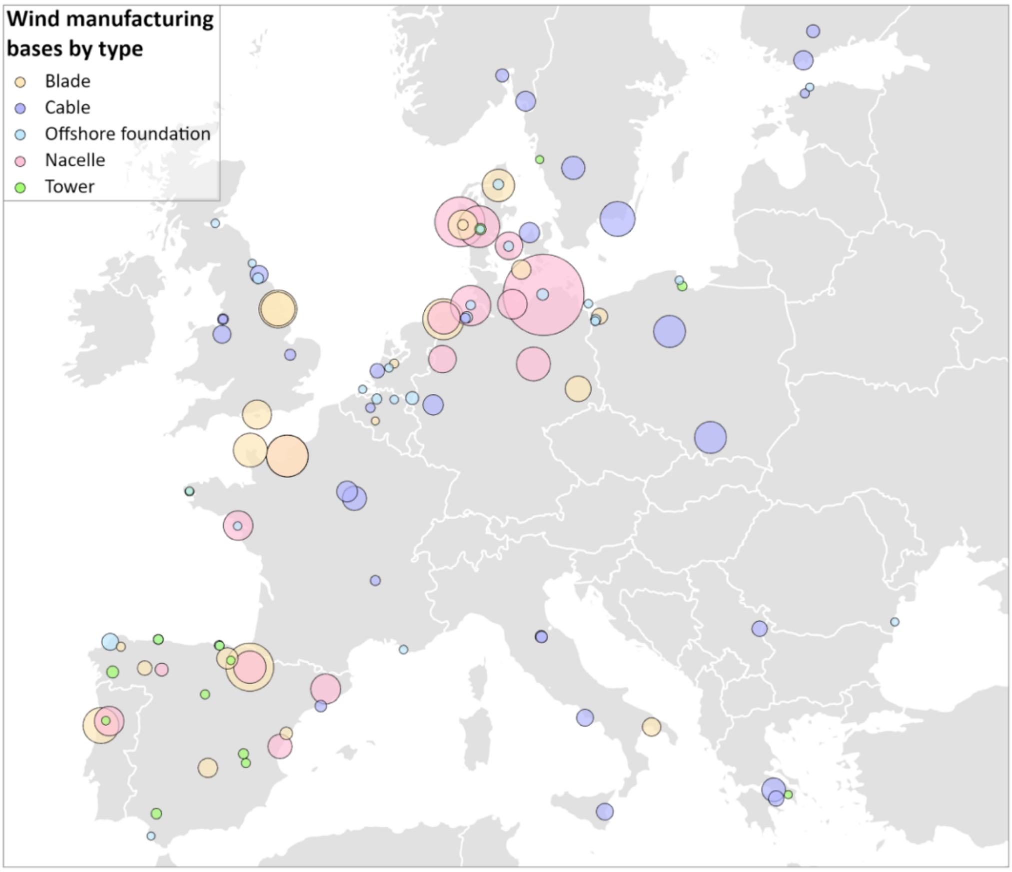


Figure 13: Adapted fromWindEurope. (2022). The state of the European wind energy supply chain: A "what-would-it-take" analysis of the European supply chain's ability to support ambitious capacity targets towards 2030. Rystad Energy in cooperation with WindEurope

4.4.2. Global Development Dynamics

After the world's first offshore wind power plant was installed in 1991 in Denmark, the growth of offshore wind farms had been remarkable by 2020. The industry showed strong indications that growth would continue in the following years. By 2018, there were 112 offshore wind farms operational, with 712 projects in various stages of development and 53 projects under construction (Soares-Ramos, 2020). This surge underscored the expanding interest and investment in offshore wind technology. Countries such as Greece, Finland, Norway, India, Brazil, Canada, Australia, Poland, and Croatia were beginning to get involved in offshore wind development. At that time, the total installed offshore wind capacity had reached approximately 18.9 GW, with a steady year-on-year growth trend (Soares-Ramos, 2020).

According to projections available at the time, the offshore wind industry was expected to grow significantly. Estimates suggested that by 2030, global offshore wind capacity could surpass 154 GW, reflecting a 412% increase in capacity over two decades (Walter et al., 2018).

By 2018, offshore wind farms were concentrated mainly in Europe, followed by Asia and America. The United Kingdom led in installed capacity with 7.3 GW, followed by Germany with 5.3 GW and Denmark with 1.2 GW. In Asia, China was emerging as a major player with 2.4 GW of installed capacity, while the United States was still in the early stages, with just 30 MW of capacity (Soares-Ramos, 2020). The distribution of offshore wind farms reflected Europe's dominance, accounting for nearly 85% of the global installed capacity by 2018. In Asia, significant developments were underway in countries such as China, Japan, South Korea, and Taiwan. The United States represented the nascent stage of offshore wind development in the Americas.

Table 2: Adapted from Global Offshore Wind Power Capacity and Investments (2018)

Continent	Country	Investment (M€)	Installed Capacity (MW)	Cost per MW (M€)	Number of Turbines
Europe	UK	25,643	7,347.8	3.5	1,796
	Germany	23,030	5,342.3	4.3	1,167
	Denmark	2,828	1,273.1	2.2	510
Asia	China	4,729	2,409.9	2.0	676
America	US	308	30.0	10.3	5

These figures highlight the significant investment required for offshore wind projects, particularly in Europe, which led the market in terms of capacity and infrastructure (Soares-Ramos, 2020). Also, you could see the difference between the cost differne per MW is particalty high between the US and China underscoring the relative low-cost manufacturing capacity of China.

China's dominance

China's dominance in the global wind energy supply chain reflects decades of investment, strategic policies, and innovation. With 20 offshore nacelle assembly facilities (one owned by a Western OEM) and 77 onshore facilities, China is a leader in wind turbine manufacturing, further supported by its announcement of 47 new offshore nacelle assembly facilities. The country also accounts for over 80% of global rare earth element production, a critical component for turbine magnets, and is a major producer of silicon and steel, essential for turbine construction (Hayley, 2024; WindEurope 2022). In contrast, the EU is heavily dependent on China for critical raw materials, relying on it for 100% of both light and heavy rare earth processing and 96% of silicon. These dependencies make the EU vulnerable to supply chain disruptions, especially amid geopolitical tensions. Recent sanctions on Russian exports due to the invasion of Ukraine have further complicated material flows, affecting critical supplies like steel, aluminum, and nickel. While the EU has launched the Net Zero Industry Act and the Critical Raw Materials Act to bolster domestic manufacturing, these policies risk shifting bottlenecks rather than resolving foundational dependencies (WindEurope 2022).

China's current leadership in wind energy stems from its evolution from a technological importer in the 1980s to a global innovator. By 2011, China had 40% of global wind generation capacity, supported by state policies like the Five-Year Plans and R&D programs (Gallagher, 2006; CWEA, 2012). In 2023, it installed 77.1 GW of wind capacity—65% of the global total—and manufactured 60% of the world's wind turbines, compared to 19% in Europe and 9% in the U.S. This dominance is further bolstered by low-cost upstream components and a domestic supply surplus, making Chinese turbines 20% cheaper than their Western counterparts (Hayley, 2024).

China's manufacturers, such as Goldwind and Envision, lead global orders, with 55.3 GW in 2022 compared to 26.7 GW from Western competitors. Additionally, China introduced 426 new turbine models in four years, while Western firms introduced only 29. This rapid innovation positions China as a key player in renewable energy, controlling 70–80% of core wind components and refining nearly 100% of the critical minerals needed for turbine manufacturing. These factors underscore China's unparalleled influence in the global renewable energy market and highlight the challenges of diversifying supply chains (Hayley, 2024; CWEA, 2012; WindEurope 2022).

4.5. S-Curve Analysis

This section will cover the evolution of the offshore wind value chain over time, the current activities, its financial aspects and global supply network. For each phase the 4 countries of Denmark, The United Kingdom, Germany and The Netherlands are covered to as these are countries with the most ambitious goals for offshore wind development in the North Sea

Innovation Phase

The Innovation Phase (1991–2001) marks the inception of offshore wind energy development in the North Sea, characterized by experimental projects and the establishment of foundational policies and regulations.

Denmark: Denmark pioneered offshore wind deployment with the commissioning of the Vindeby wind farm in 1991, the world's first offshore wind project. The project's eleven 450 kW turbines demonstrated the feasibility of offshore wind despite facing construction and maintenance challenges in the marine environment (Kaldellis & Kapsali, 2013). This early success was followed by the Middelgrunden wind farm in 2000, a 40 MW project that marked Denmark's continued expansion in offshore wind energy (Kaldellis & Kapsali, 2013). During this period, Denmark's regulatory environment emerged with early frameworks to facilitate offshore wind development (Maegaard et al., 2013).

United Kingdom: Early offshore wind development in the UK gained traction with projects like Blyth Offshore Wind Farm (2000), contributing to the country's initial deployment efforts. The Crown Estate played a pivotal role in facilitating offshore wind development by organizing leasing rounds that designated offshore wind zones for developers, ensuring streamlined site identification and permitting (Fitch-Roy, 2016).

Germany: In Germany, early offshore wind development was limited during this phase, focusing instead on environmental assessments and offshore site selection. Although no major projects were deployed at the time, these efforts laid the groundwork for large-scale development in later phases (Shittekatte, 2016). Grid connection responsibilities remained with developers during this period, adding financial risks for offshore wind investors (Markard & Petersen, 2009).

The Netherlands: The Netherlands saw minimal offshore wind development during this period, with no major offshore wind farms constructed before the Market Adaptation Phase. Early policies focused on environmental assessments and spatial planning to identify suitable offshore sites (RES Legal, 2024).

Value Chain Activities:

1. **Pre-Development and Consenting**: During this period, North Sea countries began exploring offshore wind potential through small-scale demonstration projects. The regulatory environment was nascent, with governments formulating initial frameworks to facilitate these pioneering projects. Denmark led the way with the Vindeby Offshore Wind Farm in 1991, which set a precedent for offshore wind development (Maegaard et al., 2013).
2. **Manufacturing:** The initial offshore turbines were adaptations of onshore models, not yet optimized for marine conditions. This adaptation phase involved collaboration between manufacturers and research institutions to address challenges unique to the offshore environment, such as corrosion and accessibility. The supply chain was in its infancy, with limited specialized components available, leading to higher costs and reliance on bespoke solutions (Maegaard et al., 2013).
3. **Installation and Commissioning**: Early installations faced logistical hurdles due to the lack of specialized vessels and equipment. The oil and gas industry's existing maritime infrastructure were often repurposed, but this was not always ideal for wind turbine installation. Challenges included securing stable foundations in varying seabed conditions and ensuring the safety of operations in unpredictable marine environments (Halldorsson & Svanberg, 2013).

4. **Operation and Maintenance (O&M):** Maintenance strategies were predominantly reactive, addressing issues as they arose due to the limited operational data available. The harsh marine environment posed challenges such as biofouling and mechanical wear, leading to higher maintenance costs and efforts to develop more durable materials and components (Shafiee, 2015).
5. **Decommissioning and Disposal:** Given the novelty of offshore wind farms, decommissioning was largely uncharted territory. Early projects did not have comprehensive decommissioning plans, prompting regulatory bodies to begin considering guidelines to address future needs, including environmental impact assessments and financial provisions for dismantling (Johnston et al., 2020).

Market Adaptation Phase
The Market Adaptation Phase (2001–2008) signifies a transition from experimental projects to more standardized and commercially viable offshore wind developments in the North Sea. During this phase, offshore wind farms became larger, and regulatory frameworks were refined to facilitate scaled deployment. Technological innovations improved turbine efficiency and expanded development into deeper waters.
Denmark: In Denmark, offshore wind expansion accelerated with the commissioning of Horns Rev 1 in 2002, one of the first large-scale offshore wind farms with a capacity of 160 MW. This project demonstrated the potential for offshore wind at a commercial scale and contributed to technological advancements (Kaldellis & Kapsali, 2013). Denmark's tendering system, introduced in 2003, became a key policy mechanism for promoting offshore wind deployment. This system combined pre-selected offshore sites with reverse auctions, awarding projects to developers that bid the lowest production cost (Fitch-Roy, 2016).
United Kingdom: The Crown Estate's leasing rounds in the United Kingdom, which began with bilateral arrangements in 2000 and 2003, were reformed in 2009 to introduce designated offshore wind zones, designed to provide developers with flexibility in project siting (Fitch-Roy, 2016). This strategic shift aligned with the UK's increasing offshore wind ambitions. Additionally, The Crown Estate's role as seabed landlord ensured organized site allocation through commercial leasing agreements, enhancing investor confidence in offshore wind expansion. By 2008, the UK had several operational offshore wind farms, including Scroby Sands and Kentish Flats (Fitch-Roy, 2016). The introduction of the Renewables Obligation (RO) in 2002 further supported offshore wind investment by providing financial incentives for renewable energy generation (Fitch-Roy, 2016).
Germany: In Germany, the offshore wind framework shifted toward a centralized grid connection model during this phase. Transmission System Operators (TSOs) were tasked with connecting offshore wind farms to the onshore grid. This proactive approach provided developers with greater certainty and reduced financial risks.
The Netherlands: In the Netherlands, offshore wind development gained momentum with the commissioning of the Egmond aan Zee wind farm (108 MW) in 2006 and the Prinses Amalia wind farm (120 MW) in 2008. Despite these projects, Dutch offshore wind capacity remained relatively modest compared to the UK and Denmark during this phase (Fitch-Roy, 2016). Spatial planning in Dutch waters was guided by the National Water Plan (NWP), which limited available offshore sites to designated areas. Land tenure and permission to build were combined in a single consent process coordinated by Rijkswaterstaat Noordzee, ensuring environmental and social considerations were integrated into offshore wind development (Fitch-Roy, 2016). The Netherlands also introduced the MEP scheme in 2003, enhancing investor confidence by offering feed-in tariffs for renewable energy projects (RES Legal, 2024).

Value Chain Activities:

1. **Pre-Development and Consenting:** Governments in the region introduced more structured policies to streamline the development process. The United Kingdom initiated the first offshore wind leasing rounds in 2001, identifying specific zones for development and establishing clearer consenting processes. The Netherlands implemented the MEP (Environmental Quality of Electricity Production) scheme in 2003, offering feed-in tariffs to support renewable energy projects, thereby enhancing investor confidence (RES Legal, 2024). Denmark introduced a tendering system in 2003, combining pre-selected offshore sites with reverse auctions, awarding projects to developers that bid the lowest production cost (Fitch-Roy, 2016).
2. **Manufacturing:** Technological advancements led to the development of turbines specifically designed for offshore conditions, with increased capacities and improved reliability. The supply chain matured, with more specialized manufacturers entering the market, leading to economies of scale and cost reductions. Collaborative efforts among North Sea countries facilitated knowledge sharing and standardization, further driving down costs (Rodrigues et al., 2015).
3. **Installation and Commissioning:** The experience gained from initial projects informed better planning and execution strategies. Purpose-built installation vessels were developed, reducing dependency on repurposed oil and gas infrastructure. Innovations in foundation designs, such as monopiles and jacket structures, allowed for installations in deeper waters, expanding the potential sites for development (Halldorsson & Svanberg, 2013).
4. **Operation and Maintenance (O&M):** The adoption of condition monitoring systems enabled a shift towards predictive maintenance, reducing downtime and operational costs. The establishment of maintenance hubs in strategic coastal locations improved response times and logistical efficiency. Training programs were developed to build a skilled workforce specialized in offshore wind O&M activities (Shafiee, 2015).
5. **Decommissioning and Disposal:** As the industry anticipated the end-of-life phase of early installations, preliminary guidelines and best practices for decommissioning were developed. Emphasis was placed on environmental protection, safe removal of structures, and recycling of materials. Financial mechanisms, such as decommissioning funds, were established to ensure that resources would be available for future dismantling activities (Johnston et al., 2020).

Market Stabilization Phase

The Market Stabilization Phase (2008–present) marks the period in which offshore wind energy transitioned into a fully commercialized and competitive industry. This phase is characterized by the emergence of large-scale offshore wind farms, cost reductions driven by economies of scale, and increased policy standardization across the North Sea region. Countries such as the United Kingdom, Germany, the Netherlands, and Denmark played key roles in shaping the offshore wind industry during this phase.

Denmark: Denmark continued to expand its offshore wind portfolio with projects like Horns Rev 3 (407 MW), reinforcing its position as a leader in offshore wind. The Danish approach emphasizes a stable policy framework with clear permitting processes and coordinated grid planning (Kaldellis & Kapsali, 2013). As part of this phase, Denmark adopted a two-sided Contract for Difference (CfD) system, which allows for both fixed price guarantees and exposure to wholesale electricity market prices (Jansen et al., 2022). This design encourages competition among developers while offering a safety net against market volatility. Denmark's model also includes revenue stabilization measures to mitigate price risks, providing developers with top-up payments if market prices fall below a predetermined level. However, there are concerns that such mechanisms, as seen in projects like the Thor auction, expose investors to higher risks when revenue caps are reached (Jansen et al., 2022). The Danish Energy Agency (DEA) continued its coordinated permitting system, acting as a one-stop-shop for project developers and maintaining Denmark's efficient development timeline (Fitch-Roy, 2016).

United Kingdom: The UK emerged as the largest offshore wind market in the North Sea, aided by the Contracts for Difference (CfD) scheme that replaced the Renewables Obligation (RO). The CfD scheme ensures stable revenue streams for developers, encouraging continued investment in large-scale projects such as the London Array (630 MW) and Hornsea 2 (1.3 GW) (Fitch-Roy, 2016). The UK model employs both one-sided and two-sided CfDs, providing strong revenue stabilization that reduces investor uncertainty and fosters a competitive bidding environment (Jansen et al., 2022). The Crown Estate's leasing rounds evolved into a more structured process with designated zones that allowed developers greater flexibility in project planning, improving site selection outcomes (Fitch-Roy, 2016). Additionally, the UK's competitive Offshore Transmission Owner (OFTO) model allowed third-party investors to bid for the ownership and operation of transmission assets, promoting efficient capital use and reducing developer risks (Fitch-Roy, 2016).

Germany: Initial delays in grid connections led to concerns about project timelines (Shittekatte, 2016). In response, Germany introduced the Offshore Grid Development Plan (O-NEP) in 2013, aligning transmission development with offshore wind project timelines. The plan enabled more proactive grid planning to avoid project delays (Fitch-Roy, 2016). Additionally, Germany's Federal Maritime and Hydrographic Agency (BSH) implemented a Marine Spatial Plan (MSP) in 2009, which designated priority areas for offshore wind development to ensure environmental protection and efficient project coordination (Fitch-Roy, 2016). Germany transitioned from fixed feed-in tariffs to competitive auction-based pricing mechanisms, improving cost efficiency. The German model primarily relies on one-sided CfDs that guarantee payments for energy produced, fostering competition while exposing developers to some price risks (Jansen et al., 2022). While this strategy has enabled aggressive bidding and reduced costs, the emergence of zero-subsidy bids in recent auctions raised concerns regarding the financial viability and stability of projects (Jansen et al., 2022). Germany's Offshore Grid Development Plan (O-NEP), which TSOs develop and update annually, improved coordination between offshore wind developers and TSOs, ensuring better integration into the grid (Shittekatte, 2016).

The Netherlands: The Netherlands implemented significant reforms to accelerate offshore wind deployment. The Dutch approach combined seabed lease auctions with a mix of one-sided and two-sided CfDs to mitigate market risks and ensure stable revenue streams (Jansen et al., 2022). By designating specific wind farm zones and assigning grid connection responsibilities to TSO TenneT, the Netherlands reduced risks for developers, increasing investment appeal (Fitch-Roy, 2016). Revenue stabilization features in Dutch auctions provide developers with consistent financial support across varying market conditions (Jansen et al., 2022). Later auctions include zero-subsidy bids to further increase revenues for the government. The Dutch National Water Plan (NWP), established under the Water Management Act, restricted wind farm development to designated zones to minimize conflicts with other marine users, improving coordination (Fitch-Roy, 2016). The streamlined permitting process, which integrates land tenure, construction approval, and environmental compliance, further strengthened the Dutch offshore wind sector's stability (Fitch-Roy, 2016).

Value Chain Activities:

1. **Pre-Development and Consenting:** During this phase, governments refined regulatory frameworks to create a more predictable and efficient development environment for offshore wind energy. In the United Kingdom, the Contracts for Difference (CfD) scheme was introduced as a replacement for the Renewables Obligation Certificate (ROC) system, ensuring stable revenues for developers while encouraging competition (United Kingdom Government, 2019). Similarly, Germany transitioned from fixed feed-in tariffs to an auction-based CfD system to reduce subsidy costs while maintaining investment security (Vieira et al., 2019). The Netherlands streamlined offshore wind development with the

Offshore Wind Energy Act of 2015, which centralized site selection and permitting under the government, reducing development risks for private investors (RES Legal, 2024). Denmark introduced competitive tendering processes, requiring developers to bid on pre-approved offshore wind sites, eliminating uncertainties associated with initial feasibility studies (NERA Economic Consulting, 2017).

2. **Manufacturing:** Technological advancements enabled the development of larger and more efficient wind turbines. By the late-2010s, the industry moved from 3–5 MW turbines to models exceeding 10 MW, reducing the number of turbines needed per wind farm and improving overall efficiency (Rodrigues et al., 2015). The modular production of wind turbine components improved supply chain logistics, reducing lead times and costs. The North Sea countries invested heavily in local supply chains, fostering regional manufacturing hubs and reducing reliance on distant suppliers. Grid connection policies also played a crucial role in stabilizing the offshore wind sector. The North Sea Wind Power Hub initiative proposed an interconnected offshore grid to optimize resource distribution and improve energy security. Additionally, subsidy schemes in the Netherlands prioritized offshore wind integration into national energy strategies, ensuring continued demand for offshore-generated electricity (RES Legal, 2024).
3. **Installation and Commissioning:** Innovations in foundation designs and installation techniques allowed offshore wind farms to be built in deeper waters, further expanding the potential for deployment. Floating foundations emerged as a viable alternative to traditional monopile and jacket structures, especially for sites with deeper seabeds. Additionally, purpose-built installation vessels and jack-up rigs increased installation efficiency, reducing project timelines and lowering costs (NERA Economic Consulting, 2017). The expansion of port infrastructure in North Sea countries facilitated larger turbine components and improved logistics. Ports in the UK, Germany, and the Netherlands were upgraded to handle the next generation of offshore wind projects, further enhancing the industry's ability to scale up.
4. **Operation and Maintenance (O&M):** The introduction of predictive maintenance systems and advanced remote monitoring technologies significantly reduced O&M costs. Autonomous drones and robotics became widely used for blade inspections and repairs, decreasing the need for expensive vessel-based maintenance (Shafiee, 2015). In addition, specialized offshore service hubs were established in major wind farm clusters, allowing for quicker response times and more efficient maintenance operations. Transmission System Operators (TSO) improved grid connection reliability, ensuring that offshore wind farms could feed electricity into national grids with minimal disruptions. Insurance mechanisms also evolved to reflect the lower risk profiles of offshore wind farms, making financing more attractive to investors (United Kingdom Government, 2019).
5. **Decommissioning and Disposal:** As some early offshore wind farms approached the end of their operational life, governments introduced clearer decommissioning regulations. The EU and North Sea countries emphasized circular economy principles, encouraging turbine component recycling and material repurposing. Tradable certificate system provided financial incentives for dismantling and reusing components, ensuring that decommissioning was carried out sustainably (RES Legal, 2024).

Chapter 4 provided a comprehensive analysis of offshore wind energy development in the North Sea, addressing the value chain, financial structure, and global supply network. Here after change of offshore wind development over time was analyzed using a S-curve and with a focus on Germany, The United Kingdom, The Netherlands and Denmark. The core findings from this analysis are summarized as follows:

Firstly, the value chain analysis highlighted the breadth and complexity of offshore wind energy processes, emphasizing that significant scaling in all phases is required to achieve ambitious growth targets. While the industry has experienced substantial growth over recent decades, further expansion requires substantial investments in the value chain, such as installation capacity, grid infrastructure, and specialized personnel.

Secondly, the financial analysis demonstrated that the viability of offshore wind projects depends heavily on significant initial investments and stable financing models. Technological advancements and economies of scale have considerably reduced the levelized cost of energy (LCOE), enhancing offshore wind's competitive position. However, recent macroeconomic developments—such as inflation, rising interest rates, and expensive materials—have partially offset these cost advantages.

Lastly, the global supply chain analysis underscored the interdependency between Europe's offshore wind industry and international market dynamics. Critical components and materials for wind turbines are predominantly sourced from outside Europe, notably from China, which has emerged as a dominant player in the global wind market. This reliance on imported components introduces vulnerabilities such as disruptions in global trade, price volatility, and geopolitical tensions, which could significantly impact North Sea offshore wind projects. Conversely, global interconnectedness has contributed to cost reductions and rapid sector innovation.

The development of offshore wind energy in the North Sea exemplifies a classic S-curve of innovation, transitioning through distinct phases: Innovation, Market Adaptation, and Market Stabilization. During the Innovation Phase (1991–2001), offshore wind was characterized by experimental projects and substantial risks, heavily reliant on governmental support and subsidies. Denmark led the way with the Vindeby wind farm in 1991, showcasing the feasibility despite significant logistical and financial challenges. Similarly, early UK projects like Blyth Offshore Wind Farm (2000) relied on strategic support from leasing arrangements by The Crown Estate, underscoring the dependence on existing maritime and wind industry expertise due to immature supply chains. Germany and the Netherlands primarily focused on preliminary assessments and spatial planning, laying the groundwork without significant early deployments. In the Market Adaptation Phase (2001–2008), offshore wind began achieving commercial viability. Denmark accelerated deployment with the Horns Rev 1 project in 2002, leveraging structured tendering systems to encourage competitive bidding. The UK's Renewables Obligation (2002) and strategic site allocations by The Crown Estate improved market conditions, resulting in operational projects like Scroby Sands. Germany shifted towards a centralized grid connection model managed by Transmission System Operators, significantly reducing developer risks. In the Netherlands, initial commercial deployments like Egmond aan Zee (2006) were supported by the MEP feed-in tariff scheme, indicating growing confidence and governmental backing. Currently, in the Market Stabilization Phase (2008–present), offshore wind has evolved into a mature, commercialized industry characterized by competitive market mechanisms, larger projects, and advanced technologies. Denmark continued leadership with projects like Horns Rev 3 (407 MW), supported by a refined two-sided Contract for Difference (CfD) model that balances market risk and revenue stability. The UK reinforced its position through the CfD scheme and innovative Offshore Transmission Owner (OFTO) model, exemplified by large-scale deployments such as Hornsea 2 (1.3 GW). Germany streamlined grid connections with its Offshore Grid Development Plan (O-NEP) and implemented competitive auctions, while the Netherlands enhanced its offshore wind framework by centralizing site selection, integrating environmental compliance, and employing mixed CfD models, thus attracting robust market-driven investments. Overall, the progression along the S-curve highlights a transformative journey from experimental, subsidy-dependent technologies to a highly competitive, commercialized market. Despite reduced direct subsidies, market mechanisms increasingly drive investments, introducing new financial dynamics like price volatility and competition for site allocations. Technological innovation continues with larger, more efficient turbines, streamlined manufacturing processes, and advanced installation techniques.

However, the industry now faces macroeconomic challenges, including rising interest rates, inflationary pressures on component costs, and critical global supply dependencies, particularly on China. Further analyzing these interconnected challenges will be essential for understanding offshore wind development in the North Sea.

5. Offshore Wind Development Challenges Analysis

This chapter will cover the challenges that hinders offshore wind development in the North Sea and can lead to stagnating growth of offshore wind energy in the North Sea. These challenges were collected through interviews with stakeholders and actors at different stages of the value chain and a literature review on academic articles and industry reports covering the challenges. See Appendix A and B for the process of how the interviews and literature review were conducted. The section starts with an analysis of the interviews and what trends can be seen in the information. This information is then structured in the three categories earlier developed. The information is compared with findings from the literature review to provide some verification of the data used from the interviews. After this the CRT and the CLD are developed, showing which underlying causes led to challenges occurring and how these challenges can lead to stagnating growth of offshore wind development. The chapter ends with an interim conclusion.

5.1. Challenges found in Interviews

Across the 13 stakeholder interviews, a broad array of challenges in North Sea offshore wind development was repeatedly emphasized, with many common threads emerging alongside distinct concerns by individual experts. Numerous interviewees underscored serious supply chain bottlenecks – for example, a shortage of installation vessels and limited port capacity coupled with sharply rising costs of steel, turbines and other components – which have driven up project expenses and caused delays (Interview 2; Interview 8; Interview 10; Interview 13). Many also highlighted market and demand-side uncertainties undermining project viability: unpredictable electricity prices (especially in zero-subsidy contexts) and the slow growth of green power demand leave business cases on shaky ground, prompting calls for price-stabilization mechanisms and faster industrial electrification to absorb new capacity (Interview 4; Interview 1; Interview 12). There was broad agreement that regulatory and permitting hurdles significantly impede progress: lengthy, complex permitting processes and misaligned tender criteria across different countries were cited as slowing both projects and the expansion of manufacturing capacity (Interview 13; Interview 10; Interview 2).

Stakeholders further noted an overstretched value chain and workforce – a chronic shortage of skilled labor (from engineers and turbine technicians to specialized ecologists) alongside suppliers struggling to keep pace with ever-larger turbine designs – which in turn strains timelines and finances (Interview 1; Interview 9; Interview 5). Environmental and spatial constraints were another recurrent theme: stricter ecological requirements (e.g. mandatory turbine shutdowns to protect bird migrations) and limited space at sea are introducing new costs and uncertainties for developers (Interview 3), and some noted that the Netherlands' particularly stringent wildlife rules, while well-intentioned, can disadvantage its projects unless there is better international alignment (Interview 1). At the same time, several unique insights shed light on specific vulnerabilities. For instance, equipment manufacturers and contractors warned that the relentless "race" toward ever-bigger turbines is nearing physical and economic limits, forcing continuous reinvestment in new vessels, cranes and factories (Interview 6; Interview 7). They – along with others – also voiced concern about heavy dependence on non-European suppliers (especially from China) for key materials and components, which introduces geopolitical risks and tough low-cost competition for Europe's industry (Interview 5; Interview 6). Operations and maintenance specialists observed that inadequate collaboration and a short-term cost focus – such as developers keeping data siloed or deferring maintenance planning – are leading to repeated technical issues and higher long-term O&M costs (Interview 11). In sum, the interviews portray an offshore wind sector striving to scale up but grappling with interrelated challenges: the urgency to accelerate deployment is being tempered by grid integration struggles, mismatches between supply and demand, and a pressing need for more coordinated planning, standardization, and knowledge-sharing across the industry (Interview 4; Interview 13).

5.2. Structuring of the Challenges.

This section examines the key challenges that hinder offshore wind development, aligning them with the respective stages of the value chain, financial structure, and global supply network. By structuring the analysis in this way, the systemic nature of these challenges becomes clearer, highlighting how regulatory, financial, and supply chain barriers intersect across different phases of offshore wind deployment.

5.2.1. Value Chain Challenges

Pre-Development and Permitting Delays

The offshore wind sector heavily depends on government intervention, particularly in permitting and regulatory frameworks. As outlined in the Understanding Offshore Wind Development chapter, the industry has transitioned to auction-based financing mechanisms, such as Contracts for Difference (CfD) in the UK and Germany's auction-based feed-in tariff system. However, permitting delays remain a major bottleneck for developers, slowing project timelines and increasing costs (Interview 13). Interview findings emphasize that national permitting frameworks vary significantly across EU countries, creating inconsistencies and inefficiencies (Interview 1). Additionally, evolving tender criteria introduce uncertainty for project developers, with new ecological and circularity demands increasing administrative burdens and project costs (Interview 2). These challenges align with broader research, which highlights how complex permitting procedures remain a major obstacle in offshore wind deployment (Berk, 2024; WindEurope, 2022; Soares-Ramos, 2020).

Manufacturing and Installation Capacity

The rapid increase in turbine size, now exceeding 15 MW per unit, has outpaced infrastructure development, resulting in logistical bottlenecks. The limited availability of specialized installation vessels and port capacity presents a significant constraint on offshore wind deployment (Interview 9; Interview 12).

Interview 13 noted that installation vessels remain scarce globally, causing cascading project delays. Simultaneously, critical components such as hydrohammers and monopiles face supply shortages (Interview 9), further exacerbating these bottlenecks. The statements align with the findings of Dinh and Mckeogh about the identification of critical areas in the supply chain (e.g., turbine manufacturing and installation) that can cause delays and increased costs (2019).

The urgent need for expanded port capacity in the North Sea region has been emphasized by industry stakeholders (Interview 10). These findings are consistent with research from WindEurope (2022), which suggests that without increased investment in port infrastructure, offshore wind expansion may stagnate.

Operations and Maintenance Workforce Shortages

The offshore wind sector requires a highly skilled workforce to support turbine installation, maintenance, and logistics. However, the industry is experiencing a significant labor shortage, particularly for vessel operations, heavy lifts, and maintenance services (Interview 11; Interview 12). Bulski (2024) has also highlighted the lack of trained personnel as a critical bottleneck, slowing production speed and increasing operational costs.

Interview findings reveal that the training pipeline for new workers has not kept pace with industry growth. The oil and gas sector remains a direct competitor for skilled labor, making it even more difficult for offshore wind companies to attract talent (Interview 9).

Turbine Technology Risks and Standardization Issues

The rapid upsizing of offshore wind turbines has introduced significant engineering and operational risks. Interviewees noted that constantly evolving turbine models increase costs and require adaptation periods (Interview 7). This is supported by the findings of Soares-Ramos Advancements in technology are crucial for improving the efficiency and reliability of offshore wind farms (2020). Furthermore, there is a lack of standardization in turbine components, with custom designs increasing costs and inefficiencies (Interview 5; Interview 8). These challenges align with findings from the International Energy Agency (IEA, 2024) and Janipour (2023), which indicate that the rapid innovation in turbine sizes is outpacing vessel and infrastructure readiness, adding financial and logistical risks to projects.

5.2.2 Financial Structure Challenges

Investment Uncertainty and Rising CAPEX Costs

The previous chapter detailed how offshore wind projects are financed through project finance structures, relying on future revenues for repayment. However, rising capital expenditure (CAPEX) costs and suboptimal investment decisions have increased financial risks (Interview 3; Interview 7). These issues are further supported by Greve (2020) and Dinh & McKeogh (2019), who note that financial uncertainty is a key obstacle in offshore wind expansion. The high upfront investment required for offshore wind infrastructure—such as vessels, factories, and ports—presents another challenge. Developers face a trade-off between minimizing CAPEX and reducing operational expenditure (OPEX) over a project's lifetime (Cortizo et al., 2019). Short-term cost-saving measures in early project phases often lead to higher long-term expenses, increasing the Levelized Cost of Energy (LCOE) (Interview 3).

High Costs in the EU vs. Global Competitors (China)

European offshore wind manufacturers face higher costs than their Chinese competitors, making it difficult to attract investors (Interview 6). While China benefits from state-backed subsidies and vertically integrated supply chains, European developers must navigate complex market-based financing mechanisms, increasing financial risk (WindEurope 2022).

Interviewees highlighted how Chinese monopiles and turbines are significantly cheaper than their European counterparts, placing European manufacturers at a competitive disadvantage (Interview 6). The IEA (2024) similarly found that cost disparities between European and Chinese wind manufacturers hinder Europe's ability to scale up offshore wind projects at the same pace as China.

5.2.3 Global Supply Challenges

Dependence on China for Critical Materials and Components

As outlined in the Global Manufacturing Dynamics section, China controls over 80% of global rare earth element (REE) production, which is essential for offshore wind turbine magnets (Hayley, 2024). This dependence exposes the European market to geopolitical risks, price fluctuations, and supply chain disruptions (Interview 6). Industry stakeholders emphasized that if access to Chinese turbines and components is restricted, European offshore wind deployment will slow down significantly (Interview 4; Interview 6). This reliance increases the risk of project delays and cost fluctuations, as confirmed by Janipour (2024), who warns that supply chain vulnerabilities could impact Europe's wind energy targets.

Steel, Copper, and Rare Earth Element Supply Risks

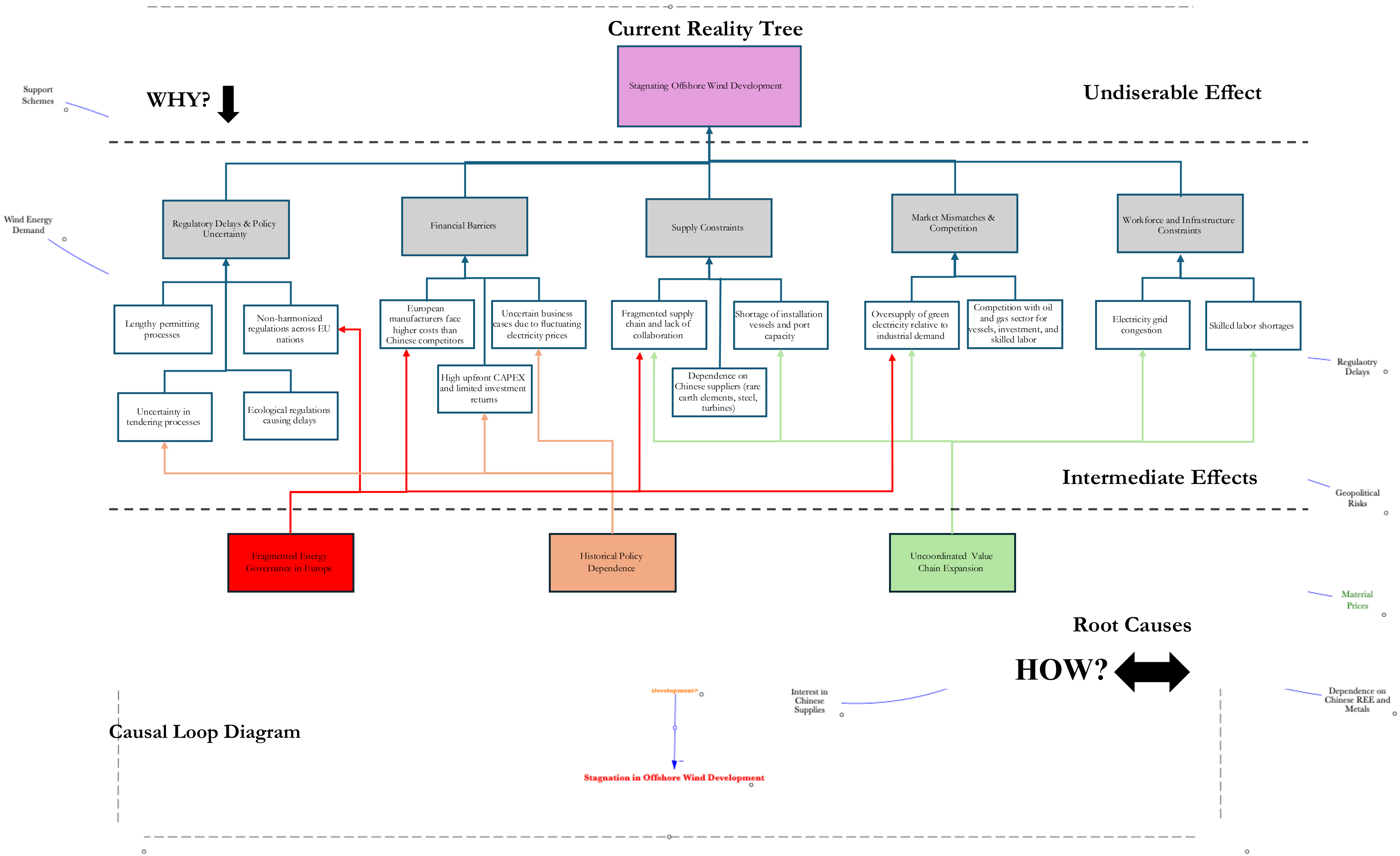
The offshore wind sector requires significant volumes of steel, copper, and REEs, all of which are subject to price volatility and supply risks. Interview findings indicate that disruptions in steel supply following the Russia-Ukraine conflict have increased costs (Interview 5; Interview 9). Additionally, offshore wind projects remain highly sensitive to copper price inflation, given the material's role in power transmission and turbine manufacturing (IEA, 2024).

Geopolitical Risks in Offshore Wind Logistics

Beyond material shortages, geopolitical risks further complicate offshore wind deployment. Industry stakeholders cited concerns about tensions around the Suez Canal and potential trade sanctions, which could disrupt logistics and increase transportation costs (Interview 8). Research from WindEurope (2022) suggests that geopolitical instability could become a significant factor in shaping future offshore wind supply chain strategies.

The identified challenges in offshore wind development illustrate a complex web of issues that have evolved alongside the industry's growth in the North Sea. These challenges are not isolated but are deeply interconnected across the offshore wind value chain, financial structure, and global supply network. While these obstacles have been shaped by recent developments, some of their root causes can be traced back to earlier stages of offshore wind expansion. Understanding how these challenges emerged and how they have contributed to the current stagnation requires a structured analysis of their underlying causes. To achieve this, a Current Reality Tree (CRT) will be employed to map the causal relationships between these challenges, tracing their origins and identifying key points where structural issues began to emerge. The CRT is not intended to directly propose solutions but rather to uncover the deeper systemic barriers that have progressively contributed to stagnation in offshore wind development. By visualizing these causal pathways, the CRT will provide insights into how regulatory shifts, infrastructure limitations, and financial uncertainties have collectively hindered progress in the offshore wind sector. This analysis will connect the identified challenges to their historical roots, revealing how decisions made in earlier phases of offshore wind development continue to shape the industry's current state. The CRT will serve as a tool to better understand the chain of events and systemic weaknesses that have led to stagnation, offering a foundation for subsequent analysis in the causal loop diagram (CLD) that will illustrate feedback mechanisms and reinforcing loops.

Current Reality Tree



5.3. Current Reality Tree

The Current Reality Tree (CRT) reveals that stagnation in offshore wind development arises from a combination of regulatory, financial, and supply chain challenges. These issues are linked to broader systemic causes, which reflect the historical development of offshore wind in the North Sea. By examining the evolution of offshore wind, it becomes evident that three primary root causes have contributed to the stagnation: Fragmented Energy Governance in Europe, Historical Policy Dependence, and Uncoordinated Value Chain Expansion. Each root cause has influenced specific challenges in the offshore wind value chain, financial structure, and global supply network.

Fragmented Energy Governance in Europe:

Fragmented energy governance has been a persistent barrier to offshore wind development in Europe. This fragmentation stems from inconsistencies in national regulatory frameworks and the lack of coordinated planning across North Sea countries. During the Innovation Phase (1991–2001), Denmark's early adoption of a centralized permitting framework through the Danish Energy Agency (DEA) enabled faster project development. In contrast, Germany, the UK, and the Netherlands lacked streamlined regulatory frameworks during this period, resulting in slower project timelines and less efficient permitting processes. In the Market Adaptation Phase (2001–2008), the UK and Germany introduced auction-based financing mechanisms such as the CfD system and Germany's auction-based feed-in tariff model. While these schemes improved financial stability, they were not accompanied by harmonized permitting frameworks, creating inconsistencies between national development processes. This lack of regulatory alignment continued in the Market Stabilization Phase (2008–Present), as ecological and circularity demands further complicated permitting frameworks. The CRT highlights how these issues have resulted in lengthy and inconsistent permitting processes, non-harmonized regulations, and ecological regulations causing delays, and contributing to stagnation in offshore wind expansion. This fragmented governance has introduced uncertainty for developers, requiring them to adapt to varying regulatory frameworks, which delays investment decisions and increases project risks. As identified in both interviews and literature (Berk, 2024; WindEurope, 2022), these fragmented regulations have led to inefficiencies in offshore wind development and remain a significant challenge for scaling up North Sea capacity.

Historical Policy Dependence

Historical policy dependence has played a critical role in shaping offshore wind financing structures, with lasting effects on project viability and investment stability. In the Innovation Phase (1991–2001), Denmark and Germany's early adoption of feed-in tariffs created stable investment conditions but relied heavily on government intervention. These state-backed subsidies successfully incentivized offshore wind deployment but created long-term dependence on financial support mechanisms. As offshore wind development matured in the Market Adaptation Phase (2001–2008), policy frameworks shifted toward more competitive mechanisms. The UK's Renewables Obligation (RO) and Germany's CfD model sought to attract private investment through market-based financing. However, this transition introduced new risks as developers faced greater exposure to fluctuating electricity prices and volatile market conditions. The CRT illustrates how this shift contributed to uncertain business cases and fluctuating electricity prices, which undermined investment confidence. During the Market Stabilization Phase (2008–Present), these financial risks intensified as the offshore wind sector experienced rising CAPEX costs driven by turbine upscaling, port expansion, and vessel shortages. The CRT highlights that developers are increasingly burdened by high upfront CAPEX costs and limited investment returns, adding financial pressure and delaying project completion. This ongoing reliance on fluctuating market mechanisms, combined with insufficient financial safeguards, has hampered offshore wind growth in the North Sea.

Uncoordinated Value Chain Expansion

The CRT identifies uncoordinated value chain expansion as another critical root cause, resulting in infrastructure bottlenecks, supply chain fragmentation, and manufacturing constraints. During the Innovation Phase (1991–2001), offshore wind relied heavily on repurposed oil and gas infrastructure, which limited deployment capacity. While this approach enabled early progress, it created long-term inefficiencies as the sector scaled up. In the Market Adaptation Phase (2001–2008), turbine capacities increased rapidly, yet port expansions, installation vessel availability, and manufacturing capabilities failed to keep pace. As highlighted in interviews and literature (Dinh & McKeogh, 2019), this imbalance created infrastructure bottlenecks that persist today. The CRT reflects these issues, identifying fragmented supply chains, shortages of installation vessels and port capacity, and dependence on Chinese suppliers as key obstacles. The Market Stabilization Phase (2008–Present) introduced new complexities. As turbine capacities exceeded 15 MW, the need for specialized vessels, cranes, and expanded port facilities intensified. At the same time, Europe's dependence on Chinese suppliers for critical materials (such as rare earth elements and steel) heightened geopolitical risks and price volatility. The CRT illustrates how this dependence has resulted in increased delays, rising costs, and vulnerability to supply chain disruptions.

Uncoordinated value chain growth has also contributed to market mismatches, where offshore wind supply has outpaced industrial electricity demand. This imbalance has led to temporary oversupply, exacerbating revenue uncertainty for developers. Furthermore, competition with the oil and gas sector for vessels, skilled labor, and port infrastructure has further strained offshore wind deployment timelines. The CRT illustrates that stagnation in offshore wind development is not driven by a singular factor but is the result of interconnected challenges stemming from fragmented energy governance, historical policy dependence, and uncoordinated value chain expansion. These root causes have manifested in permitting delays, financial instability, and infrastructure constraints, collectively undermining offshore wind development in the North Sea. As discussed in the Understanding Offshore Wind Development chapter, the evolution of offshore wind reflects how early-stage policy interventions, technological advancements, and financial mechanisms shaped the industry. The CRT now demonstrates how these past developments have led to systemic vulnerabilities that must be addressed to overcome stagnation and ensure sustained growth in the sector.

5.4. Causal Loop Diagram

Causal Relations

The relationship between CAPEX Costs and Project Costs is direct: as CAPEX Costs increase, Project Costs also increase. Dependence on China for Materials influences both High EU Cost vs Chinese Competitors and Materials Supply Risks. Specifically, an increase in Dependence on China for Materials leads to a rise in High EU Cost vs Chinese Competitors and greater Materials Supply Risks. The Dependence on Chinese REE and Metals influences Dependence on China for Materials, suggesting that an increase in reliance on Chinese REE and metals intensifies the dependency on Chinese materials. On the other hand, Developer Cost Pressure positively influences Upsizing and Value Chain Investment Uncertainty, implying that higher development cost pressures lead to a need for upsizing and create uncertainty in investment decisions within the value chain. Development Timelines directly affect Project Costs: delays in timelines lead to an increase in overall project expenses.

Similarly, Financing Costs influence Project Costs, as higher financing costs tend to drive up the overall expenses of the project. Geopolitical Risks directly influence Materials Supply Risks, suggesting that increased geopolitical instability exacerbates risks associated with material availability. Moreover, High EU Cost vs Chinese Competitors influences Interest in Chinese Supplies, indicating that as costs in the EU increase relative to Chinese competitors, the interest in Chinese supplies grows. Interest in Chinese Supplies, in turn, influences Dependence on China for Materials and has a negative influence on Project Costs. When interest in Chinese supplies increases, the reliance on China for materials grows, while Project Costs tend to decrease due to potentially lower material costs. Maintenance Bottlenecks have a direct influence on OPEX Costs, meaning that delays or issues in maintenance operations increase operational costs. Similarly, Manufacturing & Installation Bottlenecks influence both CAPEX Costs and Development Timelines, as bottlenecks in these areas increase capital expenditure and extend project timelines. Material Prices influence both CAPEX Costs and Materials Supply Risks. As material prices increase, both the costs for capital investment rise, and the risks associated with securing materials escalate. Materials Supply Risks, in turn, influence Development Timelines, as uncertainties in material availability may cause delays. Offshore Wind Development influences both Maintenance Bottlenecks and Manufacturing & Installation Bottlenecks as wind energy development uses value chain capacity creating bottlenecks.

Moreover, it negatively influences Stagnation in Offshore Wind Development and Value Chain Investment Uncertainty, implying that as offshore wind development progresses, it reduces stagnation and uncertainty within the value chain. OPEX Costs directly influence Project Costs, meaning higher operational expenditures lead to higher overall project costs. Project Costs influence Developer Cost Pressure and High EU Cost vs Chinese Competitors, while also negatively influencing Value Chain Investment Attractiveness. This suggests that as project costs increase, the pressure on developers rises, the competitiveness of the EU relative to China worsens, and investment attractiveness decreases.Regulatory Delays influence Development Timelines, meaning that regulatory bottlenecks directly lengthen project timelines. Support Schemes influence Value Chain Investment Uncertainty, suggesting that more robust support schemes reduce uncertainty in value chain investments. Upsizing influences both CAPEX Costs and Offshore Wind Development, suggesting that increasing project scale raises capital expenditure while also driving further development. Additionally, Upsizing influences Value Chain Investment Uncertainty, implying that scaling up projects can add uncertainty to investment decisions. Value Chain Investment Attractiveness has a negative influence on both Maintenance Bottlenecks and Manufacturing & Installation Bottlenecks, while positively influencing Offshore Wind Development. As value chain investments become more attractive, bottlenecks decrease however this comes with a delay as investment in value chain capacity take time before they can come operational, and the development of offshore wind projects accelerates. Value Chain Investment Uncertainty Influences Financing Costs, making investments less predictable and thus raising financing costs. It also negatively influences Value Chain Investment Attractiveness, as higher uncertainty reduces investment appeal. Wind Energy Demand Influences Value Chain Investment Uncertainty, suggesting that increased demand for wind energy lowers uncertainty in value chain investments because there is an increased market size. Finally, Workforce Shortages influence CAPEX Costs, Development Timelines, and OPEX Costs, indicating that shortages in the workforce can increase both capital and operational costs, while also extending project timelines.

Lastly, Workforce Shortages influence multiple critical internal factors, including CAPEX Costs, Development Timelines, and OPEX Costs. Shortages cause increases in project expenses and timelines highlighting the importance of effective workforce management within offshore wind development. The system boundary has been defined by external factors such as Support Schemes, Wind Energy Demand, Material Prices, Workforce Shortages, Regulatory Delays, Geopolitical Risks, and Dependence on Chinese REE and Metals. These external factors significantly influence system dynamics but remain outside the immediate system boundary due to their exogenous nature. According to guidelines provided by Tip (2011), establishing clear boundaries is crucial to avoid unnecessary complexity and to focus on variables with significant impacts on the system's core dynamics. Now that the direct influences of the variables with its neighbors is explained an analysis of the causal loops occurring in the diagram can be made.

Casual Loops Analysis

The causal loop diagram provided illustrates several reinforcing (positive feedback) and balancing (negative feedback) loops within the offshore wind development system, emphasizing complex interactions and dependencies between various factors (see Appendix B for highlighted loops of the CLD).

A key reinforcing loop emerges around CAPEX Costs, Project Costs, and Developer Cost Pressure. Rising CAPEX Costs drive Project Costs higher, intensifying Developer Cost Pressure, prompting the upsizing of turbines. While upsizing potentially increases energy yield, it simultaneously escalates Value Chain Investment Uncertainty and subsequently feeds back into elevated CAPEX Costs, creating a self-perpetuating loop of escalating investment risks and project expenses. This relationship is also subject to delays because the upsizing trend requires substantial time before it translates into improved infrastructure and ultimately boosts offshore wind development, exemplifying a classic delayed feedback loop scenario (Špicar, 2014). Although increased Wind Energy Demand and supportive policy measures partially counteract this uncertainty, persistent financial unpredictability remains a significant reinforcing factor hindering investment flow into necessary infrastructure and technologies. These illustrate a self-reinforcing cycle of rising costs and investment uncertainty, aligned with Greve (2020) and Dinh & McKeogh (2019), who emphasize financial uncertainty as a key obstacle.

Another reinforcing loop is formed around Dependence on China for Materials, High EU Cost vs. Chinese Competitors, and Interest in Chinese Supplies. Greater Dependence on China for materials raises costs relative to Chinese competitors, enhancing the attractiveness of Chinese supplies and further deepening reliance on these resources (WindEurope, 2022; IEA, 2024). A balancing loop emerges from Project Costs, High EU Cost vs. Chinese Competitors, and Interest in Chinese Supplies. Rising Project Costs enhance the attractiveness of cheaper Chinese supplies, eventually reducing overall Project Costs, stabilizing the system's cost dynamics (Interview 6). While this balancing loop might initially mitigate rising Project Costs, it concurrently deepens Europe's geopolitical and supply chain vulnerabilities.

Additionally, there is a reinforcing loop connecting Offshore Wind Development, Maintenance Bottlenecks, and Manufacturing & Installation Bottlenecks. Increased development intensifies the use of existing value chain capacity, initially creating bottlenecks. Although Value Chain Investment Attractiveness eventually addresses these bottlenecks, improvements are delayed due to the time needed for investments to become operational, creating a dynamic delay loop (WindEurope, 2022). Conversely, another balancing loop is evident in how Value Chain Investment Attractiveness negatively influences Maintenance and Manufacturing & Installation Bottlenecks. Increased investment attractiveness gradually alleviates these bottlenecks, thus supporting further Offshore Wind Development and reducing Stagnation and Uncertainty within the value chain, illustrating a stabilizing mechanism within the system. Attractiveness can gradually alleviate these constraints, significant delays between investment initiation and operational readiness create persistent short-term stagnation pressures, reinforcing the "Growth and Underinvestment" archetype (Špicar, 2014).

Offshore wind development demonstrates the classic "Limits to Growth" system archetype, characterized by initial reinforcing loops driving rapid growth (e.g., increased investment leading to capacity expansion and technological advancements). However, these reinforcing loops eventually encounter balancing feedback mechanisms such as grid congestion, environmental concerns, and supply chain constraints, which restrict further development and stabilize growth (Špicar, 2014). These Loops are underscored by the following findings by researchers of TNO and Invest NL According to researchers, the Dutch offshore wind industry finds itself trapped in a vicious circle. On the demand side, companies are reluctant to commit to long-term energy purchases, driven by uncertainties in electricity demand, rising inflation, and the high costs associated with renewable energy. Consequently, this creates uncertainty regarding the sector's earning capacity. Meanwhile, supply chain companies lack the certainty and scale needed to reduce costs, keeping offshore wind expensive. This situation hampers investments in new technologies and infrastructure. As a result, investors perceive the offshore wind sector as high-risk, making capital difficult to secure and limiting innovation (JBR & InvestNL, 2025).

This chapter has outlined a range of persistent and emerging challenges that collectively constrain the development of offshore wind in the North Sea. Drawing from both in-depth stakeholder interviews and literature, three overarching domains of challenge have been identified: value chain limitations, financial structural issues, and global supply vulnerabilities. These barriers are not isolated; rather, they are deeply interwoven and rooted in the historical development path of offshore wind in Europe. Across the value chain, the most frequently cited obstacle is the delay in permitting and consenting, driven by fragmented regulatory frameworks across EU countries and evolving ecological requirements that increase administrative complexity and costs. These delays slow down not only project timelines but also the pace of scaling manufacturing and infrastructure capacity. Additionally, the supply chain is under increasing stress from the upscaling of turbines, which has outpaced port, vessel, and installation readiness, creating physical and logistical bottlenecks. Workforce shortages further exacerbate deployment challenges, especially in operations and maintenance. A lack of standardized training, competition with the oil and gas sector, and insufficient long-term workforce planning leave critical roles unfilled. Financially, developers are contending with increasing CAPEX costs, rising interest rates, and uncertain revenue projections in a market environment dominated by competitive auctions and zero-subsidy bids.

The shift from state-backed subsidies to market-based mechanisms has introduced volatility that deters long-term investment and delays final investment decisions. European developers are also losing ground to global competitors—particularly China—whose vertically integrated, state-supported models offer significantly lower production and installation costs. On the supply side, Europe remains highly dependent on imports for critical materials, particularly rare earth elements, steel, and copper—often sourced from China. This dependence introduces price volatility, heightens exposure to geopolitical risks, and undermines EU manufacturing resilience. Interviewees also noted growing concerns about logistical vulnerabilities, such as bottlenecks around critical shipping routes and the impact of trade restrictions. These challenges were further analyzed using the Current Reality Tree (CRT), which identified three root causes: Fragmented Energy Governance, Historical Policy Dependence, and Uncoordinated Value Chain Expansion. Fragmented governance explains ongoing permitting delays and misaligned national policies.

Historical reliance on subsidies has left the sector exposed to market volatility without sufficient financial safeguards. Meanwhile, uncoordinated growth in infrastructure, labor, and manufacturing capacity has led to supply chain fragility and rising deployment risks. The Causal Loop Diagram (CLD) then illustrated how these systemic issues reinforce one another through self-perpetuating feedback loops. For instance, rising CAPEX costs lead to project delays, which reduce developer confidence and discourage investment in value chain capacity—further increasing bottlenecks and costs. Similarly, increasing interest in cheaper Chinese supplies creates cost relief in the short term but deepens strategic dependency in the long term. In summary, the offshore wind sector in the North Sea is experiencing stagnation not because of a singular failing, but due to a web of interdependent challenges that trace back to foundational design and policy choices. These challenges have evolved with the sector's growth, and their effects are magnified by a lack of synchronized governance and coherent long-term planning. Understanding and addressing these challenges is essential to propose interventions in order to unlock the full potential of offshore wind in the North Sea.

6. Offshore Wind Development Intervention Analysis

This chapter covers the interventions that address the challenges in offshore wind development in the North Sea discussed in the previous chapter. The chapter begins with an analysis of the interventions that the interviewees think could address this chapter. As will be seen is this analysis policies implemented by the EU are seen as a much-needed intervention and thus the next subsection will cover the different proposed or just introduced policies and what their intended effect will be. Here after an analysis will be done on what challenges remain unaddressed and self-developed interventions will be covered.

6.1. Interventions discussed in Interviews

Interviewees across the offshore wind sector converged on several interventions to overcome North Sea development challenges. A central theme is the need for a more supportive and predictable policy environment. Many stressed streamlining permitting and tender processes to reduce delays and uncertainty. For example, multiple interviewees call for harmonizing and accelerating permitting procedures at national and EU levels, noting that lengthy approval timelines hinder both project deployment and supply chain expansion (Interview 13). A consistently applied, long-term tender agenda was widely seen as critical for investment certainty (Interview 10). Such stability in tender criteria – rather than constantly shifting requirements – would allow developers and suppliers to plan with confidence (Interview 7). Involving power purchasers more directly in the tender process was even suggested to guarantee offtake for new projects (Interview 12). Taken together, these governance-oriented solutions, from an EU-wide permitting "unification" to predictable national tender schedules, are aimed at de-risking projects and encouraging timely capacity build-out. Another frequent recommendation is infrastructure investment, both in the electricity grid and in maritime logistics.

Grid capacity upgrades onshore must keep pace with offshore expansion: developers argued for accelerating high-voltage network reinforcements and even socializing grid connection costs across society to ensure wind power can be delivered to users (Interview 2; Interview 4). Likewise, port operators and installation companies highlighted that port space and vessel availability are becoming bottlenecks. Expanding port marshalling yards and quays – potentially with government support – is needed to handle the larger components and volumes coming online (Interview 8; Interview 10). Interviewees also urged proactive measures to alleviate the shortage of specialized installation vessels, such as public-private investments in new-build ships and incentives for shipyards (Interview 13). In the interim, better coordination – for instance, booking vessels and heavy-lift ships further in advance and sharing them across projects – was suggested as a practical short-term fix (Interview 13). These measures address the physical capacity constraints that threaten to slow the deployment of planned wind farms. Nearly all experts underscored supply chain collaboration and standardization as pivotal long-term solutions. Several interviewees observed that the offshore wind supply chain is fragmented by extreme competition, with each firm focusing narrowly on its piece of the puzzle (Interview 5; Interview 11). To counter this, they propose more integrated planning and risk-sharing across the chain. For example, vertical partnerships or consortia between developers, equipment manufacturers, and service firms could synchronize decisions and optimize the overall process (Interview 5; Interview 11). Such partnerships would also facilitate knowledge-sharing of operational lessons that are currently kept proprietary. Standardization was a recurring mantra in this context. Technical standardization of turbine and foundation designs, if agreed industry-wide, would yield scale efficiencies and reduce the need to continuously redesign vessels and equipment for ever-larger turbines (Interview 6; Interview 8). Interviewees argue that curbing the "ratrace" for size and adopting a North Sea standard turbine rating (for example, around 15 MW) would stabilize the market and enable a mass-production mindset (Interview 7; Interview 9). Common designs for components like transition pieces would likewise shorten learning curves and conversion times for vessels (Interview 8). In short, by breaking down competitive silos and agreeing on common standards, the industry can lower costs and relieve the intense pressure on its supply chain. Several financial and market mechanisms were also advanced to improve the viability of projects amid rising costs and market volatility.

To tackle revenue uncertainty in a zero-subsidy market, developers favor instruments that ensure a minimum price for green electricity – for instance, Contracts for Difference or green guarantee funds underwritten by government (Interview 4; Interview 12). Such support would secure steady income for wind projects and unlock financing even when power prices fluctuate. On the investor side, stringent bidder requirements (like higher bid bonds and penalties for non-delivery) were suggested to discourage speculative zero-sum bidding and ensure only serious, well-capitalized players win leases (Interview 7). Another common proposal is for developers to mitigate risk by splitting large investments with partners or selling stakes at certain milestones (Interview 2). This strategy, already used by some firms, can recycle capital and spread risk during the lengthy project lifecycle. From the demand perspective, many interviewees pointed out the need to stimulate power demand from industry in tandem with supply growth. They note that without substantial electrification of industrial processes (and possibly new hydrogen or datacenter loads), abundant offshore wind could depress prices and undermine project economics (Interview 3; Interview 6). Accordingly, policy measures to accelerate electrification and guarantee industrial offtakers for green power are seen as integral to the long-term market balance. Overall, these financial and market-based solutions reflect a drive to shore up the business case for offshore wind through risk-sharing and coordinated demand growth. The sector's workforce constraints were acknowledged as an urgent challenge requiring both immediate and long-range solutions. In the short term, companies face acute shortages of skilled technicians, mariners, and projectmanagers. One prominent proposal is to streamline international labor mobility – for example, easing visa and work permit rules within Europe – so that qualified workers from abroad can fill gaps quickly (Interview 8).

Over the longer term, building a domestic talent pipeline is crucial. Interviewees advised ramping up specialized training programs and apprenticeships in offshore wind trades, often in partnership with universities and technical institutes (Interview 3; Interview 11). Several noted that the industry must make itself attractive to younger workers by adapting to modern expectations for work-life balance and career development (Interview 9). By investing in human capital development now, the sector can alleviate the labor bottleneck that threatens to delay projects and inflate costs. Finally, in addition to these widely shared ideas, some novel or more radical solutions emerged from individual perspectives. One such idea is to embrace strategic use of Chinese-produced turbines and components to meet capacity targets, despite geopolitical concerns – a point raised by one developer who warned that excluding non-European suppliers could slow the roll-out of North Sea wind farms (Interview 4). Others offered innovative technology pathways: the concept of hybrid-powered installation vessels was introduced to cut fuel costs and emissions, turning a cost challenge into an innovation opportunity (Interview 8). Similarly, some suggested diversifying into floating wind and exporting European expertise to new markets to relieve pressure on the fixed-bottom supply chain while opening future revenue streams (Interview 8). From an operational standpoint, service providers drew parallels with the oil & gas sector's cooperative models – for instance, proposing that offshore wind firms take cross-shareholdings in each other to reduce internal competition and foster joint solutions in operations and maintenance (Interview 11). These more unconventional proposals, while not yet consensus, highlight the creative thinking by some interviewees seeking to fundamentally rethink business-as-usual in the face of scaling challenges. In summary, industry experts collectively envision a multi-pronged approach to ensure North Sea offshore wind ambitions can be realized. Common recommendations focus on de-risking through policy stability and collaboration: streamlining permits, guaranteeing markets and prices, and uniting the supply chain around shared standards and goals. At the same time, capacity-building measures – from grid upgrades and port expansions to workforce training and vessel construction – are seen as imperative to keep growth on track. By implementing near-term fixes (such as adjusted tender rules, earlier final investment decisions, and short-term labor mobility improvements) alongside strategic long-term investments in skills, infrastructure, and technology, the North Sea offshore wind sector can overcome its growing pains. Crucially, many interviewees emphasize that no single actor can solve these issues alone; a coordinated effort by developers, suppliers, consumers, and governments is required. The solutions they propose, both the frequently mentioned and the refreshingly novel, together form a comprehensive agenda to tackle the intertwined permitting, grid, supply chain, labor, and financial challenges on the horizon (Interview 1–13).

6.2. Policy Interventions

There are numerous EU policies addressing these challenges. Either they are in force, agreed upon or announced. This subsection covers these policies per categories of offshore wind development and their intended goal. These policies are Renewable Energy Directive revision (RED), Technical Support Instrument Regulation (TSI), Wind Power Package (WPP), Electricity Market Design Reform (EMDR), Critical Raw Materials Act (CRMA), Net Zero Industry Act (NZIA), Grid Action Plan (GAP).

6.2.1. Value Chain Policies

1. The Renewable Energy Directive (RED III) introduced measures to accelerate permitting, addressing one of the most prominent bottlenecks in offshore wind development. RED III sets a two-year cap on permitting procedures for new renewable energy projects, including administrative approvals, environmental impact assessments, and grid connections (European Commission, 2023c). Additionally, "Renewable Energy Acceleration Areas" have been designated to fast-track project approvals to within one year for new projects and six months for repowering projects. These measures streamline processes that previously contributed to costly delays (Interview 13).
2. The Wind Power Package enhances value chain stability by improving project predictability. By requiring member states to publish medium-term auction schedules and deployment targets, developers, vessel operators, and manufacturers can better align their planning strategies (European Commission, 2023b). This improved visibility encourages early investments in essential infrastructure such as port expansions and specialized installation vessels, mitigating logistical bottlenecks that have historically hindered offshore wind deployment (Interview 9; Interview 12).
3. The Technical Support Instrument (TSI) supports value chain stability by improving administrative processes. The TSI Regulation provides technical guidance and digitalized permitting tools to help national authorities streamline regulatory processes. By improving coordination between authorities and simplifying permitting frameworks, the TSI reduces delays that have frequently disrupted offshore wind project timelines (European Commission, 2024d)
4. The Green Deal Industrial Plan introduces measures to expand Europe's manufacturing capacity for offshore wind components. By promoting domestic production of key components such as turbine blades and nacelles, the plan reduces dependence on foreign suppliers and minimizes risks linked to logistical delays (European Commission, 2023a). The plan’s support for research and development in automated manufacturing processes further mitigates production inefficiencies that have contributed to project delays (Interview 9; Interview 12)
5. The Net Zero Industry Act (NZIA) reinforces these efforts by requiring 40% of clean energy components to be produced domestically by 2030 (European Commission, 2024a). This target stabilizes the value chain by ensuring a stronger local supply base for offshore

wind components. Additionally, the NZIA introduces a streamlined permitting framework for manufacturing plants dedicated to clean energy technologies, further mitigating risks of production bottlenecks.

6. The Critical Raw Materials Act (CRMA) complements these efforts by setting self-reliance targets to ensure a stable supply of key materials for offshore wind manufacturing. The CRMA mandates that 10% of critical raw materials must be extracted domestically, 40% processed domestically, and 25% sourced from domestic recycling efforts (European Commission, 2024b). This diversification reduces Europe's dependence on single-source suppliers and strengthens offshore wind's material security.
7. Lastly, the Grid Action Plan addresses offshore wind integration challenges by accelerating permitting for critical cross-border grid infrastructure (European Commission, 2024c). By working with ENTSO-E to define long-term grid expansion needs, the plan ensures that offshore wind deployment aligns with grid readiness, reducing project delays and improving overall coordination between infrastructure providers.

6.2.2. Financial Structure Policies

1. The RED III stabilizes financial conditions for offshore wind projects by improving investment predictability. Its binding target of 42.5% renewable energy by 2030 provides market stability, boosting developer confidence for large-scale offshore wind investments (European Commission, 2023c). This directly addresses earlier financial concerns about fluctuating market signals hindering investment decisions (Interview 3). Enhanced predictability supports clearer revenue projections and easier financing. Additionally, RED III's accelerated permitting processes reduce CAPEX risks related to project delays. By fostering regulatory stability, RED III facilitates new financial instruments, encouraging governments and financial institutions to expand loan guarantees, insurance mechanisms, and risk-sharing schemes to mitigate investment risks.
2. The Wind Power Package addresses financial instability and investment uncertainty caused by rising CAPEX and volatile material prices (Interview 3). Its indexation mechanism for auction prices enables developers to adjust budgets to market fluctuations, significantly reducing financial risks from inflation or critical material price increases (European Commission, 2023b). This stability is essential for maintaining investment confidence during market turbulence. Moreover, harmonizing tender designs across EU member states reduces inconsistencies, further improving investor confidence and facilitating stable financial planning. Enhanced financial predictability also helps unlock financing by reassuring banks and private investors about stable revenue streams.
3. The TSI Regulation indirectly reduces financial risks by streamlining administrative processes, thereby minimizing permitting delays and associated cost overruns (European Commission, 2024d). Accelerated and simplified permitting enhances project predictability and budget planning. Furthermore, better-trained staff and digitalized procedures promoted by the TSI ensure more efficient permitting, further reducing financial risks.
4. The Green Deal Industrial Plan provides targeted financial incentives to reduce investment risks for offshore wind manufacturing, addressing high CAPEX costs. Subsidies and tax incentives support European turbine and component manufacturing, reducing dependency on external suppliers (European Commission, 2023a). Public-private partnerships are encouraged for large-scale infrastructure investments, such as port expansions and specialized vessels, vital for meeting renewable energy targets. Additionally, targeted funding for R&D supports innovations aimed at cost reduction and improved financial feasibility.
5. The NZIA supports offshore wind manufacturing investments through enhanced access to financing, including leveraging the EU Innovation Fund and European Investment Bank

guarantees to reduce upfront costs and investment risks (European Commission, 2024a). These measures directly address uncertainties related to volatile market conditions and CAPEX risks, thereby strengthening market stability.

6. The CRMA improves financial predictability by incentivizing investments in European extraction, processing, and recycling of critical raw materials (European Commission, 2024b). By enhancing domestic supply chains, it reduces reliance on volatile global markets, stabilizing material costs for developers. Moreover, promoting public-private investment partnerships accelerates supply chain development, mitigating delays and associated financial risks.
7. The Grid Action Plan addresses financial barriers related to grid connection delays by streamlining permitting for critical infrastructure and introducing financial incentives for grid infrastructure upgrades (European Commission, 2023c). These actions reduce upfront investment burdens, enhance budget certainty, and improve developers' ability to plan and execute large-scale offshore wind projects efficiently. Enhanced collaboration with ENTSO-E also improves grid planning predictability, further mitigating unforeseen financial risks.

6.2.3. Global Supply Chain Policies

1. The RED III indirectly strengthens global supply chain resilience by streamlining permitting processes and providing market predictability. Accelerated permitting reduces project slowdowns, minimizing logistical bottlenecks and enhancing supplier timelines (European Commission, 2023c). Clearer deployment targets allow manufacturers to anticipate demand for critical components such as monopiles, turbine blades, and electrical systems, encouraging them to expand production capacity and infrastructure confidently (Interview 9). Additionally, sustained market growth fostered by RED III promotes diversification of supply chains, reducing reliance on non-European suppliers and enhancing Europe's energy security by mitigating geopolitical risks.
2. The Wind Power Package, although not directly targeting supply chain security, significantly improves supply chain resilience through increased project visibility and clearer deployment schedules. By requiring member states to set explicit deployment targets and publish auction schedules, the package enables component manufacturers to better forecast demand and manage inventory efficiently (European Commission, 2023b). This predictability encourages manufacturers to confidently scale production facilities and reduce Europe's dependency on Chinese suppliers. Improved coordination of timelines also ensures logistics providers and vessel operators can effectively align material deliveries, further reducing supply chain disruptions (Interview 9).
3. The TSI Regulation indirectly addresses supply chain stability by streamlining permitting and enhancing project predictability. Faster and more consistent permitting allows suppliers to reliably schedule production, secure contracts, and align capacity with upcoming demands, thus reducing risks related to material shortages and logistical disruptions (European Commission, 2024d). The TSI's focus on administrative coordination also mitigates the risk of design changes and compliance issues, further stabilizing supply chains by providing clearer project timelines and reducing uncertainties.
4. The Green Deal Industrial Plan directly addresses supply chain vulnerabilities by emphasizing increased domestic sourcing of critical materials, including rare earth elements, copper, and steel. By setting procurement targets and enhancing material recycling, the plan reduces Europe's dependency on external suppliers and exposure to geopolitical risks (European Commission, 2023a). Furthermore, encouraging new international partnerships and alternative sourcing strategies further diversifies the supply chain, mitigating risks associated with geopolitical disruptions.

5. The NZIA strengthens supply chain resilience by promoting domestic manufacturing capabilities, mandating that at least 30% of components for offshore wind projects be sourced locally (European Commission, 2024a). This reduces reliance on non-European suppliers, particularly Chinese producers, for critical turbine components (Interview 6). The NZIA also enhances workforce capacity through specialized training programs, addressing skilled labor shortages critical to supply chain stability and project execution (Interview 11; Interview 12). Overall, these measures bolster local production, mitigate international supply risks, and stabilize the supply chain.
6. The CRMA significantly enhances supply chain security by mandating diversification in the sourcing of critical raw materials, limiting dependency on single-country suppliers, especially China (European Commission, 2024b). By promoting alternative international partnerships and investing in domestic recycling capabilities, the CRMA reduces exposure to global price volatility and import disruptions, fostering a sustainable and resilient supply chain.
7. The Grid Action Plan indirectly improves supply chain resilience by enhancing grid infrastructure reliability and project coordination. Accelerating permitting for cross-border projects and ensuring clearer long-term grid planning minimizes supply chain inefficiencies linked to mismatched timelines (European Commission, 2023c). Improved synchronization between grid readiness and project delivery enables suppliers to effectively coordinate component production schedules, reducing inventory bottlenecks and costly delays. Enhanced EU-wide collaboration further facilitates integrated supply chain strategies, minimizing material sourcing disruptions.

6.3. Intervention gaps

While EU policy and industry interventions have significantly evolved to support offshore wind development, not all challenges are fully resolved. Permitting delays, grid bottlenecks, and labor shortages have been widely acknowledged as critical constraints. In response, the EU has introduced fast-tracked permitting reforms, digital tools, and additional funding for authorities, while developers emphasize aligning national regulations and streamlining requirements across borders. On infrastructure, coordinated EU efforts to accelerate grid and port upgrades are underway, and industry voices have called for improved logistics planning and grid capacity to avoid curtailments. These steps directly address some of the most pressing barriers, though implementation progress varies by country. Financial uncertainty—driven by volatile electricity prices and rising capital costs—has prompted calls for more stable tender frameworks and revenue guarantees. The EU-has responded by refining auction criteria to balance sustainability with bankability and boosting access to low-cost finance via the European Investment Bank. However, concerns remain over unpredictable tender demands and a lack of demand-side certainty, such as industrial power purchase guarantees, which some developers see as key to investment confidence. In terms of global supply chain resilience, both interviewees and EU strategies converge on the urgency of reducing dependency on Chinese turbines and rare earths. The EU's Net-Zero Industry Act and Critical Raw Materials Act are designed to localize manufacturing and secure critical inputs, while industry stakeholders recommend further standardization and supplier diversification. However, expanding domestic production capacity and achieving cost competitiveness will take time, and current projects remain exposed to price and import shocks. Overall, many of the key challenges—permitting inefficiencies, grid limitations, financial risk, and supply dependence—are being actively addressed through a mix of policy and industry measures. Still, the pace of implementation, fragmentation of national approaches, and unresolved risks around demand and manufacturing scale highlight areas where further action is needed. These gaps underscore the importance of the next wave of targeted interventions.

6.4. Proposing Interventions

While recent EU interventions—including permitting streamlining, standardization efforts, and investment incentives—address core structural bottlenecks in offshore wind development, significant gaps remain that threaten long-term scalability and resilience. Several complementary interventions, building on both EU-wide initiatives and stakeholder insights, can fill these critical gaps. A major unaddressed issue is fragmented coordination across the value chain, rooted in historical policy dependence and uncoordinated expansion. Vertical integration, as exemplified by China, offers a compelling solution by consolidating supply chains, which directly addresses manufacturing and installation bottlenecks, material price volatility, and geopolitical dependency on external suppliers. By forming integrated cross-sector partnerships—such as public-private consortia between developers, manufacturers, grid operators, and logistics providers—Europe could better manage resource availability, ensure secure sourcing of critical components, and streamline project timelines. Implementing such vertical integration demands an enabling policy framework with clearly defined regulations that support co-investment structures, shared R&D platforms, and flexibility in antitrust legislation.

The European Commission, along with national energy ministries, must lead this initiative, ensuring competitive integrity while promoting coordinated industry growth. Secondly, despite EU efforts to modernize the grid, port infrastructure and logistics capacities still fall short compared to rapid advancements in turbine size and deployment targets. Establishing a dedicated North Sea Infrastructure Fund—aligned with the EU's Green Deal Industrial Plan—would directly resolve logistical bottlenecks through targeted financing for modular port upgrades, specialized installation vessels, and centralized logistics hubs. Coordinated planning by national governments, notably the Netherlands, Germany, and the UK, is crucial to prevent redundant investments and ensure regional capacity alignment. Such coordinated infrastructure expansion, coupled with precise alignment to offshore wind leasing and permitting schedules, would significantly reduce deployment delays and enhance overall project viability.

Financial fragility remains a systemic barrier, particularly due to rising CAPEX costs, fluctuating electricity prices, and insufficient incentives for smaller developers. The existing CfD mechanisms have mitigated some market risks but fail to adequately stimulate early investment or technological innovation. Adopting a tiered financial support approach—combining long-term loan guarantees and concessional capital for emerging developers, with robust bid performance guarantees for larger market players—could stabilize investment risks and incentivize timely project completion. Joint management of these financial instruments by the European Investment Bank (EIB) and national development banks would enhance accessibility while ensuring rigorous accountability, reducing speculative bidding practices, and reinforcing investor confidence. Addressing workforce shortages is another critical intervention area, necessitated by a lagging training infrastructure that has failed to match industry demand. A "Wind Skills Pact" could mandate binding national targets for offshore wind training and certification, leveraging resources from the EU's Just Transition Mechanism. Offshore developers would then be required to source certified labor from these national training pools, simultaneously enhancing labor quality, reducing operational and maintenance bottlenecks, and stimulating regional job creation. Lastly, while current policies primarily seek risk mitigation concerning Chinese supplier dependency, a more proactive industrial strategy is essential to ensure EU supply chain sovereignty. Initiatives to reshore critical manufacturing—including nacelles, turbine blades, and rare earth magnets—should include direct subsidies, tax incentives, and preferential procurement policies for EU-origin components. Alternatively, controlled joint ventures with Chinese manufacturers, under strict conditions such as mandatory local content and technology sharing, could rapidly bolster European manufacturing capacities. Implementation of these industrial policies would require strategic regulatory adjustments by DG COMP and national competition authorities, facilitating targeted collaborations without compromising EU market integrity. Collectively, these interventions comprehensively tackle the interlinked challenges of fragmented governance, historical policy dependencies, and uncoordinated value chain expansion. Vertical integration and enhanced financial instruments directly reduce project and investment uncertainties; strategic infrastructure and workforce development ensure delivery capabilities; and reshoring manufacturing bolsters strategic autonomy. Success, however, hinges on well-coordinated governance structures, integrating actions by EU institutions, national governments, and industry stakeholders around a shared vision for resilient, competitive offshore wind growth.

In conclusion, the interventions outlined in this chapter collectively form a robust strategic response to the multifaceted challenges of offshore wind development in the North Sea. Insights from industry experts and stakeholders emphasize that while recent policy measures at the EU level—including RED, TSI, WPP, EMDR, CRMA, NZIA, and GAP—are critical and address key structural barriers such as permitting, financial risks, and supply chain vulnerabilities, these alone are insufficient to fully secure the future trajectory of the sector. The analysis reveals persistent gaps in implementation, notably in the alignment and harmonization of permitting procedures, grid readiness, and the scale-up of port and vessel infrastructure. Stakeholders highlight that while recent EU initiatives provide essential regulatory and financial stability, the efficacy of these policies heavily depends on coordinated national implementation and clearer cross-border frameworks. Specifically, permitting delays and infrastructure constraints remain significant bottlenecks despite targeted interventions, underscoring the urgent need for integrated national and EU-wide cooperation.

Further, the industry's call for more predictable tendering frameworks, standardized technical requirements, and enhanced financial instruments underscores an ongoing need for comprehensive policy refinement. Strengthening financial certainty through innovative risk-sharing mechanisms, including improved Contracts for Difference and green guarantee funds, is crucial for sustaining investor confidence in a volatile market environment. Concurrently, addressing global supply chain dependencies through increased domestic manufacturing capabilities and strategic international partnerships remains an imperative intervention for long-term sector resilience. Importantly, the chapter identifies a critical role for coordinated vertical integration and strategic partnerships across the offshore wind value chain. Enhanced collaboration between developers, suppliers, grid operators, and logistics providers is suggested as essential for streamlining project execution, reducing financial risks, and accelerating innovation. Additionally, robust workforce strategies—such as improved training programs, facilitated labor mobility, and industry-driven skill development initiatives—are emphasized as key interventions for addressing labor shortages that threaten project timelines and operational efficiency. Ultimately, the collective effectiveness of these interventions hinges on harmonized policy actions, timely infrastructure investments, and strengthened industry cooperation. The proposed multi-dimensional strategy, combining immediate practical measures with longer-term structural reforms, provides a comprehensive framework to overcome current limitations and drive sustainable offshore wind development. Realizing this ambitious vision will require persistent coordination and proactive engagement from policymakers, industry leaders, and stakeholders across the entire offshore wind ecosystem.

7. Discussion

This chapter synthesizes the findings from the analysis of offshore wind development in the North Sea and aims to address the research questions posed at the outset of this study. By integrating insights from the value chain analysis, the Current Reality Tree (CRT), and the Causal Loop Diagram (CLD), this chapter reflects on the interconnected challenges and underlying causes that have contributed to stagnation in offshore wind deployment. The discussion connects these insights to the broader context of offshore wind development in Europe, addressing the research questions in turn.

7.1. How can offshore wind development be categorized and how did these offshore wind development in the North Sea change over time?

The evolution of offshore wind energy in the North Sea has been shaped by distinct developmental phases characterized by policy interventions, technological advancements, and evolving financial frameworks. Initially, the Innovation Phase (1991–2001) set the stage through early demonstration projects such as Denmark's Vindeby. These pilot projects underscored both offshore wind's technical feasibility and environmental challenges, providing critical lessons that informed subsequent development stages. Germany, the UK, and the Netherlands played relatively minor roles in this early period but laid critical groundwork through preliminary site assessments and experimental initiatives. The subsequent Market Adaptation Phase (2001–2008) saw the transition from demonstration to commercial-scale projects, heavily influenced by structured policy interventions. Key developments included the UK’s introduction of structured leasing rounds by The Crown Estate, which significantly improved coordination and investor confidence. Concurrently, Germany implemented a centralized grid connection approach, reducing barriers related to infrastructure readiness and facilitating investment decisions.

During this phase, Denmark continued its pioneering role with projects like Horns Rev 1, and the Netherlands entered commercial-scale offshore wind through notable projects such as Egmond aan Zee and Prinses Amalia. Collectively, these developments indicated a strategic policy shift from experimental setups towards structured commercialization, highlighting the importance of coordinated policy frameworks and infrastructure planning. The current Market Stabilization Phase (2008–present) has solidified offshore wind as an established, economically viable energy source, characterized by significant advancements in turbine technology and increasingly competitive financial models. The shift from subsidy-dependent projects to auction-based mechanisms like the UK's Contracts for Difference (CfD) and Germany’s competitive auctions has notably reduced costs and improved the investment climate by stabilizing revenue streams. Denmark’s adoption of two-sided CfDs further exemplifies policy innovation aimed at balancing market competition and financial risk mitigation. This phase also saw substantial upscaling of wind farms and turbines, significantly reducing Levelized Cost of Energy (LCOE) and enhancing competitiveness against other renewable sources. The implications of these developments are profound, as offshore wind has matured into a cornerstone of Europe's renewable energy strategy, underpinned by a robust financial and regulatory environment. The interplay between policy consistency, technological improvements, and optimized financial structures has propelled significant capacity growth, positioning North Sea countries as global leaders in offshore wind energy deployment. However, this rapid growth also introduced complexities, including elevated capital expenditures (CAPEX), infrastructure bottlenecks, and global supply chain vulnerabilities, notably the reliance on Chinese manufacturing and materials. This historical analysis captures mainly policy-driven and financial dynamics but offers less insight into localized environmental or socio-economic impacts, which also significantly influence development trajectories. Furthermore, the analysis does not fully account for rapidly evolving geopolitical landscapes, which could introduce unforeseen disruptions. Future studies could expand this analysis by incorporating deeper assessments of socio-economic impacts at local and regional scales and exploring more detailed geopolitical scenario analyses to better anticipate external risks. Additionally, examining the interactions between offshore wind and other renewable sectors could offer valuable insights into optimizing Europe's broader renewable energy portfolio, ensuring resilient and sustainable growth in offshore wind capacity.

7.2. What are the current challenges in offshore win development in the North Sea and what are the underlying causes of these challenges?

The findings revealed that stagnation in offshore wind development arises from multiple interconnected challenges across the value chain, financial structure, and global supply network. Key identified issues include regulatory delays and policy uncertainty, financial barriers, supply chain constraints, and workforce and infrastructure limitations. These challenges emerge from three primary root causes identified through the Current Reality Tree (CRT): Fragmented Energy Governance, Historical Policy Dependence, and Uncoordinated Value Chain Expansion. Fragmented governance among North Sea countries has led to inconsistent regulatory frameworks and lengthy permitting processes, causing significant project delays. Historical reliance on government-backed subsidies has complicated the transition to market-based mechanisms like Contracts for Difference (CfDs), increasing financial uncertainty and discouraging investment. Moreover, rapid but uncoordinated expansion of offshore wind projects has exposed supply chain vulnerabilities, especially regarding the shortage of specialized vessels, port capacities, and dependence on critical materials sourced primarily from China. The interconnected nature of these results highlights the complexity of offshore wind energy development, emphasizing that no single challenge exists independently. Instead, delays and stagnation result from cumulative effects, where governance issues amplify financial uncertainty, which, in turn, exacerbates supply chain risks and infrastructure bottlenecks.

This systemic interpretation implies that addressing stagnation requires coordinated interventions across multiple domains rather than isolated solutions targeting single issues. The findings underscore the necessity for more integrated and harmonized regulatory frameworks across North Sea countries to streamline permitting processes and reduce administrative burdens. They also point toward the urgency of developing robust financing models capable of stabilizing market risk perceptions, thereby attracting sustained private investment. Additionally, strengthening local and regional supply chains to reduce dependencies on vulnerable global suppliers emerges as a critical priority, alongside investments in workforce training and port infrastructure to mitigate competition with established sectors like oil and gas. Nevertheless, this study does not provide insights into country-specific nuances or quantify the precise impacts of individual challenges on offshore wind development. Additionally, the dynamic and rapidly evolving nature of the sector limits the ability of current results to predict future developments accurately. Broader contextual factors such as geopolitical shifts, technological innovations, or sudden policy changes could significantly alter these dynamics, representing limitations beyond the scope of this analysis. Future research should explore deeper quantitative analyses that measure the relative impact of specific challenges and root causes on offshore wind projects, particularly across different countries or regions. Comparative studies examining successful mitigation strategies in other renewable energy sectors or regions could further illuminate potential solutions. Lastly, longitudinal studies tracking policy, financial, and supply chain developments over time could provide valuable insights into the evolution and potential resolution of these systemic issues.

7.3. How do these challenges affect the offshore wind development in the North Sea, and how can they lead to stagnation?

The comprehensive analysis of the updated Causal Loop Diagram (CLD) has highlighted the complex interactions of reinforcing and balancing loops underpinning stagnation in offshore wind development. Central findings indicate that escalating CAPEX Costs significantly heighten Project Costs, subsequently increasing Developer Cost Pressure. This situation motivates developers to upscale turbines to achieve higher energy yields, yet this strategic choice inadvertently exacerbates Value Chain Investment Uncertainty. As uncertainty rises, CAPEX Costs further inflate, creating a self-reinforcing cycle of growing investment risks and escalating project expenditures. Moreover, the sector's dependence on China for critical materials introduces another layer of complexity. While initially serving to moderate Project Costs through more affordable supplies, this reliance ultimately reinforces Europe's dependency on Chinese materials, amplifying geopolitical risks and vulnerabilities in the global supply chain.

The immediate cost advantage offered by Chinese manufacturers paradoxically exacerbates long-term supply chain insecurity, deepening stagnation risks rather than alleviating them. The analysis also reveals significant bottlenecks in Maintenance, Manufacturing, and Installation capacities, directly influencing both CAPEX and OPEX Costs while lengthening Development Timelines. Though improved investment attractiveness could gradually relieve these bottlenecks, the substantial time lag between initial investments and tangible operational improvements ensures persistent short-term stagnation pressures. Thus, even beneficial policy measures and rising market demand cannot swiftly overcome these entrenched operational delays. Value Chain Investment Uncertainty further emerges as a central impediment, directly raising Financing Costs and weakening overall attractiveness for investment in infrastructure and technologies. While supportive policies and growing Wind Energy Demand partially offset this uncertainty, the persistence of financial unpredictability represents a key reinforcing loop limiting the flow of necessary investments. Additionally, Workforce Shortages significantly compound stagnation pressures by directly increasing CAPEX and OPEX Costs and extending project timelines. Persistent labor constraints create cyclical patterns of heightened financial pressures and delayed project completions, positioning workforce management as crucial to stagnation mitigation. Collectively, these insights underscore the necessity for comprehensive, strategically coordinated interventions aimed at disrupting reinforcing cycles of financial uncertainty and operational inefficiencies. Addressing these complex interactions will require targeted policies that systematically reduce investment uncertainties, strengthen supply chain resilience, and enhance workforce and infrastructure capabilities. Future studies could further explore specific policy mechanisms capable of efficiently breaking reinforcing loops or quantitatively model impacts of targeted workforce and infrastructure interventions on overall sector growth and resilience.

7.4. How do current interventions address these challenges, and which actors are responsible?

The analysis of current European Union (EU) actions reveals a comprehensive approach to addressing key challenges hindering offshore wind energy development. By implementing targeted policies such as the Renewable Energy Directive (RED III), Wind Power Package, Technical Support Instrument (TSI), Green Deal Industrial Plan, Net Zero Industry Act (NZIA), Critical Raw Materials Act (CRMA), and Grid Action Plan, the EU has directly tackled significant bottlenecks in the value chain, financial structure, and global supply chains. Through measures such as streamlined permitting processes introduced by RED III and the TSI, permitting bottlenecks, previously a major barrier causing project delays and inflated costs, are significantly reduced. These policies establish clearer timelines and increase administrative efficiency, directly translating into improved project predictability and faster deployment cycles. Enhanced visibility, provided by medium-term auction schedules and deployment targets in the Wind Power Package, further stabilizes planning strategies across the value chain, stimulating early investment in necessary infrastructure and logistics. This strategic foresight mitigates historically persistent delays associated with inadequate port facilities or insufficient specialized vessels. Financial predictability is significantly enhanced through these actions, addressing historical volatility and uncertainty in investment environments. Binding renewable energy targets under RED III provide long-term market stability, bolstering investor confidence essential for capital-intensive offshore wind projects.

Additionally, financial instruments introduced through the Wind Power Package, such as auction price indexation mechanisms, cushion developers against market fluctuations, thus ensuring more secure investment conditions. The targeted financial support provided by the Green Deal Industrial Plan and NZIA effectively reduces CAPEX burdens and investment risks, addressing key barriers that have traditionally limited project financing. Actions addressing the global supply chain notably enhance Europe's resilience to geopolitical and logistical disruptions. Policies under the CRMA and NZIA strengthen domestic sourcing capabilities for critical materials and components, reducing reliance on external suppliers and associated geopolitical risks. By fostering diversified sourcing strategies, Europe secures a more stable and resilient supply chain environment. The indirect influence of RED III and the Wind Power Package further strengthens supplier confidence by providing market clarity and deployment certainty, promoting stable and predictable demand conditions. While these EU measures significantly advance the sector, notable limitations persist. The practical effectiveness of these policies hinges on the timely and consistent implementation at the national level. Although legislative frameworks establish clear timelines and targets, actual administrative capacities and coordination between national authorities remain uncertain factors that could undermine expected outcomes. Additionally, while targeted financial support mechanisms exist, criticisms from industry highlight the insufficiency of these measures in addressing specific technological or infrastructural gaps, particularly concerning storage integration and specialized financial incentives tailored to distinct market conditions across member states. Future research and policy development should emphasize robust monitoring and evaluation mechanisms to ensure the effective translation of EU-level policy frameworks into national practices. Comparative analyses between member states could provide insights into best practices and pinpoint remaining implementation gaps. Further studies exploring the financial incentives tailored specifically for storage solutions and other emerging technological innovations are necessary to support long-term competitiveness and comprehensive sector integration. Additionally, deeper exploration of alternative international partnerships and strategies for supply chain diversification would bolster Europe's offshore wind resilience amidst global market volatility and geopolitical uncertainties.

8. Conclusion & Recommendations

8.1 Overall Conclusions

This thesis set out to investigate how current challenges in North Sea offshore wind development have led to stagnating growth and what underlying causes drive these challenges. Understanding why growth occasionally stalls require a holistic system view. The thesis used a self-developed framework as a lens to thoroughly examine offshore wind development over time. Offshore wind development in the North Sea has progressed through distinct S-curve phases of innovation, market adaptation, and market stabilization (Ortt & Schoormans, 2004; Rogers, 1962). Three interdependent aspects are particularly critical in a theoretical framework for analyzing this development: (1) the offshore wind value chain, (2) the financial structure of projects, and (3) the global supply network. The analysis of offshore wind development in the North Sea underscores the complexity and interconnected nature of the industry's value chain, financial structure, and global supply dynamics.

The value chain analysis revealed that substantial scaling across all phases—particularly installation capacity, grid infrastructure, and specialized workforce—is imperative for meeting ambitious growth targets. Despite significant industry advancements and cost reductions achieved through technological innovation and economies of scale, recent macroeconomic factors, including inflation, rising interest rates, and increased material costs, have eroded some competitive advantages and introduced financial vulnerabilities. The examination of global supply chain dynamics highlighted Europe's pronounced reliance on international suppliers, especially China, for critical components and materials. While this global interdependence has contributed positively to innovation and cost efficiency, it simultaneously exposes the sector to substantial risks from geopolitical tensions, price volatility, and disruptions in global trade. Furthermore, tracing the development of offshore wind through the S-curve of innovation—from the initial Innovation Phase marked by pioneering yet subsidy-dependent projects, to the Market Adaptation Phase where commercial viability was pursued through structured financing and regulatory enhancements, and finally to the current Market Stabilization Phase characterized by mature market-driven mechanisms and larger-scale developments—demonstrates a significant evolution of industry practices and policy frameworks. Notable milestones across Denmark, the UK, Germany, and the Netherlands underscore diverse strategic approaches and regulatory improvements that collectively advanced sector competitiveness.

Nevertheless, despite these advancements, the offshore wind industry now faces renewed macroeconomic and supply chain pressures. Through a combination of literature review, stakeholder interviews, and qualitative systems modeling (using a Current Reality Tree and a Causal Loop Diagram), the research reveals that stagnation is not attributable to a single issue but to a confluence of systemic bottlenecks across regulatory, financial, and supply-chain domains. Key findings indicate that protracted permitting processes, limited grid infrastructure, rising capital costs, and an overreliance on a constrained global supply network (e.g. dependence on a few turbine manufacturers and critical materials suppliers) have together created a challenging environment for offshore wind expansion. The Current Reality Tree (CRT) distilled these interlinked challenges to several root causes – notably, fragmented and slow decision-making processes, insufficient domestic industrial capacity, and historical support scheme dependency – which collectively undercut the pace of deployments. The Causal Loop Diagram (CLD) further illustrated how these factors reinforce one another in feedback loops: delays in grid and permitting slow down projects, which in turn discourage investment and innovation, thereby reinforcing a cycle of slow growth. Crucially, this systemic perspective showed that without intervention the industry could become locked in a vicious cycle of delays, escalating costs, and missed targets. In answer to the research questions, the study concludes that offshore wind development in the North Sea has reached a pivotal plateau due to these intertwined challenges. Historical analysis showed how early exponential growth has given way to a slower phase as the sector grapples with its growing pains. The underlying causes of stagnation were traced in detail (addressing RQ1 and RQ2), revealing that regulatory hurdles (like complex permitting and grid connection lags), financing difficulties amid market volatility, and supply chain constraints are the principal culprits. These challenges materially affect development outcomes (RQ3) by lengthening project timelines and inflating costs, which together threaten the achievement of 2030 expansion goals. At the same time, the thesis found that current efforts to counter these issues (RQ4) – from EU policy initiatives to industry adjustments – are under way but remain partial. For instance, new policies are targeting faster permitting, and programs aim to bolster local manufacturing and workforce training.

However, gaps persist in coordination and scale: many interventions have yet to fully neutralize the root causes identified. This diagnosis underscored the need for a more concerted and strategic approach to break the stagnation cycle. To respond to the root causes and leverage points highlighted by the CRT and CLD, thesis analyzed a suite of targeted interventions. These strategic interventions directly address the diagnosed challenges: streamlining permitting and planning processes, accelerating grid and port infrastructure upgrades, providing more stable revenue and financing frameworks for projects, and strengthening the resilience of the supply chain through local capacity building and diversification. Collectively, these interventions seek to transform the vicious cycle into a virtuous cycle of accelerated deployment: expediting project lead times should improve investor confidence and economies of scale, which in turn attract further investment and innovation, reinforcing growth dynamics. In sum, the findings and proposed solutions together paint a coherent picture: overcoming stagnation will require coordinated action to tackle fundamental bottlenecks and to actively reinforce the enabling conditions for sustained offshore wind expansion in the North Sea region.

8.2 Recommendations

Building on the above conclusions, this study offers a set of pragmatics yet ambitious recommendations for key stakeholders. These recommendations are logically derived from the research findings and are aimed at translating the proposed interventions into concrete actions:
Policymakers (EU and National Governments): Streamline and harmonize regulatory processes to reduce lead times – for example, by establishing one-stop permitting authorities and unified North Sea standards that align environmental and grid planning requirements across countries. Accelerate infrastructure investment in grid connections and port facilities via dedicated public funding and incentives, ensuring that transmission capacity and logistics keep pace with wind farm development. Additionally, enhance market stability by refining auction and tender schemes to balance cost-competitiveness with developer profitability; this could include indexed Contracts-for-Difference or other revenue stabilization tools to mitigate the impact of inflation and price volatility. Policymakers should also implement industrial policies for supply chain resilience, such as supporting domestic manufacturing (through the EU Net-Zero Industry Act and similar national programs) and securing critical materials via strategic reserves or trade agreements. Finally, greater international coordination is recommended – for instance, through EU forums or regional alliances – to share best practices, synchronize expansion targets, and avoid fragmented approaches that could hamper the overall North Sea wind agenda.

Offshore Wind Developers (Project Developers): In parallel, developers should adopt collaborative strategies to manage risks and drive innovation. This includes forging partnerships across the value chain – e.g. consortia with turbine suppliers, grid operators, and financiers – to align project timelines and jointly invest in solutions for common bottlenecks (like installation vessels or storage facilities). Developers are encouraged to engage proactively with permitting authorities and local communities early in the project cycle to preempt delays, by dedicating resources to stakeholder management and environmental planning that meets or exceeds regulatory expectations. They should also pursue standardization and technological innovation to reduce costs: for instance, standardizing project designs and contracting can shorten learning curves, while investing in new technologies (such as improved turbine models, floating foundations, or digital twin monitoring systems) can enhance efficiency and lower long-term O&M costs. Moreover, developers need to strategize for financial resilience by diversifying financing sources (using green bonds, institutional investors, etc.) and securing power purchase agreements that provide demand certainty. By taking these initiatives, developers can not only mitigate the immediate challenges but also demonstrate viability and bolster confidence in the offshore wind market.

Industry Stakeholders (Manufacturers and Suppliers): The broader industry must step up with capacity and resilience enhancements. Turbine and component manufacturers should expand production capacity and workforce training in Europe to meet growing demand, leveraging public support where available, but also investing in scaling up factories, assembly lines, and innovation in design to improve output and reduce dependency on single-source suppliers. Supply chain actors are advised to diversify sourcing and foster partnerships: for like rare earth elements, developing alternative supplier relationships (including intra-Europe collaborations) and recycling programs can reduce vulnerability to geopolitical or market shocks. Contractors and service providers (e.g. installation and maintenance firms) should standardize and modernize their fleets and processes, embracing modular construction techniques and advanced vessels that can handle next-generation turbines efficiently. Across the industry, knowledge-sharing platforms could be established to disseminate best practices and lessons learned from projects, ensuring that successes and innovations in one country or project can be replicated across the North Sea. By collectively committing to these improvements, industry stakeholders will play a pivotal role in translating policy support and developer demand into tangible, on-the-ground progress.

8.3 Study Limitations

While the research provides a comprehensive overview of offshore wind development, stagnation issues and potential solutions, several limitations must be acknowledged. First, the scope of the study is geographically and temporally focused – it concentrates on North Sea countries and the outlook to 2030, which means findings may not fully capture dynamics in other regions or longer-term developments beyond the next decade. The conclusions are most applicable to the context examined; different markets or post-2030 scenarios might introduce new challenges (or diminish current ones) that were outside this thesis's scope. Second, there are limitations related to data and methodology. The interview sample, though carefully selected, was relatively small, which could introduce bias or leave some perspectives underrepresented. Qualitative insights from interviews and literature were crucial for mapping challenges, but they may not cover the full spectrum of industry opinions, especially given the fast-evolving nature of the sector. Additionally, the use of qualitative systems thinking tools (CRT and CLD) entails a degree of subjectivity in how relationships are identified and prioritized. The models simplify a complex reality and do not quantify the strength of feedback loops or the probability of certain outcomes. As a result, the analysis might overlook subtle influences or emergent behaviors that only a quantitative or more granular approach could reveal. Finally, external factors such as global economic shifts, political changes, or technological breakthroughs that occurred after the data collection cut-off are not accounted for, potentially affecting the relevance of some findings. Recognizing these limitations, the results of this study should be interpreted as a structured diagnostic and set of guiding hypotheses, rather than definitive predictions.

8.4 Future Research Directions

Building on this thesis, there are clear avenues for future research that can address the above limitations and deepen the understanding of offshore wind development dynamics. Firstly, quantitative modeling should be pursued to validate and extend the qualitative CLD findings – for example, developing a system dynamics simulation or econometric model of the North Sea offshore wind sector would allow testing of how different variables (like permitting times or supply chain expansion) quantitatively impact deployment rates. Such models could assess the potential efficacy of various interventions over time and identify tipping points or threshold effects. Secondly, a scenario analysis of policy options is recommended: researchers could construct and evaluate future scenarios (e.g. a scenario with strong EU-wide policy harmonization vs. one with continued national fragmentation) to explore how different strategies might accelerate or hinder offshore wind growth. This would provide policymakers with insight into which combinations of interventions yield the most robust improvement under uncertainty (including sensitivity to economic and demand changes). Thirdly, deeper supply chain risk assessments are needed. Future studies might employ techniques like network analysis or probabilistic risk modeling to examine the offshore wind supply chain's resilience – for instance, quantifying the impact of a disruption in the turbine supply or a surge in raw material prices, and evaluating risk-mitigation strategies (such as inventory stockpiling or supplier diversification) in detail. Additionally, research could expand beyond the North Sea context to include comparative analyses: examining whether similar stagnation patterns or solutions are observed in emerging offshore wind markets (like East Asia or North America) would enrich the understanding of which challenges are globally systemic, and which are context specific. Finally, as the industry evolves, integrated socio-technical studies could look at topics like workforce development, community engagement, and environmental sustainability in greater depth, ensuring that future offshore wind expansion is not only rapid but also equitable and ecologically responsible. By pursuing these research directions, the academic and policy community can continue to refine strategies to unlock the full potential of offshore wind and guide the sector through its next phase of growth.

Literature

Beiter, P., Musial, W., Kilcher, L., Maness, M., Smith, A., 2017. An Assessment of the Economic Potential of Offshore Wind in the United States from 2015 to 2030. https://doi.org/10.2172/1349721.

Berk, N. (2024). Enhancing tender and supply contract designs for a robust offshore wind industry (Master's thesis). Delft University of Technology.

Bilgili, M., Yasar, A., & Simsek, E. (2011). Offshore wind power development in Europe and its comparison with onshore counterpart. Renewable and Sustainable Energy Reviews, 15(2), 905–915.

Blanco, M. I. (2009). The economics of wind energy. Renewable and Sustainable Energy Reviews, 13(6-7), 1372-1382. https://doi.org/10.1016/j.rser.2008.09.004

Bulski, K. (2024,). Offshore wind power is driving job growth in Europe – the question is how to meet demand? BalticWind.EU. Retrieved from https://balticwind.eu/offshore-wind-power-is-driving-job-growth-in-europe-the-question-is-how-to-meet-demand

Castle, J., & Pryor, A. (2016). Offshore wind decommissioning: Current policies and future perspectives. Journal of Marine Policy, 82, 95-105.

Castro-Santos, L., & Diaz-Casas, V. (2014). Life-cycle cost analysis of floating offshore wind farms. *Renewable Energy, 66*, 41–48. https://doi.org/10.1016/j.renene.2013.12.036

Chinese Wind Energy Association (CWEA). (2012). Statistics of Chinese wind energy installation capacity 2011.

Cortizo, I., Hodgson, T., Hiorns, T., Aqui, D., & Jones, L. (2019). Holistic offshore wind farm optimization approach. In Offshore Technology Conference (p. D021S019R004). OTC.

Del Río, P., & Kiefer, C. P. (2023). Academic research on renewable electricity auctions: Taking stock and looking forward. Energy Policy, 173, 113305.

DeCastro, M., Salvador, S., Gómez-Gesteira, M., Costoya, X., Carvalho, D., Sanz-Larruga, F. J., & Gimeno, L. (2019). Europe, China and the United States: Three different approaches to the development of offshore wind energy. *Renewable and Sustainable Energy Reviews, 109*, 55-70.

Dedecca, J. G., Hakvoort, R. A., & Ortt, J. R. (2016). Market strategies for offshore wind in Europe: A development and diffusion perspective. *Renewable and Sustainable Energy Reviews*, *66*, 286-296.

Department of Energy & Climate Change (DECC). (2011). Decommissioning of offshore renewable energy installations under the Energy Act 2004. URN 10D/1025, DECC, London, United Kingdom.

Dettmer, H. W. (1997). Goldratt's Theory of Constraints: A Systems Approach to Continuous Improvement. ASQC Quality Press.

Dettmer, H. W. (1998). Breaking the Constraints to World Class Performance. ASQ Quality Press.

Díaz, H., Guedes Soares, C., 2020. Review of the current status, technology and future trends of offshore wind farms. Ocean Engineering, 209, 107381.

Dicorato, M., Forte, G., Pisani, M., & Trovato, M. (2011). Guidelines for assessment of investment cost for offshore wind generation. *Renewable Energy, 36*(8), 2043-2051. https://doi.org/10.1016/j.renene.2011.01.003

Dinh, V. N., & McKeogh, E. (2019). Offshore wind energy: technology opportunities and challenges. In *Proceedings of the 1st Vietnam Symposium on Advances in Offshore Engineering: Energy and Geotechnics* (pp. 3-22). Springer Singapore.

Eckardt, J., & Stenzel, B. (2023). Offshore Wind Supply Chains in the US and Germany.

ENTSO-E. (2024). *TYNDP 2024 Sea-Basin ONDP Report: TEN-E Offshore Priority Corridor: Northern Seas Offshore Grids*. Retrieved from https://www.entsoe.eu/outlooks/offshore-hub/tyndp-ondp/

Esteban, M. D., Diez, J. J., López, J. S., & Negro, V. (2011). Why offshore wind energy? Renewable Energy, 36(2), 444–450.

European Commission. (2019). Overall targets. Retrieved from https://ec.europa.eu/info/energy-climate-change-environment/overall-targets_en

European Commission. (2023a). Communication from the Commission: A Green Deal Industrial Plan for the Net-Zero Age. COM/2023/62 final. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023DC0062

European Commission. (2023b). Communication from the Commission: The Wind Power Package. COM/2023/669 final. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023DC0669

European Commission. (2023c). Communication from the Commission: The Renewable Energy Directive (RED III). Directive (EU) 2023/2413. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023L2413 European Commission. (2024a). Communication from the Commission: The Net Zero Industry Act (NZIA). Regulation (EU) 2024/1735. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401735

European Commission. (2024b). Communication from the Commission: The Critical Raw Materials Act (CRMA). Regulation (EU) 2024/1252. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401252

European Commission. (2024c). Communication from the Commission: The Grid Action Plan. COM/2023/757 final. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2023%3A757%3AFIN

European Commission. (2024d). Communication from the Commission: Technical Support Instrument (TSI) Regulation. COM/2024/445 final. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52024DC0445

Fitch-Roy, O. (2016). An offshore wind union? Diversity and convergence in European offshore wind governance. Climate Policy, 16(5), 586-605.

Gallagher, K. (2006). Limits to leapfrogging in energy technologies? Evidence from the Chinese automobile industry. Energy Policy, 34, 383–394.

Green Giraffe (2019). *Recent Trends in Offshore Wind Finance*. Available at: Green Giraffe Trends.

Green, R., & Vasilakos, N. (2011). The economics of offshore wind. Energy Policy, 39(2), 496–502.

Greve, N. (2020). Zero-subsidy bids in offshore wind auctions: A German case study. *Energy Policy*, 138, 111197. https://doi.org/10.1016/j.enpol.2019.111197

Greve, T., & Rocha, M. (2020). Policy and theoretical implications of the zero-subsidy bids in the German offshore wind tenders. The Energy Journal, 41(4), 89-104.

Guidehouse & Berenschot. (2021). Offshore wind system integration 2030–2040. Retrieved from https://offshorewind.rvo.nl/blog/view/76e606cb-45c6-4fd3-85d8-77c768ce34d6/study-system-integration-offshore-wind-2030-2040-in-english

Guillet, J. (2022). Financing Offshore Wind. World Forum Offshore Wind (WFO). Retrieved from WFO_FinancingOffshoreWind_2022.

Hall, M. A. (2001, September). Root cause analysis: A tool for closer supply chain integration in construction. In *17th Annual ARCOM Conference* (Vol. 1, pp. 929-938). Salford: Association of Researchers in Construction Management, University of Salford.

Halldorsson, A., & Svanberg, M. (2013). Energy resources: Trajectories for supply chain management. Supply Chain Management: An International Journal, 18(1), 66-73.

Hansen, T. A., Wilson, E. J., Fitts, J. P., Jansen, M., Beiter, P., Steffen, B., ... & Kitzing, L. (2024). Five grand challenges of offshore wind financing in the United States. Energy Research & Social Science, 107, 103329.

Haraldsson, H. V. (2004). Introduction to system thinking and causal loop diagrams. Lund University, Department of Chemical Engineering.

Hayley, A. (2024). China's dominance in wind turbine manufacturing. Reuters. Retrieved from https://www.reuters.com/business/energy/chinas-dominance-wind-turbine-manufacturing-2024-04-10/

Hodgson, G. M. (2006). What are institutions?. *Journal of economic issues*, *40*(1), 1-25.

Howard, R. (2012). *Offshore wind cost reduction pathways project—simple levelised cost of energy model*. The Crown Estate, London, UK.

Hrouga, M., & Bostel, N. (2021. Supply chain planning of off-shores winds farms operations: a review. In Advances in Integrated Design and Production: Proceedings of the 11th International Conference on Integrated Design and Production, CPI 2019, October 14-16, 2019, Fez, Morocco (pp. 372-387). Springer International Publishing.)

Hurtado, A. (2023). Report: Offshore wind growth is "slowing down." *Offshore*. Retrieved from https://www.offshore-mag.com/renewable-energy/article/14302820/report-offshore-wind-growth-is-slowing-down

Industri, N. (2024). Delrapport – Contracting in the Offshore Wind Industry: A Guide to Norwegian Suppliers. Available at: Norwegian Suppliers Contracting Guide.

International Energy Agency (IEA). (2024). Advancing clean technology manufacturing. IEA, Paris. Retrieved from https://www.iea.org/reports/advancing-clean-technology-manufacturing

IRENA. (2019). Renewable energy auctions: Status and trends beyond price. International Renewable Energy Agency.

IRENA (2024) – with minor processing by Our World in Data. "Bioenergy levelized cost of energy" [dataset]. IRENA, "Renewable Power Generation Costs" [original data].

Jacobsson, S., & Karltorp, K. (2013). Mechanisms blocking the dynamics of the European offshore wind energy innovation system–Challenges for policy intervention. *Energy Policy*, *63*, 1182-1195.

Janipour, Z. (2023). The Bottlenecks Challenging Growth in the EU Offshore Wind Supply Chain. In RaboResearch.Retrvied from https://www.rabobank.com/knowledge/d011354306-the-bottlenecks-challenging-growth-in-the-eu-offshore-wind-supply-chain

Jansen, M. (2020). The role of Contracts for Differences in renewable energy support. Energy Economics, 88, 104786. https://doi.org/10.1016/j.eneco.2020.104786

Jansen, M. (2020). The role of Contracts for Differences in renewable energy support. *Energy*

Jansen, M., Beiter, P., Riepin, I., Müsgens, F., Guajardo-Fajardo, V. J., Staffell, I., ... & Kitzing, L. (2022). Policy choices and outcomes for offshore wind auctions globally. *Energy policy*, *167*, 113000.

JBR & InvestNL. (2025). *Improving access to finance for the Dutch offshore wind supply chain: Final Report - February 2025* [Report cover]. JBR; InvestNL; TKI Offshore Energy.

Jenkinson, O. (2023). Critical risks to European wind supply chain threaten to derail green transition. *Windpower Monthly*. Retrieved from https://www.windpowermonthly.com/article/1820082/critical-risks-european-wind-supply-chain-threaten-derail-green-transition

Johnston, B., Foley, A., Doran, J., & Littler, T. (2020). Levelised cost of energy, a challenge for offshore wind. Renewable Energy, 160, 876-885.

Kabeyi, M. J. B., & Olanrewaju, O. A. (2023). The levelized cost of energy and modifications for use in electricity generation planning. *Energy Reports*, *9*, 495-534.

Kaiser, M. J., & Snyder, B. (2012). Offshore Wind Energy Cost Modeling: Installation and Decommissioning. Springer.

Kalair, A., Abas, N., Saleem, M. S., Khan, N., & Kalair, A. R. (2016). Review of harmonic analysis, modeling, and mitigation techniques. Renewable and Sustainable Energy Reviews, 54, 1652–1668.

Kaldellis, J., & Kapsali, M. (2013). Shifting Towards Offshore Wind Energy – Recent Activity and Future Development. Renewable and Sustainable Energy Reviews, 17, 233-243.

Kitzing, L., Morthorst, P.E., 2015. Trends in offshore wind economics – the past and the future. In: 14th Wind Integration Workshop, 1–8.

Lakshmanan, V., Marinelli, M., Huerta, A., & Sørensen, P. E. (2015). A review of the emerging low-frequency AC transmission system (LFAC). IEEE Transactions on Power Delivery, 30(1), 50–57.

Lee, M. C., & Chang, T. (2012). Combination of theory of constraints, root cause analysis and Six Sigma for quality improvement framework. *International Journal of Productivity and Quality Management, 10*(4), 447-463.

Lema, A., & Ruby, K. (2007). Between fragmented authoritarianism and policy coordination: Creating a Chinese market for wind energy. Energy Policy, 35, 3879–3890.

Li, C., Cai, J., Zhang, S., & Guedes Soares, C. (2022). Material demand and supply chain analysis for offshore wind energy under different scenarios. Renewable and Sustainable Energy Reviews, 164, 112603

Li, J., Shi, P., & Gao, H. (2007). China wind power report: 2007. Beijing: China Environmental Science Press.

Liao, W.-H., Lin, H.-C., & Kuo, T.-H. (2020). An overview of Taiwan's offshore wind turbine and components testing and certification capacity and current situation. *International Journal of Smart Grid and Clean Energy, 9*(2), 170-179.

Liu, Y., & Kokko, A. (2010). Wind power in China: Policy and development challenges. Energy Policy, 38, 5520–5529.

Maegaard, P., Kruse, J., & Maegaard, F. (2013). Wind power: 50 years of Danish pioneering in wind energy. Renewable Energy and Sustainability, 4(1), 3-15.

Mahdi, M. (2023). Designing Denmark's Future Offshore Wind Policy Framework: A Pathway for Policymakers to Achieve 12.9 GW Deployment by 2030.

Maples, B., Saur, G., Hand, M., van de Pieterman, R., & Obdam, T. (2013). *Installation, operation, and maintenance strategies to reduce the cost of offshore wind energy*. National Renewable Energy Laboratory, Colorado, USA. https://doi.org/10.2172/1097920

McCoy, A., Musial, W., Hammond, R., Mulas Hernando, D., Duffy, P., Beiter, P., Pérez, P., Baranowski, R., Reber, G., Spitsen, P., National Renewable Energy Laboratory, Boston Government Services LLC, & U.S. Department of Energy. (2024). Offshore Wind Market Report: 2024 Edition (NREL/TP-5000-90525). National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy24osti/90525.pdf

Memija, A. *IMCA Publishes Standard Contract for Offshore Wind Projects*. [2024].

Myhr, A., Bjerkseter, C., Ågotnes, A., & Nygaard, T. A. (2014). Levelised cost of energy for offshore floating wind turbines in a life cycle perspective. *Renewable Energy, 66*, 714-728. https://doi.org/10.1016/j.renene.2014.01.017

Nielsen, P. (2003). *Offshore wind energy projects feasibility study guidelines*. SEAWIND-Altener project 4.1030/Z/01-103/2001, Ver. 3.0. Aalborg, Denmark.

Norwegian Water Resources and Energy Directorate & Swedish Energy Agency. (2015). The Norwegian-Swedish electricity certificate market. Retrieved from https://beta.nve.no/Media/4750/elcertifikat-2015-en_web.pdf

O'Kelly, B.C., Arshad, M., 2016. Offshore wind turbine foundations – analysis and design. In: Offshore Wind Farms: Technologies, Design and Operation, 589–610. https://doi.org/10.1016/B978-0-08-100779-2.00020-9.

Offshore Design Engineering Ltd. (2007). *Study of the costs of offshore wind generation*. Renewables Advisory Board and Department of Trade and Industry, UK.

Perveen, R., Kishor, N., & Mohanty, S. R. (2014). Off-shore wind farm development: Present status and challenges. Renewable and Sustainable Energy Reviews, 29, 780-792.

Polito, T., Watson, K. J., & Vokurka, R. J. (2006). Integrating the Theory of Constraints and Six Sigma: A case study. *Production and Inventory Management Journal*, 47(2), 47–54.

RES Legal. (2024). Legal sources on renewable energy. Retrieved from http://www.res-legal.eu

Rodrigues, S., Restrepo, C., Kontos, E., Teixeira Pinto, R., & Bauer, P. (2015). Trends of offshore wind projects. Renewable Energy, 85, 340-359.

Royal Haskoning DHV. (2023). North Seas offshore wind port study 2030–2050. Retrieved from https://offshorewind.rvo.nl/blog/view/d032ccbb-66e7-4464-aada-048a61cd9868/north-seas-offshore-wind-port-study-2030-2050-in-english

Ru, P., Zhi, Q., Zhang, F., Zhong, X., Li, J., & Su, J. (2012). Behind the development of technology: The transition of innovation modes in China's wind turbine manufacturing industry. Energy Policy, 43, 58–69.

Ruddy, B. P., MacEnri, J., & Finn, A. (2016). LFAC technology for the grid connection of offshore wind farms. Energies, 9(8), 658.

Rystad Energy. (2023). *The state of the European wind energy supply chain: A "what-would-it-take" analysis of the European supply chain's ability to support ambitious capacity targets towards 2030*. Retrieved from https://windeurope.org/intelligence-platform/product/the-state-of-the-european-wind-energy-supply-chain/

Sakdiyah, S. H., Eltivia, N., & Afandi, A. (2022). Root cause analysis using CED: Company management decision making. *Journal of Applied Business, Taxation and Economics Research*, 1(6), 566–576.

Scheinkopf, L. (1999). Thinking for a Change: Putting the TOC Thinking Processes to Use. St Lucie Press/APICS series on constraint management.

Scholz-Reiter, B., Lütjen, M., Heger, J., & Schweizer, A. (2010). Planning and control of logistics for offshore wind farms. Proceedings of the 12th WSEAS International Conference on Mathematical and Computational Methods in Science and Engineering, 242-247.

Shafiee, M. (2015). Maintenance logistics organization for offshore wind energy: Current progress and future perspectives. *Renewable Energy, 77*, 182-193.

Shafiee, M. (2016). Whole life cost assessment of offshore wind farms. *International Journal of Life Cycle Assessment, 21*(7), 961–975. https://doi.org/10.1007/s11367-016-1063-9

Shafiee, M., & Dinmohammadi, F. (2014). An FMEA-based risk assessment approach for wind turbine systems: A comparative study of onshore and offshore. *Energies, 7*(2), 619-642. https://doi.org/10.3390/en7020619

Shields, M., Beiter, P., Nunemaker, J., Cooperman, A., & Duffy, P. (2021). Impacts of turbine and plant upsizing on the levelized cost of energy for offshore wind. *Applied Energy*, *298*, 117189.

Shittekatte, T. (2016). Offshore Electricity Grid Development. Florence School of Regulation. Retrieved from https://fsr.eui.eu/offshore-electricity-grid-development/

Smyth, K., Christie, N., Burdon, D., Atkins, J.P., Barnes, R., & Elliott, M. (2015). Renewables-to-reefs? Decommissioning options for the offshore wind power industry. Marine Pollution Bulletin, 90(1-2), 247-258.

Soares-Ramos, E. P., de Oliveira-Assis, L., Sarrias-Mena, R., & Fernández-Ramírez, L. M. (2020). Current status and future trends of offshore wind power in Europe. Energy, 202, 117787.

Špicar, R. (2014). System Dynamics Archetypes in Capacity Planning. Procedia Engineering, 69, 1350-1355.

Sterman, J. (2002). System Dynamics: systems thinking and modeling for a complex world.
Steyn, H. (2002). Project management applications of the Theory of Constraints beyond critical chain scheduling. *International Journal of Project Management*, 20(1), 75–80.

Tavner, P. (2013). *Offshore wind turbines: Reliability, availability and maintenance*. The Institution of Engineering and Technology, London, UK.

The Crown Estate. (2010). *A guide to an offshore wind farm*. London, UK.

The Guardian. (2023). Giant windfarm off Norfolk coast halted as costs spiral. Retrieved from https://www.theguardian.com/business/2023/jul/20/giant-windfarm-norfolk-coast-halted-spiralling-costs-vattenfall

Thommessen, C., Otto, M., Nigbur, F., Roes, J., & Heinzel, A. (2021). Techno-economic system analysis of an offshore energy hub with an outlook on electrofuel applications. Smart Energy, 3, 100027.

Tip, T. (2011). Guidelines for drawing causal loop diagrams. *Systems Thinker*, *22*(1)

Topham, E., & McMillan, D. (2017). Sustainable decommissioning of an offshore wind farm. Renewable Energy, 102, 470-480.

Umoh, K., & Lemon, M. (2020). Drivers for and barriers to the take-up of floating offshore wind technology: A comparison of Scotland and South Africa. Energies, 13(21), 5618.

United Kingdom Government. (2019). Offshore Wind Sector Deal: Long-Term Planning for the UK Energy Mix. Retrieved from https://www.gov.uk/government/news/offshore-wind-energy-revolution-to-provide-a-third-of-all-uk-electricity-by-2030

van der Loos, A., Langeveld, R., Hekkert, M., Negro, S., & Truffer, B. (2022). Developing local industries and global value chains: The case of offshore wind. Technological forecasting and social change, 174, 121248.

Van der Zwaan, B., Rivera-Tinoco, R., Lensink, S., & Van Den Oosterkamp, P. (2012). Cost reductions for offshore wind power: Exploring the balance between scaling, learning, and R&D. Renewable Energy, 41, 389-393.

Walter et al., 2018. National Renewable Energy Laboratory (NREL) Offshore Wind Technologies Market Report.

Walter, M., Philipp, B., Spitsen, P., Nunemake, J., Gevorgian, V., 2018. 2018 Offshore Wind Technologies Market Report.

Wee, H. M., Yang, W. H., Chou, C. W., & Padilan, M. V. (2012). Renewable energy supply chains, performance, application barriers, and strategies for further development. Renewable and Sustainable Energy Reviews, 16(8), 5451-5465.

Welstead, J., Cotton, I., Lum, S.K.Y., & Wilson, J. (2013). Offshore Renewable Energy – Accelerating Decommissioning Best Practices. RenewableUK Report.

Williamson, O. E. The New Institutional Economics: Taking Stock, Looking Ahead. [2000].

WindEurope (2022) The State of the European Wind Energy Supply Chain. Retrieved from https://windeurope.org/intelligence-platform/product/the-state-of-the-european-wind-energy-supply-chain/#overview

WindEurope. (2022). Wind energy in Europe: 2022 statistics and the outlook for 2023-2027. Retrieved from [WindEurope website].

WindEurope. Wind Energy in Europe in 2019 - Trends and Statistics. [2022].

Xie, X., Ru, P., Su, J., Li, J., & Zhi, Q. (2011). The technology innovation mode evolution and policy motivation for Chinese wind manufacturers. Coal Economic Research, 2011(4), 10–14, 17.

Yang, J., Liu, Q., Li, X., Cui, X., 2017. Overview of wind power in China: status and future. Sustainability, 9, 1–12. https://doi.org/10.3390/su9081454.

Yuniarto, H., & Therese, E. (2009). Root cause analysis: A systems approach for quality improvement. Journal of Quality Maintenance Engineering, 15(1), 71–82.

Zhang, D., Jiao, Z., & Gao, J. (2011). Key technologies for offshore wind power systems. Renewable and Sustainable Energy Reviews, 15(9), 4692–4699.

Appendix

A. Interview Process

Table X shows an overview of the stakeholders in offshore wind energy interviewed for this thesis. The CRT will be built from these insights, focusing on the main challenges, root causes, and reinforcing loops. Interview notes will also be shared with interviewees for their review and approval, ensuring the accuracy of the captured perspectives.
The prepared questions for the interviews are as follows:

- What are your company's largest costs and risks in the offshore wind sector?
- What challenges do you encounter when scaling up offshore wind projects?
- What impact do these challenges have on your company?
- What potential solutions do you see to address these challenges?
- Which parties are essential to reaching a solution?

Interview #	Stakeholder	Function
1.	Tender Organizer for permits	Programme Manager Offshore Wind
2.	Project developer	Site Procurement Manager
	Project developer	Bid Developer OFW
3.	Project developer	Engineering Manager
	Project developer	Senior Advisor Regulatory Affairs
4.	Project developer	Managing Director Benelux Region
	Project developer	Senior Lead Market Development
5.	Installation Equipment Manufacturer	Product Manager
6.	Monopile Manufacturer	Product Strategy Director
7.	Turbine Manufacturer	Head Global Offshore Product Market
8.	Transport and Installation Services	Director Commerce Offshore
	Transport and Installation Services	Head of Marine Projects
9.	Offshore Wind Project Constructor	Regional Manager Offshore Wind
	Offshore Wind Project Constructor	Commercial Manager Offshore Energy
10.	Maritime Port	Chief Investment Officer
	Maritime Port	Commercial Manager
11.	Maintenance and Operations Services	European Development Manager
	Maintenance and Operations Services	Managing Director
12.	Organization Energy Use Companies	Policy Advisor Energy
	Chemicals Producer for Industry	Account Manager Energy
13.	Regulatory and Governing institute	Project officer- Innovation in Clean Energy Technologies

B. Literature Review Process

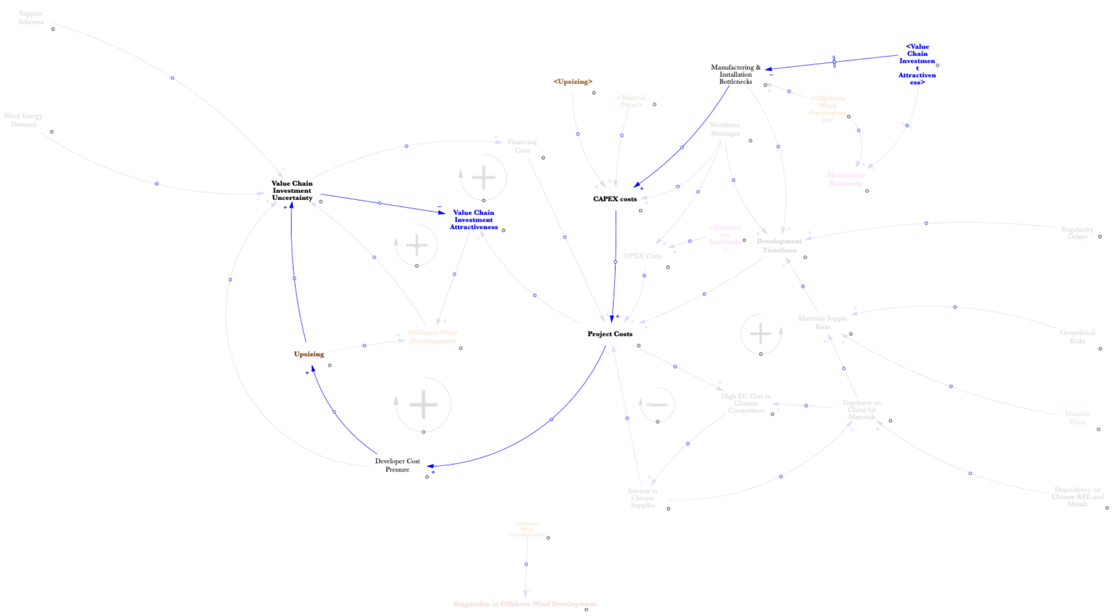
To develop a comprehensive understanding of the challenges in offshore wind development, a systematic literature review was conducted, combining academic sources, industry reports, and policy documents. The objective was to ensure the inclusion of high-quality, relevant literature that reflects the evolving landscape of offshore wind energy. The search process followed an iterative approach, allowing emerging themes to shape the final scope of the literature review rather than imposing predefined categories. The primary sources of literature included academic databases such as Scopus, Web of Science, ScienceDirect, and Google Scholar, alongside industry and policy reports from organizations like WindEurope and the International Energy Agency (IEA). The search strategy employed Boolean operators to refine results and ensure relevance across multiple disciplines. The initial search queries included terms such as "offshore wind energy AND challenges," "offshore wind supply chain AND infrastructure bottlenecks," and "offshore wind financing AND investment risks". These search terms were adapted across different databases to optimize results and capture diverse perspectives from engineering, economics, and policy literature. To complement database searches, forward and backward snowballing techniques were applied. Backward snowballing involved reviewing the reference lists of key papers to identify influential prior research, while forward snowballing tracked more recent studies that cited relevant sources, ensuring the review captured both foundational and emerging literature. Additionally, expert recommendations and conference proceedings were considered to include recent industry insights that might not yet be widely cited in academic literature. The selection process applied inclusion and exclusion criteria to filter the results. Studies were included if they directly addressed offshore wind development, focusing on governance, market structures, supply chains, financial frameworks, or technological challenges. Priority was given to sources published within the last decade (2013–2024) to ensure relevance to current industry trends. However, older sources were retained when they provided essential background on policy evolution or technological development. Studies were excluded if they primarily focused on onshore wind energy, lacked empirical evidence, or were corporate white papers with potential promotional bias. The combination of structured database searches, Boolean operator refinement, and snowballing techniques provided a rigorous foundation for assessing the challenges in offshore wind development, setting the stage for subsequent discussions in this research.

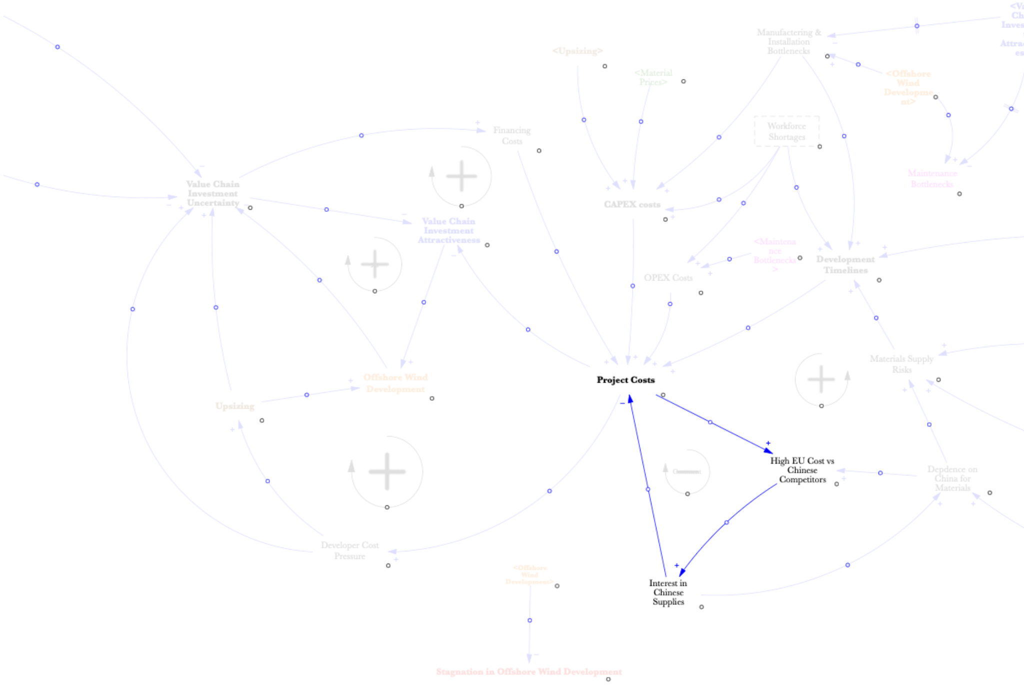
Table 3

Reference	**Topic Focus** **Relevant Finding**	**Type of Source**
Berk (2024)	Enhancing tender and supply contract designs for a robust offshore wind industry	Academic study
Bulski (2024)	Offshore wind power is driving job growth in Europe – the question is how to meet demand?	Industry article
Del Río & Kiefer (2023)	Academic research on renewable electricity auctions: Taking stock and looking forward.	Academic study
Dinh & McKeogh (2019)	Offshore wind energy: technology opportunities and challenges	Academic study
Guidehouse & Berenschot (2021)	Offshore wind system integration 2030–2040	Industry report
Greve & Rocha (2020)	Policy and theoretical implications of the zero-subsidy bids in the German offshore wind tenders	Academic study
IEA (2024)	Advancing clean technology manufacturing	Industry report
Janipour (2023)	The bottlenecks challenging growth in the EU offshore wind supply chain	Industry Article
Royal Haskoning DHV (2023)	North Seas Offshore Wind Port Study 2030–2050	Industry report

Soares-Ramos et al. DHV(2020)	Current status and future trends of offshore wind power in Europe	Academic study
WindEurope (2022)	The State of the European Wind Energy Supply Chain	Industry report
Halldorsson & Svanberg (2013)	Overlapping industries: Offshore wind and oil and gas	Academic study
Cortizo et al. (2019)	Holistic offshore wind farm optimization approach	Academic study
Hayley (2024)	China's dominance in wind turbine manufacturing	Industry Article

C. Causal Loops

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High EU Cost vs
Chinese
Competitors
Interest in
Chinese
Supplies
Value Chain
Investment
Uncertainty
Value Chain
Investment
Attractiveness
Financing
Costs
CAPEX costs
OPEX Costs
Development
Timelines
Materials Supply
Risks
Workforce
Shortages
Manufacturing &
Installation
Bottlenecks
Offshore Wind
Development
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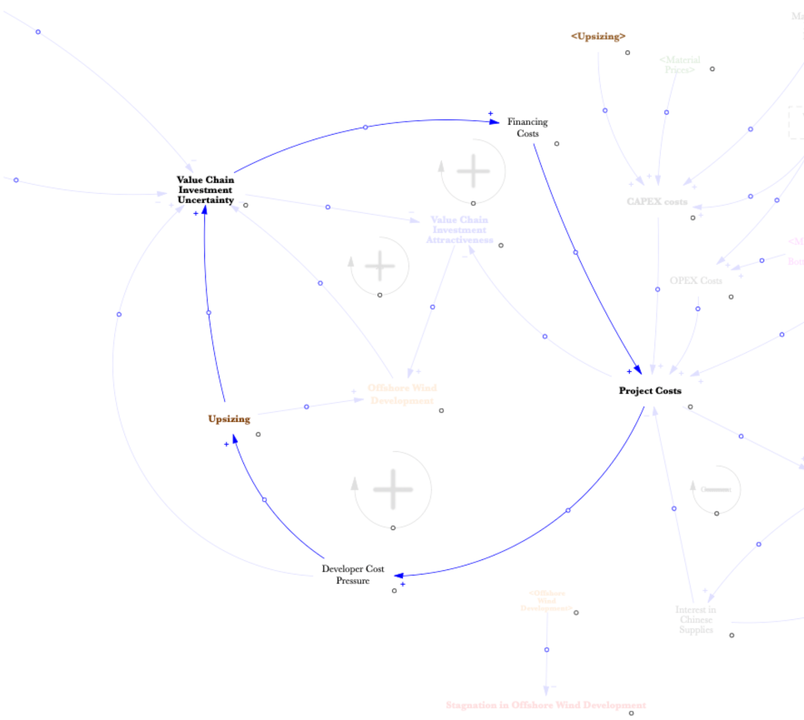
Developer Cost
Pressure
Stagnation in Offshore Wind Development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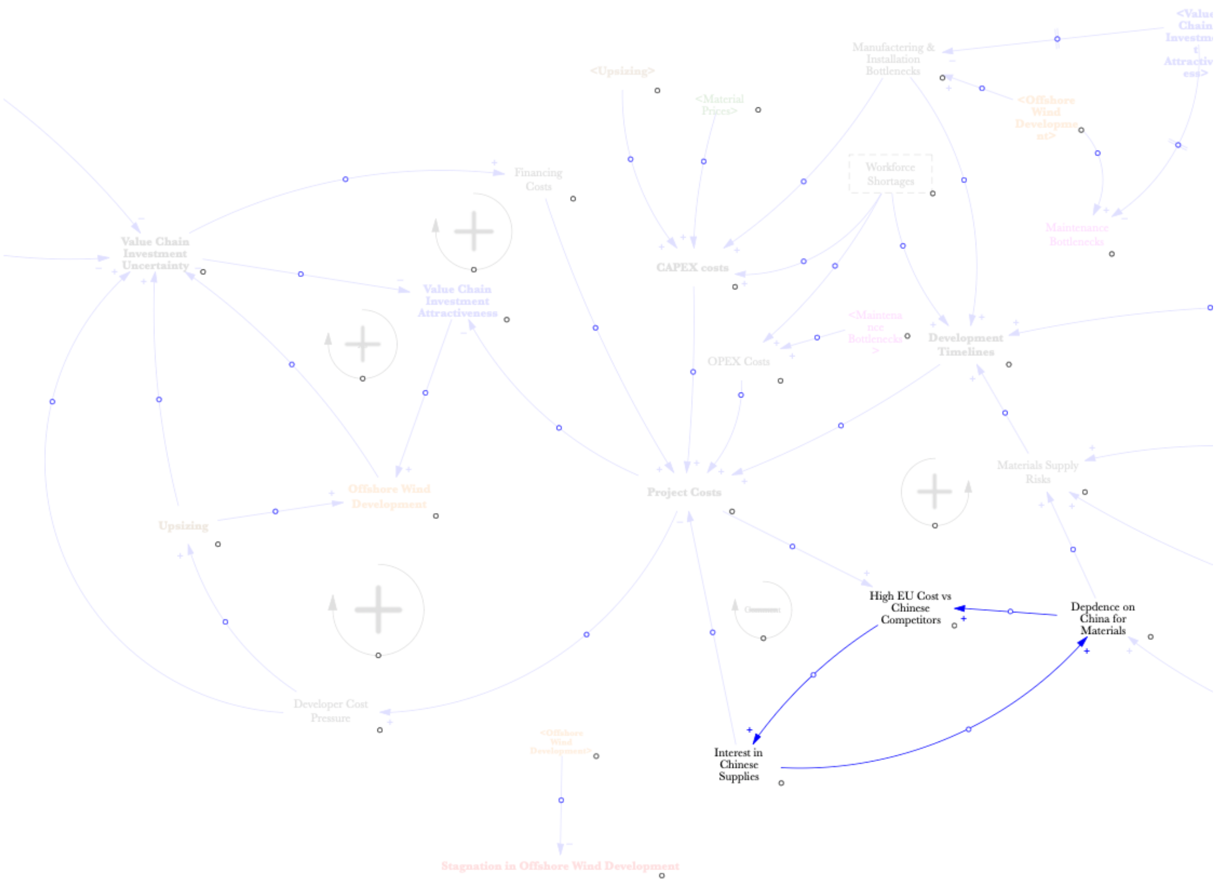
Supplies
Stagnation in Offshore Wind Development


Value Chain Investment Uncertainty
Financing Costs
Value Chain Investment Attractiveness
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Manufacturing & Installation Bottlenecks
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Workforce Shortages
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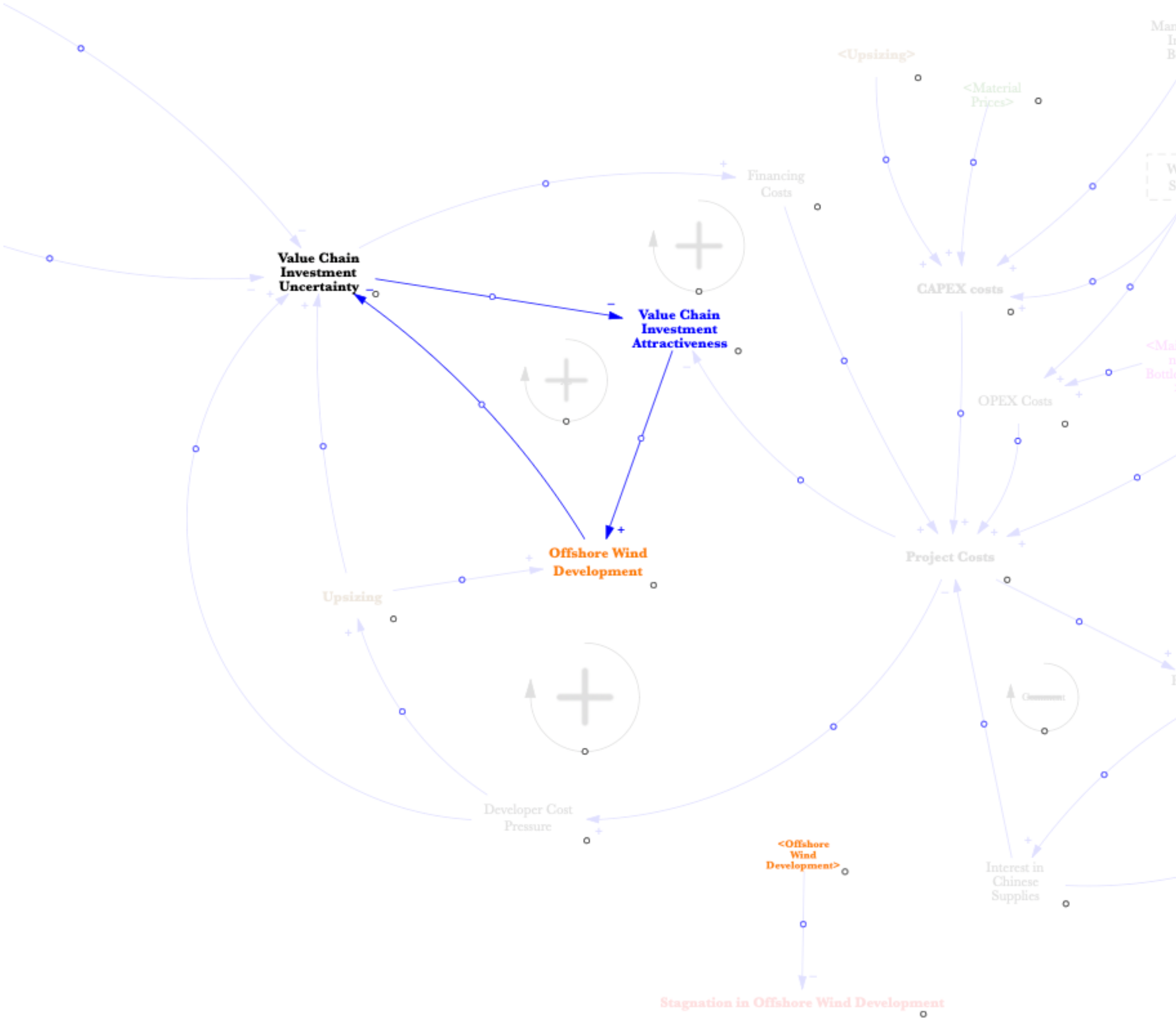
Value Chain Investment Uncertainty
Value Chain Investment Attractiveness
Offshore Wind Development
Financing Costs
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Project Costs
Upsizing
Developer Cost Pressure
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Interest in Chinese Supplies
Stagnation in Offshore Wind Development