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Slashing Through the Blade

Exploring practical perceptions of wind turbine blade circular innovations

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Abstract

Wind energy has been established since before the 2000s and has experienced significant growth, particularly influenced by documents like the Kyoto Protocol and the Paris Agreement, which shaped global perspectives on sustainability. While wind energy has contributed to desired sustainability goals outlined in these documents, it still confronts numerous challenges regarding circularity and achieving sustainable end-of-life management with current technologies such as composite materials. This qualitative study addresses these challenges by examining wind turbine blade lifecycles and stakeholder perspectives on implementing circularity models, such as product-as-a-service, to combat issues like improper disposal. Thirteen practitioners from the wind turbine market, including OEMs, Wind Operators, and Recycling Facilities, were interviewed to assess the barriers and drivers of circular practices within the industry, as well as perceptions of the product-as-a-service model. The study identified various challenges perceived by stakeholders across economic, infrastructure/product features, collaborative, and legislative settings. Economic and collaborative actions emerged as more significant than legislative and infrastructure/product features actions, although the latter remain significant but received less emphasis during interviews. Furthermore, the study revealed that while the product-as-a-service model demonstrates maturity in certain aspects in the wind market, challenges such as economic competition, lack of partnerships, and economic dissatisfaction in recycling facilities impede its full realization. The need for a framework prioritizing a transversal view in collaboration and economic factors while narrowing down policy and infrastructure/product features will benefit the implementation of circular practices and is essential in wind turbine blades. Regarding product-as-a-service, this is a very immature model where standardization of the product and design changes are needed to begin defining the requirements of this model in the market before setting the ambition to look into the development, implementation, and monitoring.

Keywords: Circular economy, Product as a service, End-of-life-Management, Wind turbine blades, Wind Energy.

Executive Summary

Background and Aim:

The global transition to renewable energies, driven by climate change concerns, faces significant hurdles in effectively managing resources, significantly in the EOL phase. Inadequate disposal practices like open field incineration and landfill contribute to environmental contamination, this needs a sustainable solution. Specifically, the disposal of wind turbines poses challenges, with low recycling rates and concerns about increasing waste volume due to materials such as composites (glass and carbon fibres). While companies like Siemens Gamesa and Vestas are exploring recycling efforts, scaling up remains hindered by various challenges. Recent research has focused on recycling solutions for wind turbine blades, aiming to reintegrate materials back into the market. Circular strategies, notably PaaS, hold promise but face implementation barriers. Practical implementation of circular models in the wind turbine industry remains limited, primarily due to upfront costs, partnership collaboration, technology, and policy framework challenges. Despite substantial waste projections by 2050, the emphasis on circular models highlights their importance in tackling wind blade disposal challenges.

This thesis looks into the challenges surrounding circularity in renewable energy technologies, with a focus on rectifying the oversight of neglecting the full lifecycle, particularly the end-of-life phase of wind turbine blades. By centring the discussion on wind blades, it aims to provide insights into their EOL management, drawing from key facts and studies from various authors and historical contexts. Through this exploration, it seeks to raise stakeholder's awareness of barriers and opinions on achieving more comprehensive end-of-life management, leveraging insights from OEMs, wind operators, and recycling facilities in the wind market. A pivotal aspect of this investigation is the examination of the Product-as-a-Service model within the wind industry. This model presents a promising avenue for bolstering circularity practices, given its potential benefits and partial implementation. Through engagement with stakeholders, the research seeks diverse perspectives on how circularity models, including PaaS, can effectively address prevalent issues such as improper disposal methods. By approaching real-world applications and soliciting feedback from industry experts, it endeavours to unearth actionable insights and recommendations to advance sustainable practices in wind turbine end-of-life management. This study then will try to answer the following research questions:

> **RQ1:** What are the main barriers for a more circular end of life model of the wind turbine blades?
> **RQ2:** What are the different practitioner's perceptions towards the application of the product-as-a-service (PaaS) model in the wind turbine industry?

Methodology:

This study uses constructivist worldview which is suitable to comprehend the meanings attributed by others to the world, rather than beginning with preconceived theories. This means that the study lacks literature review and empirical data sin some practical aspects of both end-of-life challenges and product-as-a-service model. It is a qualitative study and the methods involved reviewing literature regarding circularity frameworks, involved actors in the wind turbine market, challenges found in literature, key concepts of product-as-a-service and additional information about wind turbine blade regarding recycling and circularity.

From the initial findings regarding the first research question in the literature review it was noted that circular frameworks act from transversality which means a more complete or integrated approach in a products life cycle to properly address its end-of-life. Furthermore, a framework

was proposed to address this transversality with economic factors, infrastructure/product features factors, collaboration factors, and legislative factors.

Furthermore, for the second research question the reviewed literature was the basic concepts of product-as-a-service model, its benefits, and barriers as well as its different approaches. An initial context of this topics is really important for further understanding of the different results and analysis. Also, in this section of the literature review some examples addressing OEMs, Wind Operators and recycling facilities are given to provide context of some of the current product-as-a-service inclusion in the market. More importantly, the literature review highlights on a specific product as a service framework which is referenced in the results. This framework has the job to expose the stages of the product-as-a-service model and clarifies the scope which is going to consider in the investigation.

Main Findings

<u>RQ1: Barriers for a more circular end-of-life model</u>

Market Viability: Interviewees highlight economic barriers, particularly concerning the commercial viability of wind turbine materials, as a primary challenge in the wind turbine market. Market maturity, influenced by factors such as the lifespan of wind turbine components and lack of decommissioning experience, affects the commercial viability of recycling efforts.

Value of Recycled Materials: The value of recycled materials is expected to increase as the market matures and prices become regulated or if there can be an early incentive in this market regulation. Interviewees emphasize the importance of recognizing and profiting from recyclable materials, which can incentivize entrepreneurs and encourage the establishment of companies dedicated to recycling.

Market Opportunities and Quality Control: Existing market opportunities, such as those presented by companies like Continuum, demonstrate potential of recycled materials. However, market maturity is hindered by lack of quality control standards, particularly in heavy equipment sectors like aerospace. Improvements and expansion in quality control execution are essential for expanding the market and incentivizing further advancements in recycling technologies.

Costs and Sustainability: Interviewees stress the importance of tangible value propositions beyond sustainability claims, highlighting the need for legislative incentives and consumer demand to drive market adoption of sustainable practices. Challenges such as transportation costs and separation costs impact the feasibility of sustainable solutions as they were currently underestimated by the operators. Moreover, there is a lack of clarity regarding waste responsibility in the wind turbine market. Interviewees suggest the need for economic incentives to incentivize the recycling and responsible disposal of wind turbine blades. Market maturity influences the evolving responsibilities of users and the necessity for regulatory frameworks to address emerging challenges.

Designing for Circularity: One significant finding is the introduction of innovative solutions like Drop-In alternatives. These solutions offer customers the choice of sustainable products, such as recyclable blades or greener towers, reflecting a growing trend within the industry towards promoting sustainability through consumer options. Interviewees bring attention to existing technological limitations in fully recovering certain components, emphasizing the necessity for comprehensive planning in infrastructure projects. Scepticism is revealed regarding the sustainability of current blade recycling methods, particularly due to challenges associated with epoxy resin. This resin, primarily prioritizing endurance, poses obstacles to effective recycling. However, optimism exists for potential solutions, such as the development of recyclable alternatives by companies certain recycling companies, signalling a proactive approach in the matter.

Types of Recycling & Quality Control: Interviewees express varied perspectives on wind blade reuse, with some deeming it ineffective and others advocating its potential with proper monitoring for future recycling. Challenges in repurposing wind blades for cement production are highlighted, citing a failure to enhance cement quality and address fundamental waste issues. Lack of integration, like in other industries, worsens the challenge. While mechanical shredding technology shows promise for large-scale decommissioning and resource utilization, concerns persist over the carbon footprint associated with co-processing compared to mechanical grinding. Quality control issues pose risks, particularly for industries like aerospace, underscoring the need for investment in quality control technologies and facilities. Lifetime extension projects offer environmental benefits, yet their impact on recycling and transportation emissions must be considered. Future technologies may mitigate environmental impacts and improve recycling practices, potentially reducing the need for additional infrastructure while enhancing quality control.

Additional Cost: Infrastructure-related expenses, including turbine dismantling, transportation, and logistics, pose significant barriers to effective recycling initiatives. Health, Safety, and Quality (HSQ) principles are also crucial considerations, with potential additional costs associated with decommissioning efforts.

Partnerships: Partnerships are essential in the wind turbine market and EOL management, as highlighted by interviewees. Initiatives like Decomblades illustrate the importance of collective efforts in advancing CE objectives. Material passports facilitate CE practices, enabling recycling facilities to select appropriate methods like pyrolysis or solvolysis. Collaborations between OEMs and wind operators indicate a market shift towards sustainability. However, major decommissioning poses challenges, requiring engagement from multiple parties and networks among stakeholders for effective recycling at scale. Proactive engagement with suppliers is crucial for obtaining detailed material information. Interviewees recommend integrating material passport provisions into contractual agreements for effective recycling. They advocate for action-driven partnerships prioritising tangible initiatives in EOL blade management, aiming to enhance blade separation and recycling processes.

Competitiveness: OEMs often bundle maintenance and consultancy services with turbine offerings, leading to inflated costs. Initially, wind operators may choose OEMs for servicing due to familiarity, but may later seek cost-effective alternatives, hindering collaboration. In offshore wind projects, long service contracts are rare, with large developers often managing turbine servicing internally. This internal model competes with OEMs offering comprehensive service contracts, complicating collaboration. OEMs tend to prioritize the development of in-house recycling technologies, this while forming partnerships with existing recycling facilities. Interestingly, initiatives like Decomblades, initially seen as collaborative endeavours, are now approached cautiously by some industry players. This cautious arises from concerns about potential competition, showing off the intensifying competitiveness within the industry and its implications for collaboration.

Information Sharing / Transparency: Competition in wind turbine operation auctions poses challenges for information sharing and transparency, limiting stakeholder's insights into bid decisions and impeding knowledge exchange. Nonetheless, the government assumes a central role in market development by asking for input from developers and OEMs, ensuring that specifications are aligned with current industry capabilities and interests. Through this collaborative process, the government seeks to craft realistic and feasible tender specifications that enhance the efficacy of circularity initiatives. Moreover, concerns regarding the lack of standardization processes illustrate the need for broader industry involvement, exemplified by initiatives like Decomblades. Additionally, cross-sectoral support among stakeholders is important for advancing recycling and end-of-life management practices, emphasizing the importance of education and collaboration across industries. Furthermore, the absence of transparency in assessing wind turbines for resale in secondary markets accentuates the necessity of evaluating operational status and maintenance history to ascertain resale value, a principle that could extend to blade evaluation practices.

Government Collaboration: Government collaborations emerge as an important step according to multiple interviewees. It was highlighted the lack of supportive legislation in facilitating better end-of-life management practices. Absence of government frameworks, particularly in wind operators auctions, leads to a focus on pricing rather than sustainability, hindering incentives for end-of-life management. OEMs advocate for design initiatives and incentives, with a joint proposal to ban landfilling of wind blades by 2025. Legislative support, such as laws promoting the end-of-life management market or mandating OEMs to share blade material information, is seen as essential. Transparent and tracing legislation is also advocated to enhance recycling opportunities and secondary market access for challenging-to-recycle materials. However, current legislative gaps limit such initiatives, indicating the need for incentives to prioritize effective lifetime extension and end-of-life management for wind turbine blades.

Standardisation: legislative initiatives play a significant role in driving sustainable practices within the wind turbine market, with a focus on national regulations rather than European-wide directives. Fragmented regulatory landscapes across different countries pose challenges for international transport and recycling operations. Interviewees highlight obstacles such as varying regulations within the European Union, bureaucratic processes for obtaining permissions, and the lack of specific waste codes for composite materials. Standardization and harmonization of regulations are essential for unifying recycling efforts and overcoming barriers in the end-of-life process for wind turbine blades.

Current Efforts: Interviewees highlight different directives such as reporting directive and how these influences in the different circular objectives. Other policies such as carbon border adjustment and taxing are mentioned with the net zero industry act incorporating new criteria into the auctions.

<u>RQ2: Product-as-a-Service</u>

OEMs: Interviewees explored the model for wind turbine ownership and service provision, considering economic viability and industry dynamics. Interviewees raised concerns about shifting responsibility for decommissioned materials to wind producers, citing potential compensation challenges. However, interviewees also favoured a rental model but highlighted material fatigue as a key consideration. Insights from OEMs were discussed, the approach of selling turbines while offering performance contracts, ensuring specified performance levels and shared revenue.

Wind Operators: Economic concerns, such as liquidity reduction from annual rental payments and uncertainties about revenue, present significant barriers to turbine rental arrangements. There are doubts about the viability of selling decommissioned turbines and parts in a second-hand market due to their poor condition and uncertain longevity. Financial considerations also arise, with concerns that the leasing price of turbine components may exceed the acquisition cost, making the PaaS model economically unviable. Additionally, some see a fundamental difference between Extended Producer Responsibility and the PaaS model in addressing environmental challenges. Moreover, there's a discussion about the inherent conflict of interest in turbine rental agreements, particularly regarding operational and maintenance responsibilities. Operators renting turbines may face pressure from OEMs to prioritize longevity, while their goal is to maximize profits, potentially compromising long-term functionality and highlighting a conflict between turbine renters and owners.

Recycling Facilities: emphasized the importance of Non-Disclosure Agreements for standardizing processes and ensuring confidentiality among stakeholders. However, challenges exist in achieving comprehensive NDAs due to competition and reluctance to share information. Furthermore, there are concerns about the economic viability of the PaaS model for recycling facilities, as they prefer ownership of decommissioned products to recycle them into higher-value materials.

Concluding Remarks

Through stakeholder perspectives from OEMs, wind operators, and recycling facilities, previously undocumented barriers are revealed, emphasizing the need for increased collaboration and government involvement to enhance economic incentives and output. The study also illustrates the importance of addressing technology, economy, collaboration, policy, and product features to develop targeted strategies for CE models. While acknowledging current challenges, stakeholders demonstrate readiness to seek solutions for a future integration of these aspects into CE implementation. However, a unified criterion is essential to manage components uniformly across stakeholders and inform Europe of diverse processes and strategies. Active participation, collaboration, standardized laws, and patience are mandatory for effective CE model implementation, with government intervention crucial in addressing stakeholder needs. Design for circularity remains a key consideration, with efforts focused on creating affordable, revenue-generating products supported by recycling facilities and government initiatives. Collaboration in product design should extend to operators for ensuring similar durability and energy output in employing new blade designs. For further research, examining potential barriers from the perspectives of omitted stakeholders such as suppliers and transportation companies involved in blade logistics is important. In the case of product-as-a-service, it is crucial to uptake a narrower exploration to understand its implementation requirements more precisely, both sections were not in the current scope.

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1 Introduction

"Sustainability is not merely a concept but a profound acknowledgment of our duty to save our planet and its inhabitants."

The journey towards a more corporate sustainability commenced with the establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988. Subsequent reports, including the seminal 1990 IPCC report, showed the escalating temperatures and the urgent need for global action. The Kyoto Protocol emerged as a significant milestone, charting the course towards decarbonization, and the upcoming era of renewable energies (RE). After this milestone the adoption of the Paris Agreement became imminent as it would be the main mechanism to reduce GHG emissions (Seo, 2017).

Reducing such emissions is important as the world is now living in a continuous and sustained economic growth with different industries consuming the finite resources (Bonciu, 2014) and constantly stressing the environment and the planetary boundaries that surround it such as land system change (Rockström et al., 2009). While GHG emissions were a notable problem the overuse of resources was also being noticed by some experts. Here's where circular economy (CE) surges as a potential solution to both controlling emissions in the industry and recirculating the finite earth resources for their best use covering these two issues with a more holistic approach (de Jesus & Mendonça, 2018).

CE has gained great momentum and was created as a change in the linear production and to drastically adjust the traditional model of take-make-dispose (traditional production consumption systems) (Suárez-Eiroa et al., 2021). However, literature is still emerging and its relationship with sustainability is still weak enough to be practically considered as a trend (Suárez-Eiroa et al., 2019). Despite this its theoretical outcomes seem promising and is worth working on the development of the existent uncoordinated implementation CE currently has which in this context will be denominated circular practices in the value chain.

So far, these practices have been implemented across various sectors, including RE, due to their importance in fostering a greener transition (Lund & Madsen, 2024). In this thesis, the primary focus is on wind power, which offers significant potential for these practices to be exemplified and further explored. Yet, their path from conception to implementation has been fraught with challenges. While efforts have been made in designing sustainable technologies, the critical phases of end-of-life (EOL) management, towards a more circular use, remain underexplored, directly speaking of the wind blades of the wind turbines which contain hard materials to recycle such as fibre reinforced polymers (Delaney et al., 2023).

Today, as RE technologies reach the end of their lifecycle, the reality of inadequate management practices is sometimes evident. Reports from reputable sources such as the BBC highlight the pressing need to address the sustainability of renewable energy from "cradle to cradle." This imperative shows the essence of CE principles, where EOL considerations are crucial in establishing a sustainable ecosystem.

Wind power today is one of the dominant new green energy technologies on the rise. The European union has some interesting numbers and some of the largest shares generated were from Denmark (44%), Portugal 26%), Spain (24%), and Germany (23%). Stats are also impressive in other countries varying from 20 to 10 percent and this include countries like Sweden (19%), Greece (18%), the Netherlands (15%), Belgium (13%), Croatia, Austria and Romania (11%), and Lithuania (10%) (Wolniak & Skotnicka-Zasadzień, 2023). However, the EOL management of wind power infrastructures are problematic due to particular materials used in wind blades and other structural issues (e.g., large size of equipment, geographical spread, complicated logistics, lack of technologies enabling CE solutions, etc. The dominant EOL solution today is still landfilling and incineration for the materials that are difficult to recycle (Ramirez-Tejeda et al., 2017).

In the dynamic landscape of the CE, various practices have emerged as alternative strategies and methods to promote circularity, thereby enhancing the potential of the wind power supply chain and offering a promising frontier in sustainable energy solutions (Kramer & Beauson, 2023a). These practices aim to optimize the manufacturing process of wind turbines, reduce expenditure on virgin materials, extend the lifespan of wind turbines, and create market demand for second-life materials resulting from potential models. Additionally, they seek to minimize the amount of waste destined for landfill or incineration. As the wind power market continues to expand and technology evolves, the integration of upgraded circular practices becomes increasingly critical, especially for EOL management of wind blades (Mendoza et al., 2022).

The EU's CE Action Plan and EU Green Deal have set parameters for the EOL outcomes of wind turbines in the European market, a critical aspect considering the prevalence of improper disposal methods such as incineration and landfill for wind blades. Industry leaders like Vestas, LM Wind Power, and Siemens Gamesa RE are pledging to re-use, recycle, or recover 100% of decommissioned blades by 2040 and 2050 (Wind Europe, 2020).

In the subsequent sections, the thesis will explore the management of wind turbine blade EOL, laying the groundwork for examining potential circular practices in the industry. This exploration aims to identify suitable models for wind turbines and enhance current EOL practices.

1.1 Problem Definition

As the world grapples with the urgent need for climate change adaptation and mitigation, the transition to renewable energies (RE) emerges as a strategy to decrease emissions and promote sustainability. However, despite their potential in some sectors, managing RE resources and their EOL phase presents significant challenges. Inadequate disposal practices, such as landfill disposal and open air incineration, contribute to environmental contamination in soil and in the air, highlighting the pressing need for sustainable solutions (BBC, 2024).

An illustration of this challenge is evident in the disposal of wind turbines, which typically have an average lifespan of 20 to 25 years. After wind turbines complete their lifespan, only 30% of their materials by mass are presently recycled or reused. This is a concerning statistic, especially considering that up to 85-90% of wind turbine materials, particularly steel from the tower, are designed to be recycled (Khalid et al., 2023). This discrepancy exposes an issue: if the current recycling rate persists, projections suggest a significant increase in waste volume by 2030 due to wind turbine production, amplifying concerns about landfilling and incineration, particularly regarding the composite materials used in wind blades, such as glass and carbon fibres (Majewski et al., 2022). The wind energy sector is incorporating different recycling strategies, with companies such as Siemens Gamesa or Vestas recycling composite materials for turbine blades. This, however, is still largely at a pilot stage with several challenges hindering such practices to scale-up and making economic rationale (Siemens Gamesa, 2021).

Recently, much research has been focusing on reuse or recycling of wind turbine blades or at least finding solutions for different thermal or chemical treatments that re-generate some material or energy value (Dorigato, 2021). Such solutions could help reintegrate the post-use material or product value back into the market, be it wind turbine or other markets. This could be assisted by implementing more exhaustive circular strategies and models, giving the particular example of Product-as-a-service (PaaS). However, these types of models usually struggle to break the market due to different economic and infrastructure related barriers, lack of collaboration and finding mutual benefits and trust among partners, or regulatory misalignments (Oghazi & Mostaghel, 2018).

While theoretical evidence highlights the advantages of implementing circular models in the wind turbine industry, practical implementation remains nascent. Currently, only a few examples of small-scale initiatives such as service, maintenance, and replacement exist, primarily due to challenges such as upfront costs, partnership collaboration, technology, and policy frameworks (Mendoza & Pigosso, 2023). The scale of the problem is substantial, as evidenced by projections indicating that more than 2 million tons of wind power-related waste will be generated by 2050 (Majewski et al., 2022). The growing interest in addressing this issue highlights the need for additional steps to effectively manage this projected waste.

Furthermore, attention needs to be focused on circular models and the enhancement of various circular strategies, as they provide crucial solutions and introduce innovative frameworks within the existing wind blade market (Kristia & Rabbi, 2023). This connection is explored within the context of wind blades, investigating how existing processes can be improved and shaped, with a particular emphasis on circular models such as PaaS. This thesis serves as an example of potential new opportunities and delves into different stakeholder perspectives on what is necessary to achieve transformative change towards a world characterized by circular practices and improved wind blade EOL management.

1.2 Aim and Objectives

The thesis seeks to explore the current challenges related to circularity in RE technologies, with a specific focus on addressing the oversight of neglecting the full lifecycle, particularly EOL phase of wind turbine blades. By centring the discussion on wind blades, the thesis intends to offer an understanding of their EOL management while presenting key facts and studies from different authors. Through an examination of historical events and context surrounding wind blades, the thesis aims to raise awareness among stakeholders regarding various perceptions of barriers and opinions on achieving a more comprehensive EOL management. This exploration draws insights from the wind market, including original equipment manufacturers (OEMs), wind operators, and recycling facilities.

Given its already partial implementation within the wind industry, the investigation into the PaaS model stands as a crucial endeavour. Through engagement with various stakeholders, the research seeks to explore diverse perspectives on how current and future circularity models, such as PaaS, can effectively address prevalent issues such as improper disposal methods. By examining the real-world application of PaaS and soliciting feedback from industry experts, this investigation strives to identify actionable insights and recommendations for advancing sustainable practices in wind turbine EOL management.

To summarise, the case of EOL management of wind blades will be analysed through the exploration of its challenges and drivers. The thesis will focus on how different approaches and strategies through different stakeholder's perception (e.g., recycling facilities, manufacturers, and wind operators can lead to a more collaborative and transversal thinking. This thesis aims to contribute to the investigation of different circularity approaches and lay the groundwork for further research in the field regarding specific models such as PaaS.

Considering the problem and aim in this document, the following research questions are presented:

- ***RQ1:*** What are the main barriers for a more circular end of life model of the wind turbine blades?
- ***RQ2:*** What are the different practitioner's perceptions towards the application of the product-as-a-service (PaaS) model in the wind turbine industry?

1.3 Scope and Delimitations

The primary focus of this investigation is on the EOL management of wind turbine blades, aiming to identify barriers and drivers for improved EOL management by examining existing and potential circularity practices that avoid open air incineration and landfilling but instead aim for reuse, recycle, or repurpose. Additionally, it seeks to explore stakeholder's perceptions of a potential future engagement with the PaaS model which entails the use of constructivist approach (See chapter 3.1).

Frameworks which are going to be addressed in the thesis are the CE framework and the PaaS framework which are proposed by specific authors and disclosed in the literature review. Both of these slightly modified by the researcher for a more comprehensive analysis and adapted to the specific considerations of the thesis project in the specific case of the PaaS framework, the scope will be considering the development phase, monitoring phase and implementation phase.

The scope of investigation is qualitative, and this research relies on interviews with key stakeholders in the wind turbine value chain, including representatives from production, consumption, and recycling sectors. Interviews are chosen as the preferred method to effectively capture diverse stakeholder perspectives.

The geographical scope of the investigation primarily encompasses Europe. Specifically, the investigation focuses on Denmark for OEMs due to its proximity to Sweden, which facilitates interviews. Additionally, Denmark hosts one of the largest offshore windfarm operations, directly engaging with the interviewed OEMs. Regarding Wind operators, the geographical scope expands to include Denmark, the Netherlands, and Germany. Finally, for recycling facilities, the scope broadens to encompass Sweden, Denmark, the United Kingdom, Portugal, and Germany.

Additionally, due to interview availability, the scope for recycling facilities also includes those that manage critical raw materials and composite materials from other industries, not exclusively wind turbine blades. This approach provides diverse perspectives and insights into circular practices within the composite material sector.

1.4 Ethical Considerations

This investigation has been conducted without external funding. Participation in interviews by respondents served solely to gather data and analyse trigger points; their involvement did not influence the final analysis or conclusions drawn. Prior to the interviews, all participants were fully informed about the research intentions and the topic covered in this thesis. GDPR consent forms were provided to participants, granting permission for the recording of interviews, data analysis, and discussion within the context of the literature review. The GDPR consent form can be found in the appendix section of this document.

During the interviews, sensitive information such as age, cultural diversity, disability, gender, and sexual orientation was not addressed to maintain confidentiality. Participant's names and their respective companies were omitted from the interviews, although the professional roles of participants are referenced in the subsequent methodology section. Direct quotations were also excluded to further protect the anonymity of informants.

All interviews and collected data are securely stored on Lund University servers for a period of 10 years, following the research guidelines disclosed. Participants were informed of their rights to request corrections, deletion, or restrictions on the processing of their data, with a deadline for such requests set until May 17th.

1.5 Audience

The target audience of the project is aimed for the R&D process of circular business models and decision makers (government actors, future wind turbine auctions and bids). In the academic journals there are a few sources that are dedicated to the challenges of circular models in the wind sector. Additionally, all these challenges are theoretical and do not include practical facts or information. This thesis aims to gather useful information and perception so future decisions can be made with a small baseline and new fresh perspectives in the EU waste management collaborative setting. Other actors might be interested such as developing wind industries as the study gives a lot of practical data not covered commonly by a peer reviewed paper.

1.6 Disposition

Chapter 1 provides background information on the challenges associated with wind turbine EOL practices and their impact on waste management. It focuses specifically on wind turbine blades and their composite materials, highlighting the issues that arise without proper EOL management. The research questions posed in this context will guide the study's exploration and analysis.

Chapter 2 introduces important concepts essential for understanding the subsequent findings. It provides necessary background information and terminology, including discussions on CE principles, PaaS models, and the wind turbine market. Additionally, frameworks relevant to the analysis are presented here.

In **Chapter 3**, the methodological approach employed in the thesis is outlined, offering justifications for its selection, and explaining how it will be used to address the research questions.

Chapter 4 presents the main findings derived from 13 semi-structured interviews, organized by themes and actors involved.

Chapter 5 engages in a discussion that synthesizes the literature review with the research findings. It examines the alignment between the two and identifies areas of complementarity, disparity, and potential gaps. This chapter also explores whether the research questions posed in Chapter 1 are adequately addressed by the study's results.

In **Chapter 6**, the thesis concludes by summarizing the key findings and their significance. It offers recommendations for future research directions and the importance of effective EOL management strategies for wind turbine blades, advocating for greater consideration of circular solutions.

2 Literature Review

2.1 Key Concepts

2.1.1 Circular Frameworks

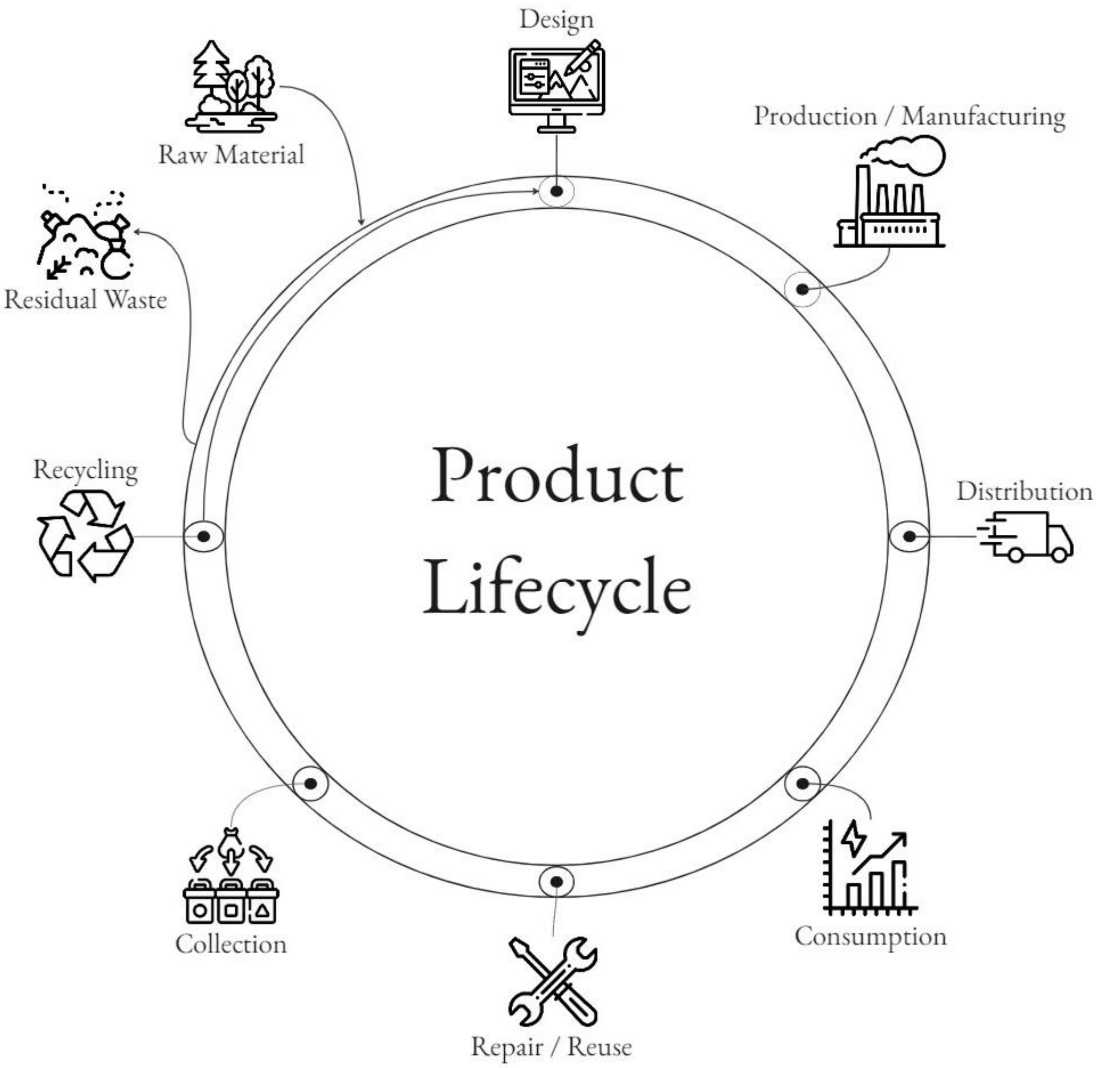
Planet Earth, a finite resource, faces significant challenges due to a linear consumption and production pattern that is unsustainable (Suárez-Eiroa et al., 2019). Introducing a CE model offers the potential not only to save costs but also to conserve vast amounts of resources, thereby advancing sustainability. However, a notable drawback of this model is the absence of a comprehensive framework that provides a macro-level understanding for companies to uniformly adopt the model (Lewandowski, 2016).

The concept of CE, although legally implemented and studied in various countries within the European Union (EU), lacks a universally agreed-upon definition. In this thesis, the definition outlined by the EU Action Plan for CE and the zero-waste program in Brussels will be adopted. According to this definition, *CE systems aim to retain the added value of products for as long as possible while minimizing waste. These systems ensure that resources remain within the economy even after a product reaches the end of its life, enabling them to be reused, repaired, remanufactured, or recycled productively to generate further value* (European Commission, 2015.). Under this definition, CE serves as a strategic approach to reincorporating a substantial portion of the natural resources extracted from the Earth into various systems throughout their value chain.

As mentioned before, there is currently no comprehensive framework, but in this case the closest adaptation is the closed loop model for a product's life cycle. This model is as follows: (1) virgin resources or materials are acquired for use, (2) companies design products using these raw materials, (3) production and manufacturing of the product occur, scaling from small to large operations, (4) distribution of the product to consumers, (5) eventual wear or damage prompts repair or reutilization of the product, (6) the product continues its life cycle at reduced performance levels until deemed no longer usable, (7) disposal of the product by the consumer, typically to a waste facility for collection and transport, and (8) recycling, reuse, or transformation of the product using various technologies and techniques (Bohra, 2024) & (European Commission, 2018).

Figure 1 illustrates the mentioned model graphically, depicting each step. In a CE model all of the materials should be completing the loop several times capturing, creating, and delivering value to reduce the consumption of the resources (Mendoza et al., 2023). However, despite its broad scope, information about this framework remains limited (Suarez-Eiroa et al., 2019). Focusing on central aspects such as collection and recycling is crucial for addressing the diverse challenges related to economic incentives, transportation logistics, and stakeholder engagement, particularly in the context of wind turbine blade management.

Figure 1 Product Lifecycle Associated With CE.



Source: Adapted from Bohra, (2024).

CE operates not only based on its definition but also relies on operational principles to guide actions and reactions within the value chain. Suárez-Eiroa (2019) categorize these principles into three groups: target operational principles, core operational principles, and transversal operational principles. ***Target principles*** serve as theoretical goals, guiding stakeholders towards sustainable development by facilitating a balance between input and output within processes. ***Core principles*** form the foundation for achieving these goals; although not directly linked to targets, they aid in devising strategies that indirectly support adjustments in input and output. ***Transversal principles*** play a crucial role in integrating target and core principles, acting as the cohesive element that enables their implementation within the CE framework.

In addition to Suarez's work, Oliveira et al. (2023) address principles related to CE, focusing specifically on Sustainable Development Goals (SDGs) such as the 6th, 7th, 8th, 12th, and 15th. These principles emphasize concepts like reducing raw materials use, minimizing waste generation, and enhancing equipment efficiency.

While various approaches to addressing CE principles exist, this thesis adopts a holistic view and primarily considers the principles outlined by (Suárez-Eiroa et al., 2019) for its framework. The following table 1 describes these principles accordingly.

Table 1 Summary of Operational Principles in CE.

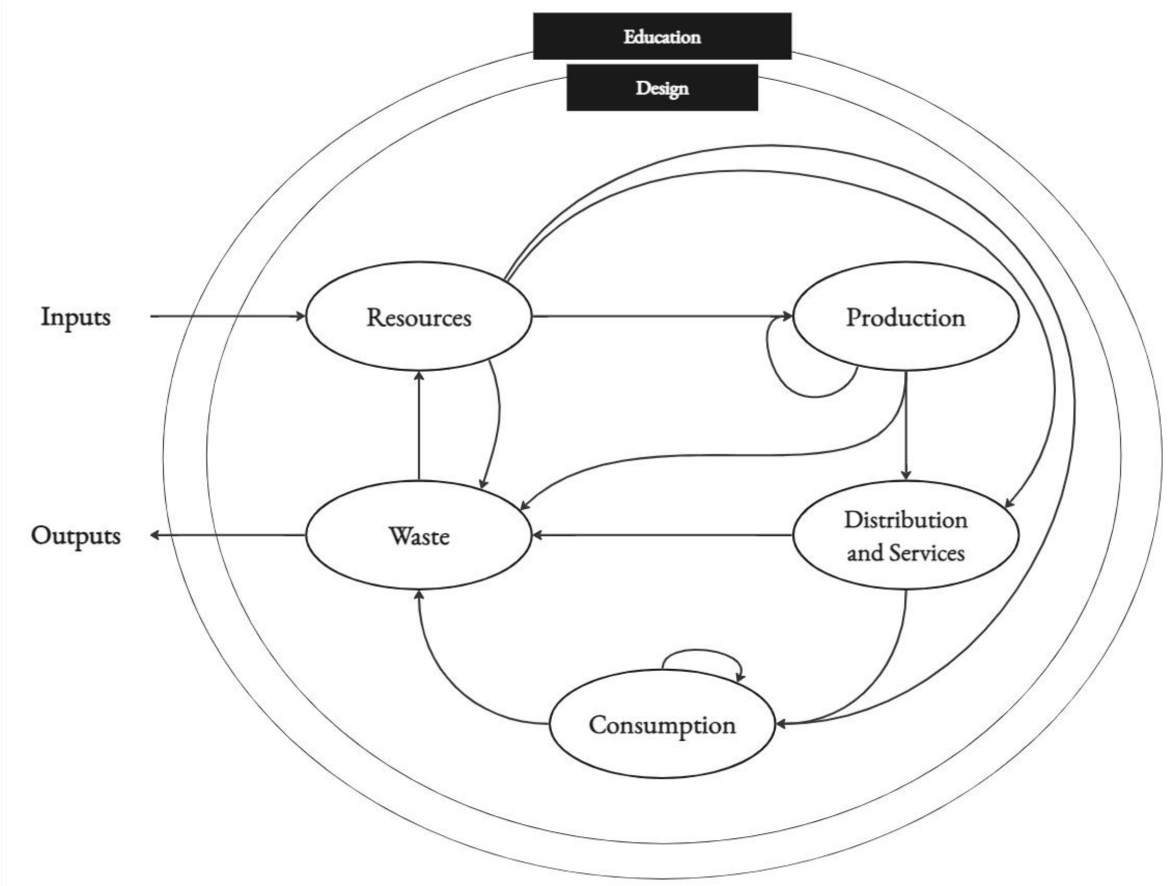
Principle	Type of principle	Description
Adjusting inputs to the system regeneration rates	Target Operational Principle	Minimize / eliminate the inputs to the operation of the non-renewable resources and at the same time evaluate suitable values for the renewable resources considering the planetary boundaries
Adjusting outputs from the system to absorption rates	Target Operational Principle	Promotes different approaches to minimize and in the best cases eliminate the outputs of tech waste and adjust the bio waste to suitable considering the planetary boundaries
Closing the system	Core Operational Principle	Directly connected to waste management and waste hierarchy framework according to the European Commission. This principle integrates 2 of the 3 Rs: Reuse and Recycle. The other R which is "reduce" is more applicable in the previous 2 principles.
Maintaining resource value within the system	Core Operational Principle	Korhonen et al., (2018) suggest two main strategies: Durability of the products and recirculation of the resources through their lifecycle. For this to happen, interconnection in between the product lifecycle is necessary: reuse, repair, refurbish, remanufacture etc. As it can be seen, this principle looks like a deeper process to the previous core operational principle meaning that the loop is closed, and the loop is extending the life of the product. Some examples include industrial symbiosis or reparation and repurpose companies.
Reducing System size	Core Operational Principle	Reducing the number of resources in a system. This means either reducing the total quantities of products for supplying humans and producing

		more sustainable products (circular products). In these strategies some professionals such as Tukker, (2015) propose higher reliance on sharing economy like renting equipment a service for example and also better informing direct and indirect consumers as transparency is essential for an extended product responsibility.
Designing for CE	Transversal Operational Principle	Here the eco-design concept is introduced for a product which can be easily recovered, recycled, reused etc. and for it to be removable and separated into the initial resource (Sauvé et al., 2016). Designing comes with innovation and issues such as the financial, political, and social issues must be innovated to emphasize the process towards a new paradigm which is the contraposition of linear economy.
Educating for CE	Transversal Operational Principle	CE is based on holistic viewpoints of a product's lifecycle. Key actors must interconnect and collaborate within each other to address key CE issues, which means improving transparency skills leading to development and expansion of the CE.

Source: Suarez-Eiroa et al., (2019).

Building upon the principles outlined in the previous table and emphasizing a holistic and transversal view of CE, authors such as Velenturf et al. (2021) argue that the relationship between sustainable development and CE is not as well-established as commonly perceived. They contend that many current solutions prioritize short-term economic gains through end-of-pipe approaches rather than focusing on genuine sustainability. This perspective challenges the prevailing economy-centric model endorsed by the European Commission, which often overlooks crucial transversal elements, notably collaboration and comprehensive policy frameworks. These elements should be consistently integrated and serve as constant reminders to exert pressure on other sectors. Recognizing this deficiency in transversality, the authors propose a model that reimagines the role of education, collaboration, and policy, incorporating such aspects. The following figure, inspired by Suarez-Eiroa's (2019) policy framework, illustrates the integration of policy, collaboration, and education, exposing their transversal significance in the current thesis.

Figure 2 CE Framework Considered.



Source: Adapted from Suarez-Eiroa et al., (2019).

Considering Figure (2) and the discussion on transversality within the principles, other scholars, such as Vermunt et al., (2019), advocate for holistic views of systems to enhance the alignment of CE with sustainability goals. As stated before, this relationship exhibits weakness, exemplified by practices like the transition from landfilling to incineration. While energy is produced through incineration, it comes at the expense of increased carbon dioxide emissions, representing a squandered opportunity for more efficient resource utilization through improved recycling efforts among companies (European Commission, 2017). Transversality is also a central concept in the Brundtland Commission report, as highlighted by Velenturf & Purnell, (2021), who identify key principles from the report relevant to the current discussion. Notably, three principles stand out: adopting a whole-system perspective, fostering changes in social values, and promoting collaborative initiatives.

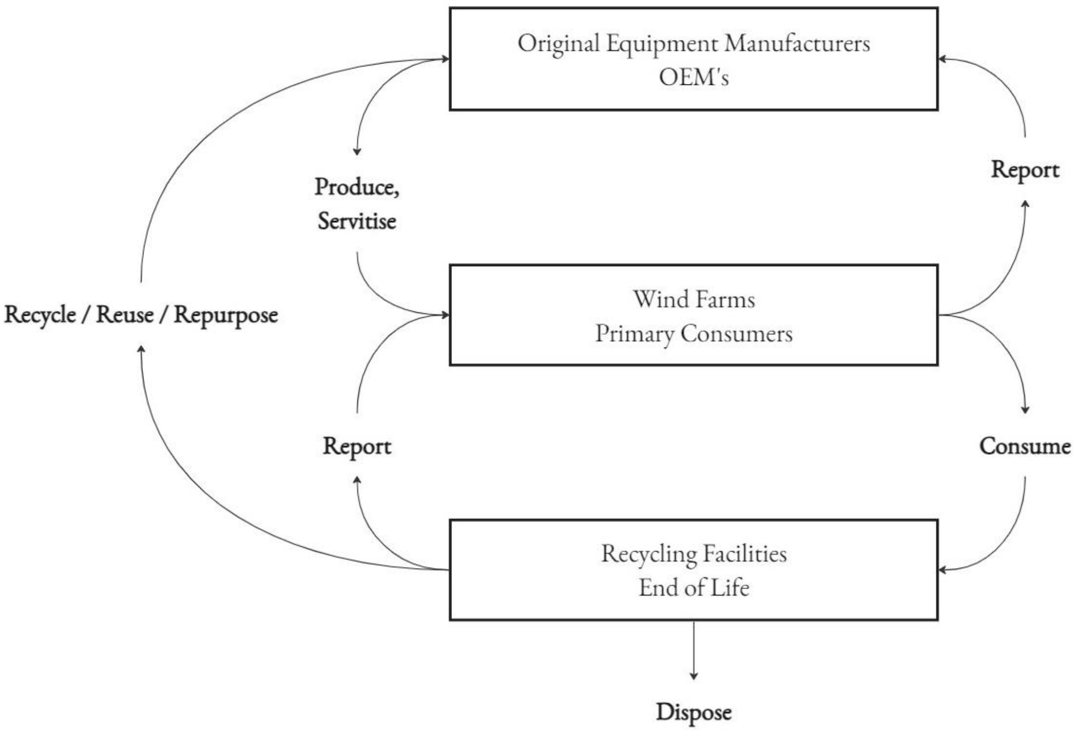
A whole system perspective considers all sustainability challenges that arise across sectors and endeavours to address them in a unified manner (Sala et al., 2015). CE solutions must respond as a suitable solution to the different stresses generated by the industrial economic activities (Lazarevic & Brandão, 2020). Changes in social values are crucial, as technology alone is insufficient to mitigate environmental damage (WECD, 1987). Education, debate, and public participation are examples of incorporating diverse social values, which are reflected in various policy approaches aimed at shaping societal change. Finally, collaborative change is vital, as sustainability encompasses multiple stakeholders and countries. It is incumbent upon these stakeholders to advocate for policies that prioritize environmental protection and enhancement over purely economic considerations (Velenturf & Purnell, 2021).

The principles discussed by Suarez and Velenturf are transversal elements of relevance and also according to the authors it is really difficult not to say impossible to attain CE goals under sustainable development.

2.1.2 Actors Throughout the Value Chain

The wind turbine sector is composed of several actors involved in the resource extraction production, distribution and services, consumption, and waste (EOL). In this particular case, the study is considering figure 2 to limit the scope of the actors considered in this thesis. Importance of these actors for circularity is going to be considered holistically as some authors like Mendoza & Pigosso, (2023), Velenturf & Purnell, (2021), Suárez-Eiroa et al., (2019) disclose in their investigation. There is no isolation when speaking of circularity but addressing the complete system is necessary for a better management of the wind energy EOL. This simple yet insightful diagram delineates the scope of key actors involved in the current investigation. It provides context for understanding the various stakeholders involved and how they interact with each other.

Figure 3 Involved Actors in the Value Chain.



Source: Adapted from Schulz et al., (2023).

2.1.3 RQ1 Current Challenges in Literature

Wind Europe waste management hierarchy is based on that established by the EU waste framework directive (2008/998/EC). Principles of CE are considered, this means minimise disposal and maximize prevention (Woo & Whale, 2022). This is also paired up with the EU's target for increasing the RE share to 27% by 2030 and also the EU commitments do decrease GHG emissions by 80-95% as of 2050. This explicitly shows how important is the wind energy for the future (Jensen & Skelton, 2018). Due to its importance, the current wind turbine market is expanding abruptly, accounting for 35% of total RE generation in 2019 (Euro Stat, 2019). In this level of expansion, wind turbine blades are also taking a toll on waste management as it is expected by 2030 that there is 570 million metric tons of plastic reinforced waste and out of this in between 35 to 58 million metric tonnes will be part of wind rotor blades (Sommer et al., 2020). Circularity performance will be important to reduce these projections, especially in design material substitution from now on and recovery of the residual blades into same or other value chains (Mendoza & Pigosso, 2023).

Lack of Standardized Frameworks and Collaboration: The absence of universally accepted guidelines or frameworks for implementing circular models in the wind industry leads to inconsistency and ambiguity (Beauson et al., 2022). Existing literature highlights the importance of government involvement and legislation as key drivers for fostering collaboration and developing collaborative programs and policies that encourage a wider industry cooperation. For instance, initiatives like blade recycling could greatly benefit from increased collaboration between industry players such as Re-Wind, Sunset Renewables, Green-Ener-Tech, and academic institutions (Woo & Whale, 2022). Authors like (Paulsen & Enevoldsen, 2021) reaffirm that industrial symbiosis could offer promising frontiers for collaboration, particularly in advancing mechanical recycling techniques for fibre components, thereby promoting their reuse and substitution for raw materials in various markets.

Economic Constraints: Financial barriers present significant challenges to the widespread adoption of circular models in the wind industry. High initial investment costs and uncertainties surrounding return on investment deter companies from investing in circular practices. The lack of a suitable market for secondary products or materials, coupled with their high price and variable quality, further complicates matters (Mendoza & Pigosso, 2023). Additionally, the popularity of glass fibres over carbon fibres in the current market is attributed to the higher energy consumption and costs associated with co-processing carbon fibres. Without economic incentives, companies are reluctant to invest in costly recycling processes (Woo & Whale, 2022). While some authors like (Rentizelas et al., 2022) argue that additional support such as incentives and regulation is necessary, they predict that by 2050, the market will reach a point of breakeven due to the abundance of available waste streams from wind blades.

Infrastructural and Technological Barriers: Limited recycling facilities and logistical constraints pose significant challenges in collecting and processing composite materials from wind blades at the end of their life. The sheer size of wind turbine blades, which can range from 15-20 meters to 75-80 meters, further exacerbates logistical challenges (Jensen & Skelton, 2018). Overcoming these barriers requires addressing essential parameters such as finding dismantling solutions, establishing access to markets for recycled material, ensuring the availability of suitable technology, and implementing effective material identification and selection processes. Transportation of the blade structure also presents a significant challenge that must be addressed (Jensen & Skelton, 2018).

Regulatory Complexities: Regulatory hurdles and policy gaps hinder the implementation of circular models in the wind industry. Inconsistencies in waste management regulations and the lack of incentives for circular practices contribute to these challenges. Additionally, the absence of standardized regulations for banning landfilling of composite materials across Europe creates uncertainty in the market (Rentizelas et al., 2022). Challenges related to legislation include the lack of economic incentives guiding the industry toward an Extended Producer Responsibility (EPR) model, difficulties in waste material classification within the European Union, and the absence of uniform waste management labels and classifications across countries. As a result, the process is further complicated, hindering progress in implementing circular practices (Beauson et al., 2022).

2.1.4 RQ2 Product-as-a-Service Model

PaaS model is defined as a system of products, services, supporting infrastructure and necessary networks which fulfil user's needs in the market. This system has a lower environmental impact (Mont, 2002). PaaS is further explained to be felt differently depending on the actors or stakeholders. For consumers it means shifting their purchases from products to buying a system of services with solutions with the potential to minimize the environmental impact. For producers on the other hand, PaaS means a higher degree of responsibility for the product's full life cycle, and design of the product's cradle to gate system. Use phase is the one getting more attention in PaaS case (Pouria, 2015). Traditional models before PaaS are based on centralizing the product as the main component making it a product-oriented business. PaaS is a concept that transforms this product-oriented business into a solution-oriented partnership between the involved stakeholders (Morelli, 2006). Because of this, other authors express the difference in the marketing strategies. Is not about selling the product, but it is about selling the service (Omann, 2003).

To effectively address environmental impacts with sustainable solutions, PaaS initiatives need to consider several key elements. Firstly, it is essential for companies to ensure the quality and sustainability of their product, particularly in the case of wind turbines for RE. Secondly, they must focus on the service aspect accompanying the product (Beuren et al., 2017). This includes maintenance and repair services provided by companies like VESTAS or SIEMENS to customers such as RWE.

Furthermore, while these service offerings already exist to some extent, there is a need to explore how PaaS can be integrated into the EOL phase of wind turbine blades, with active engagement from producers. This aims to mitigate environmentally harmful practices like landfilling and incineration. According to (Mert et al., 2017), adopting a service-oriented business approach is highly recommended for technical products like wind turbines, ensuring factors such as reliability and availability are prioritized. This holistic approach underscores the importance of integrating sustainability considerations throughout the product lifecycle.

PaaS must be addressed from its 3 different types which are product oriented, use oriented and result oriented. This to be specific on the company's goals and the type of service they want to offer with their PaaS. Following up the research will present a table with the different types of types and their main characteristics (Frederiksen et al., 2021).

Table 2 Types of PaaS Approaches.

Characteristics	**Product Oriented**	**Use Oriented**	**Result Oriented**
Product / Service Ownership	Customer	Provider	Provider
Service type	Maintenance and consultancy	Rental service	Integrate solutions
	Product advice and consulting	Product rental	Activity management Pay per service unit.

			Functional result
	Services add value to life cycle	Services enable platform to customer	Services providing final result to customer
Payment	Per product	Per use	Per result (contract)
Provider responsible for cost of activities in the use phase	No	Yes	Yes

Source: Frederiksen et al., (2021).

Product oriented services: The ownership belongs to the customer and an extended service (repair and maintenance) is kept by the provider. Company offering this type of PaaS motivates on offering a service which includes a well-functioning product which takes into consideration EOL within its design phase (Pouria, 2015).

Use oriented services: Traditional product-oriented business is considered to be the main driver; however, the product still belongs to the producer. Car Sharing models, very popular in Germany, are the perfect example of this type or PaaS (Sundin et al., 2009) & (Beuren et al., 2017).

Result oriented services: Products are replaced by services. This example can be seen in pest control service instead of buying a pesticide or hiring a cleaning service for home instead of buying the cleaning products individually and do the cleaning.

As an existent model it has its own benefits and limitations for all the involved stakeholders. Aiming to address sustainability, the following table compiles references and investigations from more than 15 sources which discuss the benefits and limitations of this model.

Table 3 Benefits and Barriers of PaaS.

Category	**PaaS Benefits**	**PaaS Barriers**
Environment	Greater use of products	Lack of legal and regulatory support
	Closing life cycle	
	Reduced resource use	Rebound effect
	Facilitates reuse and recycling	
	Durable products	

Economic and Operational	Customer loyalty	Difficult measuring results
	Increase in profit margin	Higher initial investment
	Image enhancement	Higher intensity and labour
	Reduction of costs (Energy and Material)	Resistance to change
	Customer dependency	Risk of product damage
	Value delivered throughout the supply life cycle	Necessary new organizational processes (maintenance, supply, etc.).
	Development of new markets	

Source: Moro et al., (2020).

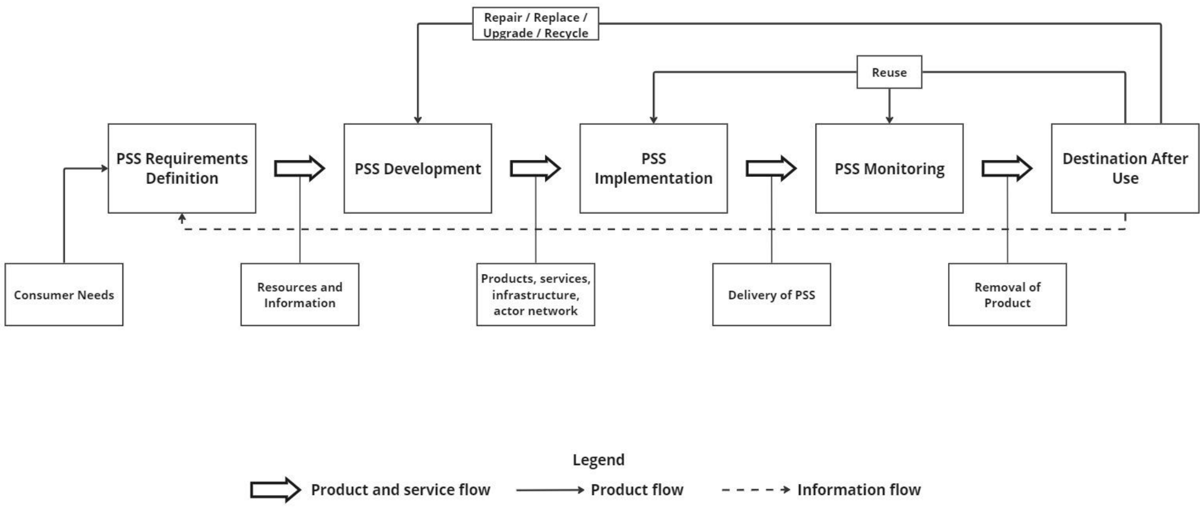
Drivers and Barriers are identified and specially, Environmental, economic, and operational ones. The PaaS model offers a variety of environmental drivers going from minimizing material consumption to reducing toxic emissions, to less energy consumption and different principles of optimizing the products lifespan. Other authors express the big advantage of always having a secondary source of raw materials as the product when reaching fatigue will go back to the producer (Mont, 2002). Under company's perspectives there are statements such as attaching additional value to the product, improve total value and financial relationships with the consumers, and anticipate legislation such as EPR or takeback programs which in the wind market they are potentially happening sooner than later (Wind Europe., 2024) & (Pouria, 2015).

PaaS is a model that lacks a standardized framework and varies in its implementation depending on the perspectives of different stakeholders. Therefore, several considerations need to be addressed before establishing a framework:

- The entire lifecycle of the product, from its inception to its EOL (Pezzotta et al., 2012).
- The implementation process involves defining system requirements, further development, and practical implementation in companies (Marques et al., 2013).
- The framework should encompass key stages such as requirements, development, implementation, monitoring, and the final destination of the product and service (Tran & Park, 2016).

Taking these considerations into account, an adapted version of the PaaS framework proposed by Beuren et al. (2017) will be utilized in analysing the wind market structure. This framework will focus on three main stakeholders: OEMs, wind operators, and recycling facilities.

Figure 4 Definition of a PaaS Framework.



Source: Adapted from Beuren et al. (2017).

The following tables adapted from Beuren et al (2017) give the conceptual elements necessary to check on the interviews when possible.

Table 4 Development Phase Elements of PaaS.

Development Phase	
PaaS Element	**Conceptual Elements**
Product	Design product components for extended life
	Design safe products
	Plan for reuse and for EOL
	Design for facilitation in operation
	Durability and standardization
	Easy access to components
Service	Design services to ensure safety in product
	Support service for consumers locally with appropriate service networks
	Design service
Network of Actors	Plan the monitoring of the product
	Plan an interface between the partnerships in the model
	Plan the technical services (near the consumer)
	Plan the qualification of operators
	Government incentives
	Consumer and other stakeholder participation
Infrastructure	Plan of the infrastructure
	design a communication system between those involved in the business
	Plan the distribution chain

	Plan PaaS in accordance with local culture

Source: Adapted from Beuren et al., (2017).

PaaS Implementation phase and PaaS monitoring phase are also very important. They contain elements such as the necessary education to the consumers in order for them to go all in with the PaaS model. This education involves the shift from the traditional model to PaaS which includes the different activities within the industry which of course represents a challenge to all stakeholders (Morelli, 2006). Finally, in the PaaS monitoring phase it is important to not only monitor the product but also the service. Consultancies, reliability, and feedback of the consumer is crucial to continuous improvement (Beuren et al., 2017).

Table 5 Implementation phase of PaaS.

Implementation Phase	
Conceptual Elements	**Description**
Testing the product	The PaaS is evaluated for improvements
Delivery	After tests are performed, the PaaS can be delivered.
Guidance for PaaS Use	It is necessary for the producer to guide the consumer about correct usage

Source: Adapted from Beuren et al., (2017).

Table 6 Monitoring Phase of PaaS.

Monitoring Phase	
PaaS monitoring during use phase	During the operation PaaS has to be supported to maintain functionality, availability, and results. Monitoring will avoid problems as during the use phase of the product there will be support at all times.
Service delivery monitoring	
Knowledge accumulation regarding PaaS (use phase)	Cost effective assessment and quality assessment are performed at this stage. System needs to meet objectives and requirements. These are maximising the profits at the lowest cost possible. Other categories such as serviceability, reliability, maintainability, and standardisation are considered.
Feedback on consumer expectations	Key consumers express their ideas and complaints to the service provider. When information returns to the company a detailed analysis is performed regarding the market and a new set of requirements.

Source: Adapted from Beuren et al., (2017).

As a case study, Power by the hour for the US Navy emerges as an example of a new performance-based contract offered by Rolls Royce back in 2003. This meant provision and maintenance of the engine by the company to Boeing. Rolls Royce would be the only provider of logistics support and that meant fixating a price for the engine usage each hour while the aircraft was flying (Smith, 2013). Repair costs plus unpredictable breakdowns was a fixed problem for the navy. Also, a visible improved level of service manifested an increased engine availability, resulting in an upgraded flying time while still providing a lower and planned cost (Rolls Royce, 2012).

Currently in the wind industry PaaS can be described as partial PaaS, this is because there are some elements present like service contracts. Companies like Vestas and Siemens Gamesa provide within their product full service or partial service contracts of maintenance for the different wind operators, taking responsibility on the different unexpected breakdowns and unplanned issues the wind turbines might have throughout their use phase. This maintenance also includes 3 crucial activities: Deploy the minimum resources required, ensure the turbine is reliable, and recover from breakdowns (Tchakoua et al., 2014). This service and maintenance not only include the unexpected breakdowns but also includes periodical condition monitoring (European Wind Energy Association, 2009).

2.2 Wind Blade Recycling

Wind energy has become a cornerstone technology, generating 2799 GW of electricity in 2020 and supporting approximately 270,000 wind turbines worldwide (Majewski et al., 2022). While wind turbines typically have a lifespan of 20-25 years and boast a high recyclability rate for components such as the tower, foundation, and nacelle, recycling wind blades poses notable challenges (Delaney et al., 2023). The difficult part of the issue lies in the composite materials utilized in wind blades, which include epoxy resins/thermosets and synthetic fibres, known for their difficulty in recycling and contribution to non-biodegradable plastic waste (Khalid et al., 2023).

The complexity of these composite materials requires innovative recycling methods, with various approaches proposed, including mechanical, thermal, and chemical processes (Chen et al., 2019). Categorized as primary, secondary, and tertiary recycling, these methods aim to tackle the challenges of wind blade disposal and offer sustainable alternatives. These alternatives involve reintegrating the composite materials into the same or different value chains, contributing to a CE (Mishnaevsky, 2021).

Despite the advancements in recycling technology, challenges remain in achieving efficient and cost-effective solutions for composite material recycling (Yang et al., 2012). Furthermore, ensuring environmental sustainability and minimizing the environmental impact of recycling processes are ongoing concerns in the quest for sustainable wind blade disposal practices. Collaborative efforts among stakeholders, including manufacturers, recyclers, and regulatory bodies, are essential to overcome these challenges and advancing towards a more sustainable future for wind energy (Vermunt et al., 2019).

Current Recycling Scenarios for Blades

Mechanical Recycling

Mechanical recycling involves breaking down waste materials, such as wind blades, into smaller components, resulting in resin-rich (epoxy) and fibre-rich (carbon fibre and glass fibre) products. While short fibres and polymers are easily separated (Kalkanis et al., 2019), this method often damages the fibres, making them unsuitable for reuse in the wind turbine industry or for remanufacturing wind blades. Instead of fully recovering and reclaiming the constituent materials for reuse in the same or different applications, mechanical recycling merely separates them into different fractions. As a result, the fibres, which are crucial components in wind turbine blades, may be compromised during the recycling process, limiting their usability in high-value applications (Fonte & Xydis, 2021). Despite these limitations, mechanical recycling remains the most commonly used commercial method for breaking down wind blade materials (Chen et al., 2019). While it helps reduce waste volume and facilitate material handling, it falls short in achieving true material recovery and circularity. One of the challenges lies in the complicated process of dismantling, separating, sorting, and cleaning the materials and finally the fibres and the resin are not completely separated (Sakellariou, 2018).

Thermal Recycling

Thermal recycling involves subjecting wind turbine blades to high temperatures, typically between 450 and 1000 degrees Celsius. This process is often employed after mechanical recycling but is more energy-intensive (Khalid et al., 2023). During thermal recycling, the blades are heated to extreme temperatures, causing them to undergo oxidation, which removes impurities and residues, and produces oil, gas, and char products (Kalkanis et al., 2019).

The essence of thermal recycling lies in the incineration of the resin component of the wind turbine blades. This incineration process allows for the recovery of glass or carbon fibres present in the blades. However, it is important to note that thermal recycling is more efficient for carbon fibres due to their higher heat resistance. In contrast, glass fibres tend to experience significant strength loss, typically ranging between 50 and 90%, making them unsuitable for use in high-tension components (Kalkanis et al., 2019).

Pyrolysis, a specific thermal treatment method, involves heating the fibres within a narrower temperature range, offering a second opportunity for fibre recovery in the industry. This method is particularly beneficial for strengthening components (Khalid et al., 2023). Additionally, the fluidized bed recycling technique is another effective method for fibre recovery in thermal recycling processes.

Chemical Recycling

The chemical process involves breaking down the polymer matrix in the blade to recover short fibres and other by-products (Khalid et al., 2023). This method is costly but yields simplified material suitable for strength and tension components. It produces smaller, refined components that retain the original material's strength and tensile properties. This, resulting in a more complete recycled fibre (Majewski et al., 2022). However, the effectiveness of fibre recovery heavily depends on the types of fibres present in the matrix compounds, making it a challenging task to discern the dominance of different materials in the EOL characteristics. Consequently, fibres recovered through chemical recycling are rarely applied to strength processes but are instead reinforced through recycled materials or transformed into fuel gas.

Finally, as a summary in the following table inspired by (Rani et al., 2021) and (Jensen & Skelton, 2018) it can be seen the use of the recovered products based on the method and the process given by the EOL management.

Table 7 Summary of Recycling Processes.

Method	**Process**	**Applications of the Recovered Product**
Mechanical Recycling	Grinding, shredding, crushing and milling	• Glass fibre and carbon fibre can be reused to make new composites with weaker properties thus not usable in new blades. Uses include sport equipment like water skis (Oliveux et al., 2015). • In concrete with a cement-based matrix, short glass fibres can be employed. • Recovered glass fibres can be reutilised in reinforcing elements process as they contain a lot of sand (Cement for example) (Tota-Maharaj & McMahon, 2021).
Thermal	Pyrolysis	• Fabricate glass-ceramic products used in different types of architecture. • Create novel composites of low-density polyethylene (LDPE) matrix with 15% reinforcement of recycled fibres. LDPE is widely used in the packaging industry, so the resulting material offers enhanced mechanical properties for more demanding packaging applications (Bayer et al., 2017).
Thermal	Fluidized bed process	• Recovered glass fibres are consumed for bulk moulding compound products manufacturing. This means they are included for example in automotive parts such as bumpers (Khan et al., 2024). • Production of thermo-electric composites.
Hybrid	Microwave Pyrolysis	• Recovered fibres are utilised to fabricate novel thermoset composite material. This, depending on the quality, can be reused in wind turbine blades for strength, stiffness, and fatigue resistance (Mishnaevsky et al., 2017). • Recovered carbon fibres are being utilised with polypropylene and nylon matrices. This opens a versatile number of applications due to combining carbon

		fibres and thermoplastics. These applications include sports equipment such as fishing rods (Wu et al., 2023).
Chemical	Solvolysis	• No reliable sources found regarding this technology.

Source: Rani et al., (2021) & Jensen et al., (2018).

Fonte (2021) outlines the challenges of recycling wind blades, primarily due to their composite materials as can be read in the previous paragraphs. The materials, designed for longevity, include polymer matrices, reinforcements, fillers, resins (primarily epoxy), and various materials in honeycomb structures, making separation difficult (Dorigato, 2021). Composite structures comprise thermoplastic coatings, thermoset glass fibre composites, occasional carbon fibre, reinforced polymers, adhesives, and wood (Mishnaevsky, 2021). Finally, thermal and chemical recycling is still far from being implemented on bigger scales and mechanical grinding is the most viable option due to the current market conditions (Kramer & Beauson, 2023b).

2.3 Wind Blade Circularity

The installation of the first wind turbines in the mid-1980s marked the inception of wind energy's role in RE and climate change mitigation (Fonte & Xydis, 2021). Despite its substantial contribution to sustainable electricity grids, wind turbines face challenges changing from their linear consumption patterns, making it imperative to adopt more circular models and approaches instead of solely relying on recycling technologies (Spini & Bettini, 2024).

Circularity must be integrated into every feasible step of wind turbine management, presenting multifaceted challenges in identifying specific activities and actions. This calls for continuous constructive engagement among stakeholders across the value chain, as effective product lifecycle management and EOL strategies heavily rely on collaboration (Kramer & Beauson, 2023b). Notably, companies often prioritize recycling over alternative strategies such as material design and waste prevention, highlighting the significance of stakeholder interaction.

The first notable strategy in wind turbine sustainability is design for circularity, which extends beyond recycling to encompass the entire product lifecycle. This approach includes design for repair, reuse, upgradeability, or recycling. While approximately 38-42% of wind turbine manufacturers have begun adopting this strategy, older turbines from the 2000s often end up in landfills or are open field incinerated due to the lack of lifecycle consideration and logistical challenges in their collection and recycling (Majewski et al., 2022). Nevertheless, recent developments in blade materials, such as thermoplastic composites and recyclable thermosets, indicate progress in addressing these challenges (Mishnaevsky, 2021).

Moreover, the EU directive prohibiting landfill disposal of wind turbine blades necessitates exploring alternative EOL management options. While some studies may continue to assume incineration and landfilling due to cost concerns, the focus should shift towards identifying practical solutions aligned with regulatory requirements (Diez-Cañamero & Mendoza, 2023). Lifecycle assessments from cradle-to-cradle offer insights into effectively managing wind turbine blades in compliance with EU regulations within the CE framework.

Another approach to extending the lifespan of wind turbines is through lifetime extension strategies. Over time, wind turbines experience wear and tear, often necessitating partial or complete replacement of components. This process of replacing aging components to improve efficiency and performance is known as repowering (Pakrashi et al., 2023). Within the framework of the EU waste hierarchy, priority is given to all wind turbine components, advocating for partial repowering whenever feasible (Kramer & Beauson, 2023b). While there are currently no widely adopted practices for significantly prolonging wind blade lifespans, various measurement techniques aim to assess blade conditions and potentially avoid extreme damage for decommissioning and future applications (Sun et al., 2022).

First, there is deformation measurement or strain measurement. Damage because deformation is determined when a selected point in the blade becomes twisted in such a way that exceeds historical recordings, then the blade is considered damaged and in need of change. (Sierra-Pérez et al., 2016). Second, there is vibration measurements, this technique can be used to measure properties of the blade such as stiffness, damping (system that compensates and softens impact) and mass using vibration sensors along the wind blade (Adams et al., 2011). This technique is perfect for measuring the previously mentioned attributes in non-contact ways (Sun et al., 2022). These previously mentioned techniques are a few examples of the current efforts made to correctly monitor in-situ conditions of these blades for a more successful decommission process afterwards.

Despite these measurement strategies to reduce heavy damage in decommissioned blades, and previously discussed recycling technologies and methods, stakeholders identify barriers hindering their widespread adoption, including the lack of a market for recirculated materials, high recycling operation costs, and limited practical experience in applying secondary materials to new products (Chen et al., 2019).

Reuse, repurpose, and recover are the next options on the list. These three options are significant for wind turbine components. Starting with reuse, it is described by some authors as the highest value obtained from decommissioning. It keeps its entire structure untouched, and it is a good way of giving a second life. Companies in the current market (Repowering solutions, Green-Ener-Tech) support this option by reusing the turbines in smaller markets and lower cost systems in Latin America and Africa (Woo & Whale, 2022).

Following up with repurposing, this involves the removal and replacement of blades upon reaching maximum fatigue, leading to their integration into a second lifecycle through repurposing, such as for bus shelters, bridges, or electricity poles, this is part of the previously mentioned mechanical, thermal, and chemical recycling (Henao et al., 2024). Other initiatives like Vattenfall's repurposing of decommissioned wind blades for non-structural walls demonstrate practical steps toward material recirculation without a major change in the wind blade structure, however, on a limited scale (Vattenfall, 2024). This is one of the highest values it can be achieved from decommissioning wind blades as the structure is not changed, they are only cut and placed in other structures, basic repurposing strategy. These efforts signify progress in diverting composite materials from landfills, although their scalability remains uncertain (Majewski et al., 2022). Finally, recovery follows the energy or material recovery exposed in the pyrolysis section of the literature review.

Another interesting initiative worth noting in the circularity section is the **Dematerialisation Circular Business Model.** This model aims for decoupling solutions, particularly relying on digital services, which are anticipated to replace and mitigate various resource consumption practices (Velenturf, 2021). Despite its promise, research in this field remains limited, as many products still require manufacturing processes. In the wind industry, this CE model is beginning to take shape through two notable projects. The first involves a small-scale technological innovation that modifies the rotor blades to harness vibrations instead, thereby reducing the need for additional materials. This change allows power generators to efficiently transform energy with vibration power, demonstrating a form of dematerialisation in the wind turbine industry. The second project focuses on reducing the weight of wind turbines and their moving parts. By minimizing weight and streamlining components, this initiative enhances the sustainability and efficiency of wind energy generation (Mendoza et al., 2022).

3 Research Design and Methods

3.1 Research Design

This thesis adopts a constructivist worldview, following the approach outlined by (Creswell & Creswell, 2021), wherein the researcher aims to comprehend the meanings attributed by others to the world, rather than beginning with preconceived theories. This method involves employing open-ended questioning and conducting subjective explorations based on information gathered from involved practitioners, including OEMs, wind operators, and recycling facilities.

This research addresses the limited exploration of circular practices in the wind turbine blade market by integrating diverse perspectives through a constructivist worldview (Creswell & Creswell, 2021). The first research question (RQ) employs the CE framework from Chapter 2.1 to analyse challenges and explore potential solutions discussed by stakeholders. Additionally, the second RQ focuses on highlighting the PaaS model as a viable implementation strategy, outlined in Chapter 2.1.4. Through qualitative analysis of interactions with OEMs, wind operators, and recycling facilities, solutions will be thoroughly examined, and data will be coded to capture multiple perceptions addressing key concepts (Creswell & Creswell, 2021).

The thesis adopts a qualitative research approach to investigate current efforts towards wind blade circularity and generate perceptions that could translate into potential solutions through qualitative data analysis from different interviews (Creswell & Creswell, 2021). This narrative exploration encompasses various stakeholder perspectives to examine historical shortcomings in EOL management observed in the wind blade market, notably open landfilling. By unifying data and examining existing models, barriers, and potential future directions, the research aims to propose actionable solutions.

The thesis employs a "top-down" approach to tackle the research questions, progressing from broad to specific information. This methodology entails involving key stakeholders within the circular product lifecycle framework, encompassing recycling facilities, wind turbine manufacturers, and wind operators. Through interviews with these stakeholders, insights are collected on the diverse factors shaping effective EOL management of wind blades, encompassing circularity practices. Furthermore, specific inquiries are made regarding the challenges hindering the implementation of circular practices and models such as PaaS. Additionally, stakeholder's viewpoints on the adaptation of circular models from other technologies to wind blades are explored, fostering transferability within the market.

3.2 Data Collection

3.2.1 Literature Review

The literature review explores the unexplored realm of various circularity practices and models concerning the end-of-life (EOL) management of wind blades. Often relegated to the "further exploration" sections of scholarly articles, this review delves into existing research topics such as wind blade recycling and circularity practices.

Firstly, a section titled "key concepts" was employed in the literature review to share crucial information with the reader. It begins by defining different frameworks and the theories behind them. Starting with the CE framework, which emphasizes the importance of cross-cutting themes in results and discussions, this step involved searching Google Scholar using terms like "Circular economy framework," "Circular economy principles," and "Circular economy" to find authors who emphasized the significance of cross-cutting themes. The next key concept is identifying the stakeholders involved and their roles in the CE as viewed by academia. Subsequently, the review addresses some of the existing challenges in achieving a more CE in wind turbine blades, aiming to contrast theoretical and practical perspectives in the thesis results. The final key concept focuses on the PaaS model, providing readers with necessary theoretical aspects to understand different types of PaaS and their environmental benefits.

Following the key concepts, the next section aims to explore wind turbine recycling techniques and their circularity. The recycling section discusses different recycling methods and their distinctions, while the circularity section highlights market practices and their implementation in the wind turbine market.

To gather insights into EOL techniques for wind blades and circularity practices, a review of academic literature was conducted using Google Scholar, supplemented by webinars, links, and videos recommended by instructors and supervisors. Key search terms included "circularity in wind blades," "Wind blade EOL management," "Wind blade recycling," and "Wind blade reuse." While these searches provided ample information for the first research question (RQ1), only one article directly addressed specific applications of PaaS for the second research question (RQ2). Therefore, the investigation into PaaS relied heavily on insights from practitioner perspectives, primarily through interviews. The coding process for this information is detailed in the subsequent sections.

3.2.2 Practitioners Perspective

Following the literature review, practitioner perspectives are integrated into the study through interviews, serving two primary purposes. First, interviews complement the literature review by providing detailed and practical insights, thereby validating, and expanding upon the information obtained from scholarly sources. Secondly, they offer valuable insights into areas where the literature may be lacking, particularly in the application of the PaaS model and its potential improvements. During these interviews, specific examples and questions related to the PaaS model were posed to participants to gather insights into the necessary steps for its implementation. The inclusion of practitioner perspectives is crucial, as their professional experience and insights enrich the understanding of implementing models like product service systems in the wind blade market. This encompasses considerations such as economic factors, infrastructure requirements, collaboration dynamics, and policy frameworks.

Stakeholder and participant selection followed a pragmatic approach, focusing primarily on the European market without many complications and through LinkedIn. The process entailed contacting all potential wind turbine operators, OEMs, and recycling facilities within the region focusing on their experience to answer the RQs appropriately. Prior to the interviews, practitioners received the interview questions to provide them with a preliminary understanding of the topics to be discussed. Additionally, the interviewee names and company will not be disclosed in any way. In table (8) the information about how the interviewees will be addressed will be provided.

To facilitate open and candid discussions, interviews were conducted anonymously, encouraging practitioners to share practices and insights more freely. Online interviews were preferred for convenience, typically lasting between 30 to 50 minutes. While practitioners received questionnaires in advance to familiarize themselves with the topics, interviews were semi-structured, allowing flexibility to explore emerging areas of interest. Recordings were made for content analysis with a recording app, with practitioners providing consent.

Table 8 Informants.

Identification of Interviewee	Practitioners (Producer, User, Recycler)	Position
1	OEM	Commercial Engineer
2	OEM	Technology Manager
3	Wind Operator	Project Developer
4	Wind Operator	Sustainability Manager
5	Wind Operator	Head Regulatory Affairs
6	Wind Operator	Senior Circularity Specialist
7	Recycling Facility	COO
8	Recycling Facility	Metallurgist
9	Recycling Facility	Chemical Engineer
10	Recycling Facility	Wind Manager
11	Recycling Facility	Sustainability & Materials Expert
12	PhD	PhD Student
13	OEM	Sustainability & Value Chain Professional

3.3 Data Analysis

The data collected from interviews is transcribed and imported into Word using the Good Tape software. Instead of utilizing a coding tool, an Excel sheet is employed to identify different topics based on the research questions. For RQ1, the information is analysed by segmenting it into economic, infrastructure/product features collaboration components, and regulatory sections. These sections are further subdivided into smaller codes representing recurrent topics in the interviews.

The selection of barrier categories was influenced by CE principles outlined by (Suárez-Eiroa et al., 2019) in the literature review, known as transversal principles. These principles emphasize innovation in areas such as financial, political, and social issues, aiming to shift towards a new paradigm counter to the linear economy. They also stress holistic viewpoints of a product's lifecycle, emphasizing interconnection and collaboration among key actors to address core CE issues, leading to development and expansion of the CE.

Regarding the analysis of results, transversality incorporates some of these aspects highlighted in the literature. Additionally, due to its connection to design, the category of infrastructure/product features was replaced with social issues, as investigating this information was of personal interest.

Economic barriers were categorized into market maturity, supply and demand, cost of recycling, relation of sustainability and economic factors, and economic responsibility. Infrastructure/product features were divided into design for circularity, types of recycling and quality control, and additional infrastructure cost. Collaboration was segmented into partnerships, competitiveness, and information sharing/transparency. Finally, legislation was categorized into government collaboration, standardization, and current efforts.

For RQ2, the information is segmented based on the participating stakeholders (OEMs, wind operators, and recycling facilities). This division allows for an analysis guided by the framework outlined in section 2.1.4 of the literature review. This framework identifies the development, monitoring, and implementation sections of the PaaS (Product-as-a-Service) model which is adapted from (Beuren et al., 2017). The model is introduced in both the literature review and discussion sections, enabling a comparison of how each element is reflected or absent in the wind turbine market.

The interview process mirrors the coding process, but with a focus on major topics relevant to both RQs. After transcription, these major topics are further broken down into smaller categories. Interviews begin with general questions to establish context, followed by more specific inquiries to solicit detailed responses. This can be referenced as the top-down approach mentioned before.

The following table presents the codes assigned to the different key words.

Table 9 Coding Examples.

Code	**Description**
RQ1	**What are the main barriers for a more circular end of life model of the wind turbine blades?**
General Questions	Existence of circular practices, perception of a true circular practice / model
Economic factors	Factors that influence the application of circular practices in the industry. (Current market, supply and demand, sustainability relation with economic costs, types of recycling costs, paying responsibility).
Infrastructure	Factors that influence the application of circular practices in the industry. (Technology, transport, logistics, facilities across Europe, types of recycling, design for circularity and quality control).
Collaboration	Factors that influence the application of circular practices in the industry.

	(Partnerships, competitiveness, information sharing and stakeholder transparency).
Regulation	Factors that influence the application of circular practices in the industry. (Lack of legislation, government collaboration, current efforts).
<u>RQ2</u>	**What are the different practitioner's perceptions towards the application of the product-as-a-service (PaaS) model in the wind turbine industry?**
General Questions	Because of the scope of the question the coding is done by asking general questions about the PaaS model referring to the leasing/renting of the wind turbines/blades Current application of the PaaS model, theoretical benefits from it, responsibility in the value chain, complexities involved in the lifetime extension services, thoughts about renting thoughts for use-oriented model, thoughts of product-oriented model.
Current PaaS practices	Questions related to framework in 2.1.4 addressing development, implementation, and monitoring areas of PaaS.

4 Findings / Results

The results section presents findings from 13 semi-structured interviews conducted with practitioners representing OEMs, wind operators, recycling facilities, and an experienced PhD student in the field. These interviews focused on exploring challenges related to circular practices in wind turbine blades within the wind turbine market. The roles of the practitioners are detailed in the methodology chapter to provide clarity on their perspectives when discussing specific topics. The barriers identified in the interviews will be categorized into economic, infrastructure, collaborative, and legislative challenges for better organization within the document. Additionally, the second chapter (4.2) will include a discussion of the perceptions about the implementation of the PaaS model in the wind turbine industry from the different stakeholders (OEMs, wind operators and recycling facilities). Both conceptual frameworks introduced in the literature review chapters 2.1.4 and 2.1.1, which are the CE and PaaS frameworks, will be utilized to analyse the findings.

4.1 Barriers and Drivers

4.1.1 Economic Based

Economic barriers begin to arise, according to various interviewees, when discussing market availability and viability. This is commonly referred in the interviews to as commercial viability, and many interviewees see this as one of the primary barriers in the wind turbine market, particularly concerning wind blade's composite materials. Large-scale decommissioning processes have not yet occurred, leading to a lack of practical scenarios or business cases to guide other market players. Interviewees (1) and (2) discuss a crucial concept related to commercial viability, which is market maturity. Wind blades, especially those made of composite materials, have only been in use for approximately 20-25 years, which is insufficient time for the market to mature adequately. This market maturity refers only to recycling as for energy production it is very powerful already in the EU. Interviewee (4) for example, has not witnessed a wind turbine decommissioning in the three years they have been in the business, indicating a lack of decommissioning experience. Interviewee (10) provides an example of market maturity in terms of recycling using steel, which has been present in different markets for about 75-80 years This of course, allowing the product to establish itself in the market and become part of various industrial processes. This example highlights the importance of a more extensive product background, which, according to the interviewee, will lead to critical factors such as price regulation of the material. This price regulation is lacking for virgin fibres, a component of composite materials. As the price is not regulated, accessing fibres, although costly, is still more affordable than accessing 100% recyclable products offered by the market.

This leads to a deeper analysis, focusing on the importance of the value of recycled materials. Interviewee (8) emphasizes that as the market matures and prices are regulated, the value of recyclable materials will gradually increase. This not only encourages the purchase of materials but also motivates entrepreneurs to establish companies dedicated to recognizing and profiting from these materials.

Interviewee (11) serves as a perfect example of existing market opportunities. During a webinar attended by the interviewee on April 25, 2024, hosted by the company Continuum, which is poised to become a leader in recycling composite materials, an intriguing opportunity in the construction sector was presented. Continuum showcased panels for different structures made with 92% recyclable material and 8% virgin material, demonstrating a new avenue for these materials to undergo a second life cycle in another production process.

It is not only Continuum that sees opportunities; Interviewee (9) highlights that market maturity is hindered by the current quality control standards of these materials. Quality control is crucial in the composite materials industry, particularly for heavy equipment sectors like aerospace and automotive. Recycled materials undergoing mechanical, thermal, and/or chemical recycling must maintain their functionality for the target product. For better market maturity, it is expected that more value chain actors will emerge, capable of utilizing these materials regardless of their quality. This expansion of the market will not only increase demand but also incentivize further improvements in recycling technologies and processes. Interviewee (12) also underlines the importance of meaningful repurposing. "Current technologies struggle to separate epoxy resin completely from the fibres, resulting in a less complex structure," explains Interviewee (12). However, Interviewee suggests that exploring alternative uses, such as incorporating recycled materials into smaller projects across various industries, can offer viable solutions.

The market demand discussed previously opens the door to discussing different costs and their relationship with sustainability. This is an important element that would greatly aid market maturity. The first factor to consider, as highlighted by Interviewee (2), is that simply being sustainable will not drive the market; consumers seek products that deliver tangible value in return. Mere sustainability stories may not necessarily translate into perceived value unless supported by legislative incentives validating sustainability claims to consumers. Moreover, consumers evaluate the value proposition of their purchases. For instance, consider a wind park's hypothetical investment of an additional $3 million in fully recyclable wind blades. This allocation redirects funds from their profits, which will then need an explanation to investors regarding the rationale behind this decision. Is it justified solely for the sake of sustainability? This scenario highlights the integral role of monetary value in the sustainability equation. Not only this previous aspect but also interviewee (8) associates the low demand with elevated transportation to recycling centres or OEM's even more difficult economy wise. This is directly related to statements from different interviewees who clearly state: "Why bother with a sustainable story if there's no specific regulation preventing the companies from taking waste to landfills?" This is where economic factors, combined with laws, start to become more influential.

Finally, Interviewee (2) mentions two key terms emerge when discussing the supply chain: "big supply chain" and "heavy supply chain." Both terminologies entail a significant increase in demand, primarily concerning the volume of demand. However, consumers currently exhibit reluctance to allocate additional economic resources toward recyclable composites and resin, as the perceived benefits beyond sustainability remain limited. Despite these options, consumer uptake is hindered by the high cost, despite the substantial investment required by OEMs themselves. This perspective shows a disparity in commitment between wind farms and OEM's, suggesting that the desired level of demand will not be fully realized until legal measures or economic incentives are implemented.

The conversation continued with an exploration of the challenges posed by profit pressures, performance targets, and the prioritization of core business activities within companies. Particularly within sectors like wind energy, where there is a strong emphasis on environmental sustainability, there is a tendency to overlook peripheral issues in favour of maintaining profitability and meeting objectives. This underlines the significance of the linkage between the different aspects in the industry like economy and legislation emphasized by Velenturf, as illustrated in the literature review with a transversal framework. Further analysis with Interviewee (11) also highlights the relationship between sustainability and economics in blade recycling. No company is inclined to engage in recycling endeavours that would result in the loss of valuable economic resources, even if the initiative aligns with sustainability goals.

Following up on the discussion, economic challenges mentioned by various stakeholders support the literature review, highlighting chemical recycling as a costly treatment method. However, two perspectives are worth considering: one from Interviewee (11), who is part of a recycling company, and the other from Interviewee (1), who is part of an OEM.

The insights provided by Interviewee (11) from the recycling company offer a perspective on chemical recycling. Despite existing literature indicating that chemical recycling is among the costliest processes available, the recycling company continues to support its implementation. However, this support comes with a key condition: for chemical recycling to be economically and environmentally feasible, at least 80% of the materials subjected to this process must be effectively utilized. This alone serves as a critical view of how with the current design, the implementation of chemical recycling is not optimal as of now the blade contains 21% of epoxy resin.

Drawing from the experiences of Interviewee (11), this broadens the spectrum of possibilities within wind blade management. Notably, the recycling company suggests exploring design modifications that incorporate higher proportions of epoxy, glass fibre, or a more uniform material composition to enhance sustainability outcomes. Interviewee (1) perspective adds to the discussion. Unfortunately, with the current model and composition of the wind blade, it is not possible to avoid separation costs using multiple techniques if true sustainability is the objective. This is the primary reason mechanical shredding technology and landfill disposal remain the most sought-after in the wind energy market. This issue of separation costs and the preference for mechanical shredding keeps highlighting a recurring economic challenge in designing for circularity and sustainability.

Interviewee (5) also mentions an important point in the sustainability and economic relationship debate. It is mentioned that increasing prices of the technologies used for the wind farm, while market maturity reaches the break-even point, raising electricity prices would be ideal to achieve a balance in the revenue granted to wind farms. Implementing these criteria from a business perspective, the interviewee emphasizes that these additional costs act as fair compensation for wind farms to operate in a more sustainable manner. Also, in simple terms, this refers to the fact that a qualitative criterion such as sustainable / recyclable goods should be implemented only and exclusively once there is a clear justification on the financial side. These financial justifications must be introduced before sustainability laws, acts, or regulations, or else businesses risk suffering significant economic losses.

Finally, market maturity has a lot of influence on the different responsibilities of users. For example, Interviewee (1) mentions that there is not enough clarity in the waste responsibility in this market. For instance, they mention that the blades that are buried underground at some point should be reclaimed for treatment and inclusion in other production processes. This is not a common thought among the interviewees since only two of them suggested this challenge, which will surely become a reality much later. Regarding this, the interviewee suggests that although there is technology to dissolve difficult components like epoxy and recycle the fibres in secondary markets, the responsibility should be instituted by some specific regulation or, alternatively, by a powerful economic incentive that states that for every blade recovered and recycled, points will be reflected for future wind operation auctions.

4.1.2 Infrastructure / Product Feature Based

The barriers related to infrastructure were few. Many of these were reflected in the obvious issue of the size of the blades and how this is a gigantic impediment to carrying out transportation and recycling operations, resulting in many more parties having to be involved in the process due to its complexity. However, some interviewees provided insights into three specific topics: Designing the structure for circularity, types of recycling and quality control, and finally, the additional incurring cost of infrastructure. With these topics in mind, the discussion proceeds as follows.

DESIGN FOR CIRCULARITY

Interviewee (2) introduces an initiative not previously encountered in the literature review, which involves providing various products with distinct capabilities. One such example is the offering of recyclable blades or greener towers, known as Drop-In solutions. Customers are presented with the option to pay a premium for these new products, with the ultimate decision left to their discretion as an alternative to standard blades. This innovative approach highlights the evolving strategies within the industry to promote sustainability.

Similarly, Interviewee (4) acknowledges the existing technological limitations in fully recovering glass fibre and carbon fibre components, along with the absence of a true circularity design. This increases the impact and significance of comprehensive planning for infrastructure projects. The interviewee emphasizes that while technology plays a crucial role, designing a plan for these infrastructures is equally vital. Furthermore, they caution against the environmental impact of constructing new facilities solely to facilitate improved EOL management. Such actions may inadvertently exceed planetary boundaries, highlighting the importance of complete circularity planning.

Moreover, Interviewee (11) contributes to the discussion by expressing scepticism about achieving sustainability through the recycling of blades with the current design. They highlight the need for more companies to transform and address the challenges posed by the circular design, particularly regarding epoxy resin. This resin, not initially intended for recycling, prioritizes endurance and longevity over recyclability. However, there is optimism regarding potential solutions. Interviewee (9) introduces Zvanko, a company claiming to have developed a recyclable epoxy resin through a straightforward chemical process, offers promise for a more sustainable future. This proactive approach, beginning at the product's inception rather than its end, presents a potential pathway forward in promoting circularity within the industry.

TYPES OF RECYCLING & QUALITY CONTROL

In their comments, Interviewee (7) describes using wind blades for furniture, bus sheds, and playgrounds as a superficial solution rather than the best one. They believe that while these changes might seem to fix the problem, they do not fully solve it. For example, repurposing wind blades into playground equipment still leaves the issue of waste disposal unresolved because the playground might end up in a landfill after use. On the other hand, Interviewee (10) suggests that preserving the shape of the blade without crushing it makes it more useful. With this method, all parts of the blade stay intact, although they may need to be cut to fit certain structures. This preservation could make it easier for future technologies to recycle and separate materials more effectively. Prioritizing research into the best reuse practices aligns with Europe's waste hierarchy proposal.

The concept of circularity is important when identifying barriers to effective solutions, as expressed by Interviewee (7). They emphasize the importance of including products in new functionalities to differently address waste management challenges. They highlight for example that involving wind blade waste in Co-processing does not improve the quality of the product, and the resulting residual product from burning them in cement kilns remains non-recyclable. This approach, they argue, merely shifts the problem to a different subproduct without fundamentally resolving it, nor does it enhance the quality of the cement. Comparing industries like automotive and electronics, where fibres can be integrated into various products such as LED TVs, Interviewee (7) shows the potential for generating recyclable waste that can be managed by electronic recycling facilities. However, they note the absence of a similar continuation in the case of cement kilns, where such integration is lacking.

Interviewee (11) emphasizes the challenges linked with grinding wind turbine blades, mainly due to their large size. They mention that the upcoming large-scale decommissioning of wind blades presents significant opportunities for their company. Currently, they are involved in constructing various projects and factories capable of handling between 30,000 and 35,000 tons of yearly waste generated from the blades. By showcasing mechanical shredding technology, this waste can be effectively transformed into panels, showcasing the potential for resource utilization and sustainable waste management practices. Additionally, Interviewee (11) discusses co-processing as a widely employed technique, particularly within the cement industry, where cement kilns are common sites for its implementation. While this practice is extensively deliberated upon in Wind Europe as a viable activity, Interviewee (11) contends that while co-processing holds prominence, it is not inherently superior to their recycling company's technology. They argue that the carbon footprint associated with co-processing is considerable, whereas the recycling company's approach, involving mechanical grinding and subsequent distribution of panels for construction, is deemed more sustainable.

Additionally, mechanical grinding leads to interviewees (9, 12) highlighting a critical concern: the lack of certainty regarding the quality of fibres obtained through various recycling methods. While expensive or complex technologies might justify the use of costly processes, ensuring quality control for recycled materials remains a challenge. Imperfect quality control could have detrimental consequences for industries like aerospace or automotive, particularly in large components where durability is essential. This issue is particularly pertinent for carbon fibre, as glass fibre is generally considered less robust. Outlining quality control is still a big barrier that needs to be surpassed by the future technologies and circular models. These outlines further look and investment into quality control technologies and facilities for better material second life distribution.

Finally, interviewee (12) expresses the importance of extending the lifespan of wind turbines, drawing from her expertise in lifetime extension techniques. Countries like Denmark and Germany lead repowering projects, replacing older turbines with newer, more efficient models. While this provides a second life to the turbines and upgrades to better technology, it is worth considering the environmental impact. Without repowering, old turbines could continue functioning, potentially reducing emissions from recycling and transportation. Future technologies may further lessen environmental impact by allowing technology to evolve, potentially resulting in reduced emissions compared to current practices. These can be further analysed to hypothetically state that more infrastructure might be needed but life extension techniques are also important as a driver towards savings in more recycling and quality control infrastructure.

ADDITIONAL COST

Some infrastructure additional cost barriers might arise in the future and interviewee (6), drawing from experience, highlight the often-underestimated expenses associated with dismantling, pre-processing, transportation, and logistics. While much attention is typically given to recycling costs and gate fees, preparatory activities such as turbine dismantling, and logistical organization also incur significant expenses. Despite optimism that recycling prices may decrease with operational scaling, it is essential to consider the entire lifecycle, including these preparatory stages, when assessing costs.

Additionally, Interviewee (8) emphasizes the importance of Health, Safety, and Quality (HSQ) principles in wind turbine extraction and decommissioning. The task of removing these large structures from the seabed, transporting them back to land, and then disassembling them poses considerable safety risks and logistical challenges. However, there is a notable lack of discussion surrounding these challenges, particularly regarding the potential for stress-induced situations and safety hazards. With significant decommissioning efforts anticipated in the market between 2025 and 2030, addressing these challenges will likely incur additional costs, particularly in the disassembly phase.

4.1.3 Collaboration Based

Collaboration barriers along with drivers are something that was not found detailed in the literature review as technical documents speak very generally about the different barriers, but do not mention at a practical level the different perspectives of the stakeholders involved. The most mentioned categories in terms of collaboration were categorized as partnerships, information sharing / transparency between companies and competitiveness.

PARTNERSHIPS

Starting with partnerships, which according to most interviewees play a particularly important role in the market and in proper EOL management. The importance of collaboration must be mentioned first, using Decomblades as an example. This initiative was responsible at the time for initiating collaboration between competitors in the market such as Vestas, LM, and Siemens for the creation of a joint material Passport for turbines between 2021 and 2023.

Interviewee (3) mentions the material passport plays a crucial role in facilitating the CE. This interviewee also highlights how it enables wind farms to easily contact recycling facilities, as these facilities often require detailed knowledge of the materials for effective recycling. For companies in the early stages of developing pyrolysis or solvolysis methods, understanding the composition of the materials is essential to determine if recycling is feasible and worthwhile. Different processes, such as pyrolysis and solvolysis, recover different components of the blades, such as fibres and epoxy, respectively. Therefore, having accurate information about the materials is highly beneficial for selecting the most suitable recycling method.

Interviewee (3) establishes that these types of collaborations are essential and mentions that it is completely necessary that while the market is growing, there are alliances to be able to generate different approaches to recycling. Interviewee (2) complements this idea in partnerships by mentioning alliances between OEMs and wind operators, based on the commitment of the parks to acquire and test 100% recyclable blades from the OEMs. These pilot tests of different recyclable wind blades are the practical demonstration with dates and numbers where a transition in the market guided by collaboration initiatives begins to be evident. By using these measures and initiatives, competition is temporarily set aside to ensure that different recycling facilities have access to accurate information about blade compounds.

These initiatives are important, but Interviewee (3) also talks about when the next major decommissioning arrives. When decommissioning offshore wind farms, the volume of blades can be substantial, often exceeding the capacity of most recycling companies. As a result, it becomes necessary to engage multiple parties with different approaches to recycling. This fragmented supply chain for recycling poses significant challenges and complexities in achieving effective blade recycling at scale. Collaboration and creating a network among the actors would facilitate this tedious process and would lead to an easier approach in this product lifecycle stage.

The possibility of obtaining this information lies in the proactive engagement with suppliers, including recent partners and other stakeholders, to integrate it into contractual agreements. For instance, interviewee (3) mentions that when procuring a turbine, stipulating the provision of a comprehensive material passport could be a requisite. However, historically, such detailed information has not been a priority due to a lack of perceived value. Consequently, efforts are now being made to advocate for its inclusion, potentially leading to access to this information at a certain level of detail. Nonetheless, defining the exact granularity in terms of materials remains challenging to articulate.

This creation of a network is seen by Interviewee (6) as the need for action-driven partnerships in the industry, moving beyond theoretical collaborations towards more tangible initiatives. While acknowledging the value of past innovative projects like Decomblades, they expressed a desire for more concrete actions. This could involve actively engaging in EOL blade management and establishing partnerships with suppliers to procure recycled materials. They highlighted the importance of bilateral partnerships focused on executing specific projects at designated times. Rather than solely focusing on research and data, the interviewee advocated for partnerships that prioritize practical action. This is supported by Interviewee (11) who has the perspective of a recycling facility and can relate to the fact that most of the time the recycling of the blades can be quite difficult with only one party participating in the matter. In this case, it is also suggested that collaboration and partnerships need to be implemented among more recycling facilities, which would greatly help to better separate the current design of the wind turbine blades.

COMPETITIVENESS

Partnerships serve as a significant form of collaboration in simple terms, yet this driver is suppressed by the remaining competition in this industry. Despite OEM companies establishing within their contracts the assurance of product service and maintenance, interviewee (2) adds that Offshore wind projects are described as "very seldom" sold with long service contracts. This rarity is attributed to the fact that most offshore developers are large companies with their own service organizations. These companies often choose to handle the servicing of their wind turbines themselves rather than purchasing long service contracts from third-party providers. This is due to two reasons: firstly, wind farms aim to expand their market and horizon with other providers offering the same or similar service to save costs, and secondly, within this expansion of horizons and market, some wind farms have created subdivisions for wind turbine repair and servicing within their own company, which means they are competing with the service contracts of the OEMs.

Typically, it unfolds as follows: Service contracts emerge as a critical aspect of the model, with Interviewee (3) highlighting on certain challenges. Currently, OEMs bundle maintenance and consultancy services within their offerings. However, their role as turbine producers often results in inflated service costs. Initially, wind farms may rely on OEMs for addressing turbine issues due to their intimate familiarity with the product. Yet, over time, wind farms may seek alternative, more cost-effective servicing options. This shift poses a collaboration barrier, as OEMs should ideally incentivize competitive market pricing to facilitate efficient wind farm operations. Their comprehensive understanding of the product positions them to extend turbine lifetimes through effective repairs.

Moreover, Interviewee 11 expresses that, while an OEM and a recycling company could feasibly enter into a contract or Non-Disclosure Agreement (NDA) regarding recycling processes, the current trend suggests that OEMs prioritize developing their own technologies rather than forging partnerships with recycling facilities. While this approach may be economically rational, it prompts reflection on future implications. Competitive dynamics such as these can impede collaborative initiatives. Interviewee (11) suggests that OEMs could potentially enhance their recycling capabilities through R&D collaboration with the recycling Company, which already possesses established processes and a sizable market share in the building materials sector. An exemplary instance is represented by Vestas, as noted by Interviewee (5), who perceives it as a potential entity poised to assume greater control over the recycling process, potentially bypassing the involvement of external facilities.

A final example of these competition barriers disclosed by interviewee (5) would be Decomblades. The interviewee observes a shift in the perception of Decomblades as a business partner. Initially viewed as an intriguing collaborator to put all the companies together, Decomblades is now being downplayed by certain companies. This change in attitude stems from the realization that Decomblades could potentially become a competitor for their own services. This situation highlights the increasing competitiveness within the industry.

INFORMATION SHARING / TRANSPARENCY

Competition in wind turbine operation auctions can hinder information sharing and transparency, which are vital for protecting a company's sensitive commercial information. Many interviewees highlighted barriers to information sharing, particularly in the auction process for wind turbine operations. Transparency and collaboration are crucial in wind operation auctions, but they are often limited in practice. For example, interviewee (3) noted that access to information is restricted even after the bidding decision, limiting stakeholder's understanding of bid decisions and hindering learning from other's experiences. Similarly, interviewee (4) mentioned that competitors typically lack access to each other's proposals, and the government often does not disclose details of the bid evaluation process, further reducing transparency.

However, the government plays a role in facilitating market development by gathering insights from developers and engaging in consultations with various stakeholders, including developers and OEMs. These consultations aim to gather perspectives on circularity aspects to be covered in tenders and their feasibility. For instance, if developers propose ambitious recycling targets for blades but OEMs express concerns about feasibility, integrating those targets into bids becomes challenging. Therefore, the government seeks input from all stakeholders to ensure tender requirements, including key performance indicators, are realistic and feasible for the industry.

By incorporating feedback from different stakeholders, including developers and OEMs, the government aims to create tender specifications that are acceptable and achievable for all parties involved. This collaborative approach aligns the interests and capabilities of various industry players and enhances the effectiveness of circularity initiatives within wind farm projects.

Another concern which is highlighted by interviewee (8) is the lack of a proper standardization process. Taking as an example Decomblades again with the accomplishment of the joint material passport as a standardization measure there has to be a next step. To achieve deeper standardization, more industry leaders need to participate to expand the process as mentioned by interviewees (11) and (12). Additionally, more standardized rules must be established, including specific guidelines for the proper recycling route for blades. If certain market actors already possess advanced blade recycling technology, a publicly available roadmap should outline how these companies can receive older wind turbine blades and continue the recycling process efficiently. This also is particularly related to education as stated by interviewee (6) and the significance of cross-sectoral support among stakeholders to improve recycling and EOL management practices.

Moreover interviewee (12) mentions the lack of transparency and information sharing in the specificity when it comes to assessing wind turbines for resale in a secondary market. The evaluation process includes determining the turbine's operational status by assessing factors like the integrity of the tower structure and its maintenance history. For example, recent major repairs, like replacing a gearbox component before decommissioning, can indicate a favourable condition, potentially enhancing its resale value. The same principles and concepts can be applied to the blade and with the incorporation of these documents.

4.1.4 Legislation Based

Market maturity once again emerges as a theme, prompting a comprehensive analysis as outlined in the literature review framework in section 2.1.1 This prompts the question: Despite the availability of technologies, why does the market not mature more rapidly? This question is evaluated under a critical variable: the role of government and the various laws that can support not only the market but also collaboration among different stakeholders. One of the most recurring findings is the correlation between the market and government efforts, particularly in standardization and promoting a more circular EOL management approach.

GOVERNMENT COLLABORATION

It is worth mentioning that government collaboration is an additional and possibly the most important step, according to several of the interviewees. Interviewees such as (1, 5, and 9) specifically mention the lack of government support in different legislations that would assist other stakeholders in carrying out better EOL management. Interviewee (2) expresses a firm stance regarding the absence of government frameworks. Their primary contention revolves around the criteria for participation in wind park auctions, which predominantly focus on pricing without considering sustainability advantages. This oversight results in sustainability efforts not being incentivized within the auction process, posing a significant challenge. Consequently, OEMs emphasize a prioritization of design initiatives and incentives over enhancements to EOL management practices. Additionally, OEMs signed a proposal together with Wind Europe banning landfill by 2025 onwards. The above, concisely, represents that the industry has been the entity leading proposals for improvements towards a more sustainable market. It is worth noting that this landfill effort is directly aimed at wind blades and their composite materials.

Among the different legislations that the interviewees see as viable to support them are, for example, laws that support the EOL market since there is a lack of a viable market for recycled materials. To address this, offering premiums, tax reductions, or increasing the cost of primary materials can promote the use of recycled materials. This approach provides tangible benefits for using recycled materials or mitigates the disadvantages of using primary materials. By addressing these two aspects, the market can be enabled, making it more appealing for developers to engage in sustainable practices with materials like blades.

Another prevalent issue, repeated among the three interviewees representing wind farms, is obtaining information about blade materials. Mentioned also in the partnership section of the results, this information is valuable, and any legislation requiring OEMs to share this information would be ideal not only for operators but also for recycling facilities. This requirement, of course, only applies to wind turbines that were manufactured before 2021, as Decomblades was present with the Joint Material Passport initiative this year. But once again, the government participated little in this initiative, which was mainly driven by the industry, and in the end this.

The interviewee (4) highlights the significance of enacting transparent and tracing legislation, which they describe as a potential significant change in tracing more challenging-to-recycle materials, such as composite materials. Through material tracing, the interviewee explains that it becomes feasible for these materials to access secondary markets, enabling not only increased recycling but also opportunities for reuse, repurposing, recovery, and even repair. Tracing could involve monitoring the wind blade's condition while it remains operational within the wind park, offering insights into its lifespan and potential for further use. However, currently, there are no legislative requirements concerning recovery rates or incentives for these processes. Consequently, wind turbine blades do not receive additional incentives for recovery or recycling efforts. Implementing such incentives could positively impact the EOL disposal and tracing auction criteria, potentially favouring stakeholders who prioritize effective lifetime extension and EOL management for blades.

STANDARIZATION

From interviewee (10) viewpoint, the drive towards sustainable practices is largely propelled by legislative initiatives. These initiatives represent a political push, with a strong focus on national regulations. Unlike other industries such as batteries or electronics, which benefit from European-wide regulations, the wind turbine market is primarily governed by national legislation. While the interviewee mainly represents the European market, their knowledge of other global markets, such as Asia, the US, and Africa, is limited. Consequently, discussions about these markets may not yield substantial insights. The European Commission occasionally introduces directives, but there has not been significant legislative action specific to wind turbines. Consequently, the regulatory landscape within the wind turbine market is fragmented and diverse, varying from one country to another.

Another example is provided by Interviewee (11), who highlights the challenges posed by legislation governing the international transport of wind turbine blades and their components. This underlines the lack of standardized policies, particularly within the European Union, which can obstruct recycling initiatives. Varying regulations across EU countries may require additional permits or impede company’s ability to proceed with recycling operations, thereby limiting the potential for blade recycling. Addressing this issue is crucial for facilitating market maturity. However, the current bureaucratic nature of transboundary legislation, as highlighted by Interviewee (12), can significantly hinder the EOL process. Interviewee (12) notes that obtaining necessary permissions for blade transport can take 5-8 weeks, further complicating recycling.

Finally, Interviewee (12) points out the regulatory challenges in standardization within waste codes. Currently, there are no specific waste codes for different composite materials, leading to uncertainty about their disposal destinations. Moreover, regulations governing cross-border movements vary between countries, adding further complexity to recycling efforts. In some cases, waste must be transported to countries with suitable recycling technology, requiring additional administrative procedures. Achieving unified waste codes and harmonized cross-border movements for composite materials would greatly streamline the transportation pathways for wind blade recycling. Such regulatory improvements are essential to overcome the hindrances in the recycling process.

CURRENT EFFORTS

In discussions surrounding sustainability reporting and emerging ESG frameworks, the Corporate Sustainability Reporting Directive (CSRD) was highlighted. Interviewee (6) stressed the importance of this comprehensive regulation, which requires companies to regularly disclose their circularity initiatives. The regulation, supported by the European Sustainability Reporting Standards (ESRS) E5 on Resource Use and Circular Economy, mandates the disclosure of circularity policies and strategies to integrate circular thinking into projects, initially focusing on qualitative aspects. Additionally, companies must disclose circularity targets, including EOL waste management and the use of recycled materials, evidencing a shift in reporting practices. Furthermore, the directive emphasizes transparency in material usage, requiring companies to report annually on the quantity of recycled materials utilized across various categories such as scrap steel, recycled copper, and glass fibre.

The interviewee discussed the potential impact of CBAM (Carbon Border Adjustment Mechanism) or carbon taxing on promoting circular practices within the industry. These mechanisms would impose taxes on products and activities, including those in wind operations, creating incentives for companies to reduce their carbon footprint. This reduction could indirectly encourage circular practices in the industry, as companies may compete to design solutions with the lowest carbon footprint. Projects with lower environmental impacts receive additional recognition in auctions, indirectly promoting circular practices, particularly in blade design and material selection. Additionally, there is a growing trend within the industry to give Life Cycle Assessments (LCAs) a more significant role in decision-making processes regarding wind farms.

Additionally, interviewee (3) mentions that while strong circularity policies may not yet be firmly established, the impetus comes from broader targets set by entities like the EU and local governments. These targets aim for a full CE by 2050, with specific milestones, such as material recovery targets, to be achieved by 2030. Fulfilling these targets is imperative for the wind sector to align with broader environmental objectives. Failure to prioritize circularity in projects can jeopardize a developer's ability to secure bids and operate wind farm sites. Thus, the importance to address circularity is not just about compliance but also about ensuring the viability and longevity of the business. In this sense complying with the auctions and bids is important and it is also crucial to set of viable proposals as it will be supervised by the government throughout the operation of the wind park.

Finally, Interviewee (5) mentions the Net Zero Industry Act, which aims to accelerate the adoption of clean technologies across the EU. This legislation is expected to attract investment and improve market conditions for clean tech (European Commission, 2023). Notably, the implementation of net zero technologies often involves considerations of product design, which can inherently contribute to circularity. It's emphasized that introducing criteria under this Act should be done with careful consideration of cost implications, rather than expecting industries to absorb them without adjusting their business strategies. This example illustrates the interconnectedness of legislation, economic incentives, and their significant impact on the output and profitability of businesses, such as wind turbine parks.

4.2 Product-as-a-Service in the Market

In the upcoming section, the findings from the 13 interviews concerning the concept of PaaS in the wind turbine sector and its market implications will be presented. Given the absence of existing literature on this subject and its emerging nature, these results are drawn from the diverse perspectives and hypothetical scenarios provided by the interviewees. They shared insights into the advantages and drawbacks of implementing a PaaS model in the market.

Furthermore, some interviewees offered their thoughts on what the ideal model would entail, particularly within the context of wind turbines. To structure the discussion effectively, the section will be segmented according to stakeholder categories, including OEMs, Wind Operators, and Recycling Facilities.

4.2.1 OEMs

Interviewee (1) addresses an important issue concerning the viability of customer interest in such a service. However, economics is one of the highlights in this intervention. Under the current model, wind farms pay recycling companies to handle decommissioned materials, fostering competition among recycling facilities. For a revised model where wind producers bear the responsibility, they would need to compensate wind farms accordingly, potentially outbidding recycling facilities. While feasible through additional negotiations, this proposition presents a formidable challenge.

The perspective of Interviewee (2) on a rental model is favourable. However, the typical lifespan of a wind blade aligns with that of the entire turbine. Therefore, renting the entire turbine while offering associated services appears to be the most suitable approach. Renting the turbine is already a feasible option, particularly with existing services such as maintenance offered by OEMs throughout the turbine's lifespan.

However, the viability of this rental model will highly depend on materials that can be reincorporated into a new blade without concerns about fatigue levels. Primarily, materials such as glass fibres and carbon fibres lose a significant portion of their properties over time, especially considering the substantial fatigue load experienced by wind turbines. While renting the turbine may alter the business model, enabling OEMs to better monitor their turbines and explore various solutions, the current design does not offer value in returning the turbine to the OEM after use. Instead, direct recycling at a facility would be the preferred course of action.

Interviewee (13) noted that certain elements of the proposed model are highly valuable and suggested that some aspects are already integrated into the wind industry. Interviewee explained that a traditional PaaS model involves leasing hardware while ownership remains with the producer to ensure its upkeep. However, they highlighted that this approach may not be suitable for industries like wind turbines, which involve significant financing needs, often amounting to billions of euros per project. The interviewee emphasized the challenge of financing entire wind turbine projects independently due to the immense capital requirements and the need for extensive bank guarantees. They doubted that any company could provide the level of bank guarantees required for such projects.

Instead, the interviewee described their company's approach, which involves selling the turbine and offering a performance contract. Under this model, the turbine owner signs a service agreement with the company, guaranteeing a certain level of performance. While ownership of the turbine is transferred to the owner, the company ensures a specified level of availability over a set period. Also explained that if the turbine's performance falls below the agreed level, the company incurs a penalty fee payable to the owner. Conversely, if the turbine exceeds the agreed performance level, both parties share in the additional revenue generated.

The interviewee highlighted the economic incentive for the service provider to surpass the agreed performance standards, as it leads to shared revenue and enhances their reputation. They emphasized that while ownership of the turbine shifts to the owner, the service model aligns with the broader principles of the PaaS model and that by incurring in a better collaboration this can be upgraded to eventually be called PaaS model in the product-oriented category.

4.2.2 Wind Operators

Interviewee (3) recognizes the sustainability advantages of the PaaS model but also highlights various barriers in this specific market, particularly economic concerns. Renting a turbine, for instance, could require spreading the investment over an extended period, potentially affecting liquidity due to annual rental payments. This liquidity reduction might present challenges for developers, especially if revenue from electricity sales is insufficient to offset rental costs. The interviewee suggests that the success of turbine rental arrangements depends on the specific contractual terms and structures, which may require adjustments for optimization.

Shifting the focus to asset management, Interviewee (6) discusses the scenario when turbines reach the end of their operational life. While it is commonly assumed that decommissioned assets will be recycled, the interviewee proposes another option: selling decommissioned turbines and their parts in a second-hand market. This raises questions about the value of these components and implications for the owning companies. Depending on how these components are managed, their value and the company's interest in new business models like PaaS could fluctuate. However, as highlighted by Interviewee (4), the likelihood of this scenario is low. Current wind turbines expected to be decommissioned in 2030 are in poor condition, making them unlikely to fetch high prices in a second-hand market. Moreover, placing the responsibility solely on the producer is challenging, given uncertainties about the longevity of companies in the market and potential transitions in ownership.

Further scepticism about PaaS implementation comes from Interviewee (5). From a financial perspective, selling turbines and recovering materials directly may yield greater economic benefits than leasing them out. This approach resonates with companies aiming to maximize profits and streamline operations in the evolving wind energy market. Additionally, Interviewee (5) points out that when purchasing a turbine, warranties provided are typically relatively short. Consequently, OEMs would need to manage various risks, including responsibility for decommissioning or handling the turbine once its operational life ends.

Uncertainty and risk surround factors such as turbine lifespan and market conditions, complicating the establishment of new departments or lines of work to implement PaaS models. This undertaking would involve significant costs and risks, particularly considering cost considerations. Interviewee (5) suggests that the leasing price of turbine components may need to exceed the acquisition cost, potentially rendering the PaaS model economically unviable.

This preference for a product-oriented model over a rental or use-oriented model by OEMs is further explained by concerns raised by Interviewee (3) regarding potential conflicts of interest in turbine rental agreements. These agreements, where operators rent turbines instead of owning them outright, often result in conflicting priorities between operators and OEMs. While OEMs may prioritize turbine longevity to ensure their turbines remain intact over their lifespan, operators may prioritize profit maximization, potentially compromising long-term functionality. This disparity highlights a conflict of interest between turbine renters and owners, particularly concerning EOL considerations.

In discussions with the interviewees, a recurring topic was the relationship between Extended Producer Responsibility (EPR) and the PaaS model. However, interviewee (6) highlighted that EPR, and the PaaS model differ fundamentally in their approach to addressing environmental challenges in the industry. EPR, characterized by external stakeholders dictating producer responsibilities through regulation, is perceived as a regulatory control imposed on the industry to manage its challenges. In contrast, the PaaS model represents a proactive approach by the industry itself, where businesses take the lead in addressing environmental issues. While EPR mandates responsibility through regulation, PaaS encourages industry-driven solutions without relying on external mandates. Therefore, Interviewee (6) views these approaches as stemming from different decision-making points, with EPR being regulatory-driven and PaaS being more business model-driven. This differentiation is crucial, as later in the discussion, Interviewee (5) mentions the potential support that EPR legislation could provide to the PaaS model.

Interviewee (5) suggests that implementing EPR to certain levels could drive OEMs and manufacturers to accelerate the transition towards sustainable practices in the wind energy industry. Specifically, regarding PaaS, EPR would establish a legal framework facilitating the adoption of the PaaS model throughout the industry. In this context, Interviewee (5) discusses EPR and PaaS within a product-oriented model. Under this model, EPR would entail dual responsibilities for both operators and OEMs. OEMs would be responsible for designing products that are easily recyclable and ensuring their longevity through mandatory service and maintenance contracts. Operators, on the other hand, would play a role in ensuring proper decommissioning. This division of responsibilities illustrates how EPR addresses legal aspects, while PaaS addresses industrial considerations, as highlighted by Interviewee (6).

4.2.3 Recycling Facilities

Interviewee (9) provides insight into the importance of NDAs in standardizing processes for implementing PaaS models. Specifically, during the development and implementation phases, it is crucial for companies to have clarity about their network of NDAs. If any contractor or supplier lacks this information, it can hinder the effectiveness of the model. Additionally, the long lifespan of turbines poses uncertainties. For instance, will all the companies involved in the agreement still be operational 30 years down the line? While collaboration is essential, transferring information in the event of a company closure or bankruptcy is not straightforward. Consequently, NDAs must encompass multiple recycling companies, OEMs, and wind farms. However, achieving this is challenging due to competition, as many companies are reluctant to share information with their rivals.

Interviewee (8) mentions the after-product value in the components as stated before is important and this is why PaaS model is seen by recycling facilities as a non-viable economic business model for them. They want to have ownership of the product because then they recycle it to a higher value material and then they sell it again to a market. Even in the perception of PaaS where the recycling facility would sign a NDA with the producer for making the service of recycling and then giving back the product to the producer is not economically feasible as there is a lot of secondary markets present, and this option would significantly reduce the amount of revenue of recycling companies even if the producer pays a high amount to have the parts back.

With interviewee (10) The discussion explored how companies in the wind industry typically take a cautious approach, and how PaaS might fit into this context. The conversation highlighted major producers (OEMs) considering strategies to recover materials from their products. These companies have extensive global networks for material procurement, which could aid in their transition to becoming recyclers or having very strong relations with recycling companies. However, this shift presents challenges, particularly in managing waste materials due to strict global regulations. Recyclers play a crucial role in ensuring compliance with waste management rules, including those related to contamination and hazardous materials. This is a very big challenge for the model as adapting to the different regulations based on waste management and national and international movement would be difficult.

The conversation also touched on the ownership of materials. Currently, recyclers are responsible for owning materials after they have been decommissioned, but apparently, OEMs might potentially consider reclaiming ownership (with the example of Vestas partnership with

Stena Metall for solvolysis). This raises questions about potentially whether companies OEMs are willing to bear the risks associated with owning their materials. As a result, there is uncertainty within the wind turbine industry about which entities should take ownership to fully implement the PaaS system.

Interviewee (11) outlines what appears to be an "ideal" PaaS model in this context. This model entails the involvement of various stakeholders in distinct capacities. During the implementation phase, stakeholders are required to sign an NDA, by an agreement between OEM, operator, and the recycling Company. This NDA ensures the confidentiality of proprietary information shared among these entities throughout the process. The selection of transportation companies and other subcontractors is also determined collaboratively among these parties. The operator assumes a significant role in monitoring the status and capacity of wind blades, with the aim of facilitating their return to the OEM for potential incorporation into subsequent batches of wind turbines, possibly at reduced rental rates owing to their prior usage. The use of a material passport is advocated to track the composition of the blade, including the proportion of recycled and virgin materials. Once monitoring is completed satisfactorily, the OEM and the operator can determine whether the OEM will claim the blade for remanufacturing or if it should be redirected to the recycling Company for integration into the construction sector. Additionally, the availability of an inspection centre near the wind farm is deemed essential for addressing operational issues effectively. Also highlighted by interviewee (12) Ideally, in a PaaS model, efficient storage and proximity to the turbines are essential for ensuring spare parts are readily available. However, in practice, when the entire turbine is decommissioned and given a second life, the blade is included in this process, reducing the need for additional spare blade parts. It is really important as of now the model only considers the entire turbine. The spare parts do not have a high market demand.

5 Discussion

In chapter four of the thesis, various results pertaining to research questions RQ1 and RQ2 were presented, incorporating insights from diverse practitioners in the field of circularity in wind turbines, particularly focusing on turbine blades. Regarding RQ1, which examines the main barriers to implementing a more circular EOL model for wind turbine blades, four categories were evaluated within a broader and more holistic context. This framework's applicability to the initial question can now be explored in the subsequent discussion section, Chapter 5. In regard to RQ2, which investigates practitioner's perceptions of the application of the PaaS model in the wind turbine industry, multiple author's perspectives were analysed. In the ensuing discussion section, Chapter 5, a deeper examination of the relationship between these perspectives and the framework provided by Beuren et al. (2017) will be conducted to assess how PaaS is already present in the market.

5.1 Discussions in Research Question Context

RQ1: What are the main barriers for a more circular end of life model of the wind turbine blades?

A significant contribution of this study lies in its practical insights by the practitioners interviewed, which uncovered barriers not previously identified in the literature. One example of these practical barriers is the limited decommissioning of offshore wind turbines. This has led the wind energy industry to perceive recycling as still in an "immature" stage, particularly in the recycling experience rather than production. This insight was provided by a recycling facility interviewee, who compared the historical journey of steel recycling to that of composite materials recycling. However, this immature stage may also create opportunities in the market for numerous collaborations between allies and competitors seeking better practices. Another example of a practical barrier is the auctions process, which receives less attention in literature reviews but is widely discussed in other communication channels such as Wind Europe. Sharing practical barriers in policy, collaboration, economy, and infrastructure/product feature settings and associating them with a common practical process like auctions broadens the scope for more insights and practical investigations. Aside of the practical barriers the discussion for RQ1 addresses the barriers seen in the results with the help of the framework inspired by (Suárez-Eiroa et al., 2019).

The framework initially identifies education and product design as the holistic or transversal components. However, it is crucial to note that the framework is designed for general application in CE and does not specifically address wind turbine blades. Contrary to this framework, the research findings reveal that economy and collaboration play more important transversal roles, displacing design, and education.

Education and product design, originally considered transversal aspects, are inherently intertwined with collaboration and economic. However, in the case of product design is deeply addressed in infrastructure / product features. Given the current market conditions and the challenges in designing products for better EOL management, stakeholders must propose and educate with economic arguments to effectively address product design issues, especially regarding wind turbine blades.

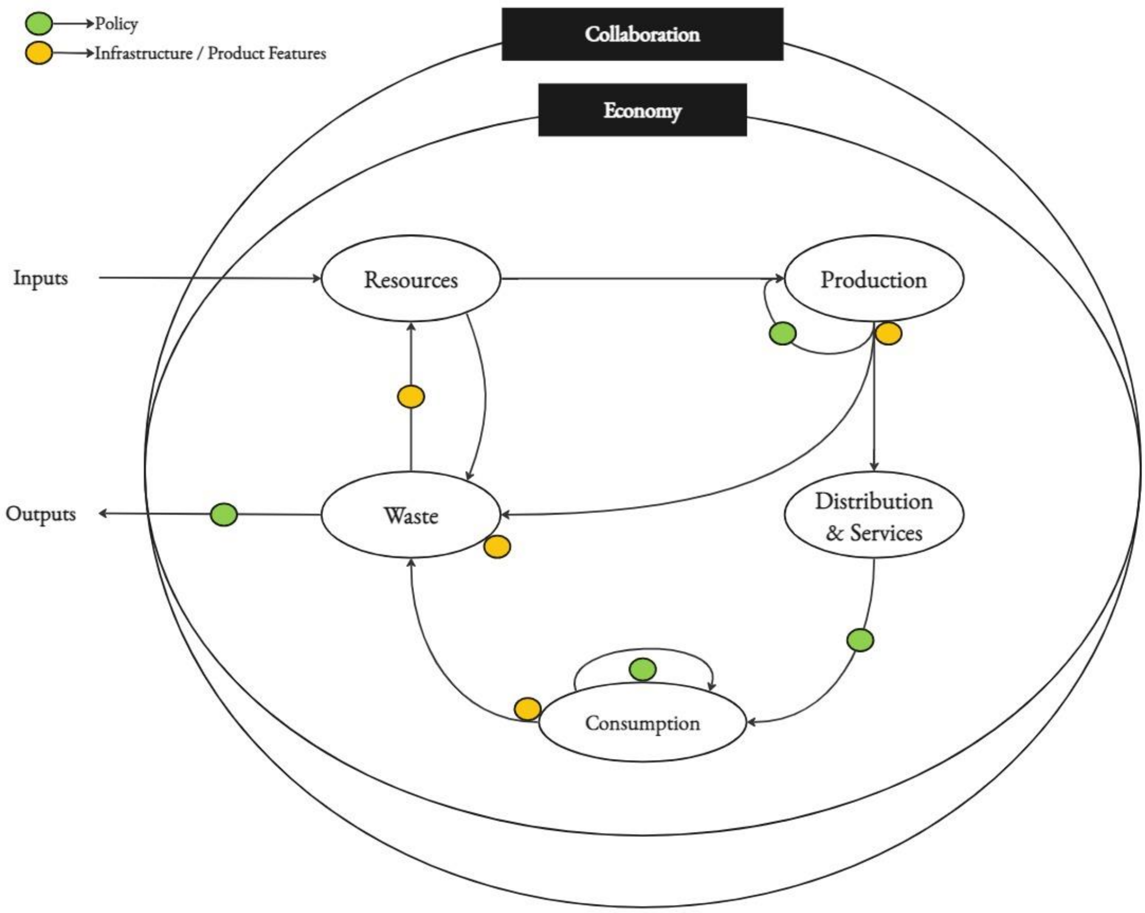
It is also important to note that collaboration and economy have replaced education and design because they are inherently linked to every aspect of the examined barriers and drivers identified in the results. This relationship is one-way as collaboration and economy influence all aspects, while the reverse is not observed.

Starting with the broader perspective, collaboration takes precedence over economic considerations. This is exemplified by one of the key economic findings in the wind turbine industry, highlighted in the results, which concerns market maturity issues. A mature market requires competition, the presence of buyers and sellers, among other factors, all of which are facilitated by collaboration. Without collaboration, economic market maturity cannot be achieved. Since economic considerations take a higher position even over policy and infrastructure/product features, collaboration naturally undertakes both of these.

Following collaboration, the economic setting is emphasized. Practitioners noted that EOL initiatives in the wind turbine market are primarily driven by industry rather than policy interventions. For instance, the results discuss Decomblades, an initiative initiated by various market competitors, rather than by governmental policies or movements aimed at EOL blade management. Furthermore, infrastructure/product features are intertwined with economic barriers and drivers. The implementation of infrastructure, such as the construction of new recycling facilities, is directly tied to economic considerations, as the costs associated with such endeavours are significant. Therefore, infrastructure/product features are inherently embedded within economic constraints.

Considering this, adjustments to the CE model for the wind turbine market are proposed in terms of transversality and the approach to education and design. The proposed model is as follows.

Figure 5 Adapted CE Framework.



Source: Suárez-Eiroa et al., (2019).

The outlined model integrates the previously mentioned key elements of collaboration and economy as overarching themes instead of product design and education. Additionally, it includes a green label for policy/legislations and a yellow label for infrastructure/product features. These labels were assigned based on the interview's identification of critical aspects however, as less transversal within the CE of wind blades. As a result, they are scoped into different stages of the CE, denoted by the green and yellow labels.

In terms of legislation (green label), the established framework begins with "Production," where policy primarily addresses consumer concerns on design standards, translating into production issues. The green label is placed in this specific place to highlight how policy and legislative work must drive the design and reincorporation of materials into production schemes. Moreover, this bubble represents and invitation to other initiatives like Decomblades which was industry driven but instead to be policy driven to reincorporate standardization concepts such as material passport in other production aspects.

Moving on to distribution and services, the green label is positioned between the "Distribution and Services" bubble and the "Consumption" bubble. This placement signifies government action and policy-driven incentives aimed at establishing stronger auction criteria in bids, resulting in a more environmentally competitive setting.

Within the "Consumption" bubble, a green label signifies the potential for policies to drive the reuse of components within the same wind farm. Currently, according to interviewees, turbine decommissioning entails dismantling all parts. Policies promoting component reuse and implement a new strategy for wind blade repowering, are essential for the development of more sustainable strategies.

Regarding waste outputs, the green label is placed between the "Waste" bubble and the outputs label, highlighting the push for a complete landfill ban from all industry stakeholders. Other policies, such as standardizing waste codes for blades on an international level, as suggested by some practitioners, could facilitate international common end-of-life coding.

Infrastructure and product features are denoted with a yellow label within the "Production" bubble of the framework. Product design, originally part of the holistic aspect in Suárez's framework, is now categorized as scoped based on interview feedback. Advances in recycling technologies, such as pyrolysis and chemical solvolysis, have made recycling complex designs with composite materials feasible, leading to this reclassification. The yellow label suggests that increased investment in infrastructure to update blade product features or design can aid the transition, particularly in EOL management.

Continuing into the "Consumption" bubble on the left side, a yellow label is assigned due to challenges in infrastructure and product features that require highly localized life extension techniques for a smoother transition. Interviewees stressed the importance of addressing this specific barrier, as repowering the turbine too soon could generate more waste material than what would naturally enter the waste stream. Additionally, repowering plays a crucial role, as these findings corroborate the literature review's mention of virtually non-existent or very limited-scale repowering techniques dedicated to wind turbine blades (Kramer & Beauson, 2023b) & (Sun et al., 2022).

Moving on, the next yellow label is on the "Waste" bubble. The establishment of more separation and distribution centres is deemed necessary for improved waste management during the anticipated significant decommissioning in 2030 according to interviewees. Literature review specifically (Sommer et al., 2020) states the fact that there is an anticipation of 35 - 58 million metric tonnes of waste by 2030 which would need to be handled. Infrastructure setting will here be important as some interviewees stated that there are going to be factories that withstand a volume of 30.000-35.000 tons of blade waste per year, however, is not going to be enough for the previously stated amount meaning that current practitioners in the recycling facility area are underestimating the quantities of the next big decommissioning.

The next yellow label located in between the "Waste" Bubble and the "Resources" bubble, this one suggests that implementing a careful look in the quality control of the fibres, more sub products can be created out of the next big decommissioning that is happening in 2030. It is emphasised by interviewees that it is important to tackle this specific barrier as imperfect quality control technologies can result in using less fibres after being recycled by thermal or chemical processes, thus more facilities and experts regarding this matter are mentioned to be necessary.

Finally, this framework transversality was chosen as it addresses the following statement: "Education, debate, and public participation represent examples of incorporating diverse social values, which are reflected in various policy approaches aimed at shaping societal change." This argument, drawn from chapter 2 literature review, finds support in the results. Although wind blades differ from typical consumer products and do not require source separation, education, debate, and public participation are integral to the auction process. Improved education from OEMs to wind operators could potentially extend the turbine's lifespan, as current operators endeavour to maximise its functionality to enhance output. Furthermore, debates occur in various committees such as Wind Europe, where diverse solutions are collectively discussed from different perspectives, with public participation playing a key role in these discussions.

RQ2: What are the different practitioner's perceptions towards the application of the Product-as-a-service (PaaS) model in the wind turbine industry?

Initially, the study aimed to validate the PaaS model by exploring the possibility of renting or leasing only the wind turbine blades. However, feedback from practitioners prompted a significant shift in focus towards renting or leasing the entire turbines, thus altering the trajectory of the study. This shift was influenced by insights from both practitioner feedback and certain aspects highlighted in the literature review.

For instance, while the initial focus was on blade rentals or leases, exploration in the literature review by Sun et al. revealed the concept of lifetime extension. This practice is still in development particularly concerning wind turbine blades. Instead, there is repowering or partial repowering which involves upgrading specific components of the turbine or/and replacing the entire unit. However, given the advancements in this area and the complexity of wind turbine systems, the study broadened its scope to consider the rental or leasing of complete turbines instead of solely focusing on blades.

When examining perceptions of the PaaS model, the study has revealed both positive and negative viewpoints from stakeholders. It is worth noting that the study focused on two specific approaches to PaaS: product-oriented service and use-oriented service as within the practitioners result oriented was discarded immediately. Among these, the product-oriented approach received favourable opinions, as it aligns with existing industry practices such as service contracts provided by OEMs. Additionally, producers (OEMs) see advantages in continuing to sell their product (wind turbine) in the product-oriented model, and consumers & recycling facilities value the service guarantees and ownership retention. However, this favourability could change if take-back programs were implemented instead of mandatory service contracts. Such programs would increase the burden of product retrieval, impacting recycling facilities directly as they would face economic repercussions, unable to profit to the same extent as before.

The use-oriented approach receives unfavourable views from OEMs, wind operators, and recycling facilities, with recycling facilities expressing stronger concerns compared to the other stakeholders. Recycling facilities prefer full ownership of the product to maximise their economic benefits. This contrasts with the gradual nature of use-oriented PaaS models, where products are rented rather than owned outright. Under this model, if OEMs retain ownership and then lease turbines to wind operators, the OEMs will likely prioritize reclaiming the turbines instead of initially sending them to a recycling facility because of the potential takeback programs. The adoption of a model incorporating takeback options presents challenges for OEMs, wind operators, and recycling facilities. One significant barrier is the lack of clarity surrounding interventions required for successful implementation. However, stakeholders are advocating for product redesign as a crucial step in integrating takeback options into the existing framework.

This process, however, is not immediate. It involves various considerations, including setting appropriate prices for products, services and resource material, redesigning products to facilitate takeback, and providing sufficient incentives or guarantees for recycling facilities. Each of these steps requires careful planning and coordination among the involved stakeholders.

When addressing the framework proposed by Beuren. (2017), the scope of the discussion centres upon the development, implementation, and monitoring phases of the framework (See chapter 2.1.4). It becomes evident based on the results that all phases, which encompasses the wind turbine product, aligns with various key conceptual elements outlined in the literature review (section 2.1.4). However, other elements are missing, contributing to barriers perceived by different stakeholders. The following tables, adapted from (Beuren et al., 2017), summarize the conceptual elements of these phases that are present. These drive or hinder the execution of a potential PaaS model.

Table 10 Development Phase with Wind Blade Application.

Development Phase		
PaaS Element	**Conceptual Elements**	**Positive and Negative Elements Associated in the Wind Market**
PRODUCT	Design product components for extended life	Components from the tower are recyclable and blades are in the process of incorporating more sustainable approaches. This process is still in a very small scale and involves projects like recyclable blade or recycling epoxy technology.
	Design safe products	Currently as big offshore decommissions have not happened is hard to state the fatality rate in a big offshore project decommissioning.
	Plan for reuse and for EOL	Reuse on the tower components but not on blades. The EOL of these still has landfill as an option. Repurposing is there with projects like Vattenfall parking building.

	Design for facilitation in operation and easy access to components	Material can be disassembled; exception are the blades which are very complex and currently can be separated by grinding it.
	Durability and standardization	Product is strong and suitable for long periods of use as lifespan is 25 to 30 years.
SERVICE	Design services to ensure safety in product	During use the product is safe, decommissioning big batches of wind turbines is an upcoming variable.
	Support service for consumers locally with appropriate service networks	OEMs currently have offerings of services, but their reach is not 100%. Windfarms take the offering for the first 2-3 years and then prefer to change the service contracts of the product
	Design service	Product and design are developed in such a way that OEMs can do repair, consultancy, and maintenance
NETWORK OF ACTORS	Plan the monitoring of the product	Monitoring is currently done by the operator; they maximise the results by sometimes compromising the lifespan
	Plan an interface between the partnerships in the model	There is a strong communication in between partners and even competitors however it is not clear if there is a specific interface to do so
	Plan the technical services (near the consumer)	Tech services are present, it is not clear if they are close to the offshore farm
	Plan the qualification of operators	Auctions are strict and operators that get the contracts undergo bid competition before
	Government incentives	There are few incentives to implement PaaS. An example out of many is CSRD with the ESRS E5 framework with circular KPIs and soon potential landfill ban.
	Consumer and other stakeholder participation	The perfect example is Decomblades as participation in trying a more circular approach. But not specific participation in PaaS.
INFRASTRUCTURE	Plan of the infrastructure	Practitioner's practical perceptions lack clarity regarding infrastructure connections and planning. While quality control centres, recycling facilities, distribution centres, and supplier support exist, the broader supply chain is not thoroughly detailed within the scope
	design a communication system between those involved in the business	There is a strong communication in between partners and even competitors

		however it is not clear if there is a specific interface to do so
	Plan the distribution chain	N. A
	Plan PaaS in accordance with local culture	N. A

Source: Adapted from Beuren et al (2017).

Table 11 Implementation Phase with Wind blade Application.

Implementation Phase	
Conceptual Elements	**Positive and Negative Elements Associated in the Wind Market**
Testing the product	Wind blades are already very advance tech equipment that undergo various tests before launching in the market.
Delivery	The package of product and service is already being delivered as service contracts within the wind industry.
Guidance for PaaS Use	Operators prioritise energy output over product durability, the current situation does not allow for the consumers to be more receptive towards producer's potential approach on product operation to make the turbine lifespan longer.

Source: Adapted from Beuren et al (2017).

Table 12 Monitoring Phase with Wind blade Application.

Monitoring Phase	
Conceptual Elements	**Positive and Negative Elements Associated in the Wind Market**
PaaS monitoring during use phase	The operator does the monitoring of the wind turbine. In this case, producers should be able to access the information of performance of the wind turbine. This includes the maintenance, and service if already provided and ensure it is working the most appropriate way possible through its lifespan.
Service delivery monitoring	
Knowledge accumulation regarding PaaS (use phase)	Not enough information (Cost effective & quality assessment).
Feedback on consumer expectations	Communication in between stakeholders is good, feedback on the different topics is provided already but the detail of this information is unclear.

Source: Adapted from Beuren et al (2017).

5.2 Limitations

Due to the new nature of the topic, the researchers encountered several challenges in effectively questioning the various stakeholders involved. As the subject matter is grounded in a constructivist worldview (See chapter 3.1), there is a need for more precise business cases to quantify many of the barriers and drivers highlighted in the results, particularly within the realm of PaaS, which has not yet been implemented in this market. Although some attributes related to PaaS exist, the absence of a fully developed model requires stakeholders to make assumptions about its functionality in this specific context. This necessity for clearer business cases became apparent during the literature review process, as the study had to rely on theoretical models to formulate relevant questions and subsequently present the findings to address the research questions.

Furthermore, this study not only identifies new practical barriers and drivers in the CE of wind turbine blades but also represents an initial step towards the potential adoption of PaaS in the wind energy sector. However, access to recycling facilities directly associated with wind blades was limited, leading to interview findings primarily focusing on broader CE challenges rather than specific blade recycling issues. The study involved 13 interviewees, although ideally, there would have been 15 representatives, including OEMs, wind operators, and recycling facilities, to ensure a more balanced representation of stakeholders.

One of the most significant limitations lies in the absence of a fully established PaaS model within the industry. While the study acknowledges similarities between existing approaches and the PaaS concept, it emphasizes the need for a more comprehensive framework to categorize these approaches accurately. Moreover, the research solely concentrated on offshore wind turbine farms, potentially overlooking valuable insights from onshore farms regarding the feasibility of implementing PaaS models.

To enhance the study, future research could focus on incorporating quantitative methodologies to analyse stakeholder's perceptions systematically. By quantifying the most prevalent barriers perceived by stakeholders and conducting a numerical analysis, researchers could provide additional insights into the feasibility and potential challenges associated with implementing PaaS in the wind energy sector.

6 Conclusions

Given the relatively new nature of the topic, the research encountered several challenges in effectively engaging the various stakeholders involved. As of 2023, renewable energy sources contribute to approximately 41% of the EU's electricity mix, with wind power representing about 37.5% of renewable electricity generation, followed by hydropower at 29.9%, and solar power at 18.2% (Eurostat, 2024).

These trends highlight the importance of ongoing projects supporting all stages of implementation, development, and, notably, EOL management of RE technologies. Given this continued growth, current efforts in CE, particularly regarding wind turbine blades, must yield positive outcomes sooner rather than later, necessitating collaborative efforts between industry and government. Although more work is required, progress is expected to accelerate as the industry matures.

The resources available for this thesis, along with insights gleaned from 13 interviewees, facilitated a deeper exploration of the practical barrier's stakeholders face concerning blade EOL management towards a more CE. It is imperative that all stakeholders recognise the existing blade-related challenges and work towards mitigating them to avoid burdening future generations.

Based on the various results presented and further discussion guided by the example of a CE framework, it can be concluded that the essential points or barriers that must be overcome first are the barriers of collaboration and economic barriers. As described in Section 5, these two characteristics play the most transversal or holistic role in the wind energy market and its CE In the specific case of blades, this industry has shown that, in the world of circularity, it has been guided or established more formally through collaboration initiatives among competitors and allies, leaving behind initiatives of policy makers such as the forthcoming landfill ban and secondary factors of infrastructure and product features such as product design. Note that this are still important, but they were mentioned as more localised and less holistically necessary as for example without the landfill ban most of the industry is already driven by their economic and collaboration capacity.

PaaS is a model that is really good for a product that already meets its characteristics and that can be viable for structures not as large as the complete wind turbine. In the case of the complete wind turbine, it is concluded that the product-oriented model is the most viable if service contracts offered by OEMs are more intensely regulated and economic compensation to recycling facilities for participating in possible take-back programs developed during the execution of the model is balanced. On the other hand, it is concluded that the use-oriented model is completely discarded for the entire turbine or for the blades. Within the results, it is mentioned that this model, which is related to leasing, could work if the individual product were smaller in size, examples such as permanent magnets could be a specific example in which the PaaS model could potentially work.

6.1 Practical Implications and Recommendations

This project has shed light on various barriers based on the diverse perspectives of stakeholders concerning EOL and CE of turbine blades, addressing four crucial concepts: economic, infrastructure/product features, collaboration, and legislation. Given the necessity of multiple stakeholders to identify barriers comprehensively, the study focused on three organizations (OEMs, wind operators, and recycling facilities) to uncover unwritten barriers not documented in previous academic journals. This study highlights the need for increased collaboration among stakeholders, including government involvement, to enhance output and economic incentives, as the current situation presents challenges.

Initially, this thesis addresses these challenges in general before underlining a more concrete CE model, namely PaaS. Providing a general perspective before addressing a specific model allows readers to gain insight into the current situation and increases the likelihood of taking specific actions in the future. While the results of this study reveal barriers, they also demonstrate stakeholder's willingness to seek solutions. These findings support a future where these four aspects are more considered in CE implementation. The transition may be slow, potentially causing market imbalances if most of these concepts are applied to the current blade design. Therefore, producers and other stakeholders must define a unified criterion to ensure uniform component management across all parties and inform Europe of various processes and strategies.

To potentially implement CE models effectively and impact EOL management, the active participation of different actors is necessary, along with collaborative efforts and standardized laws. Creating communication channels/platforms among stakeholders encourages joint decision-making, as demonstrated by projects like Decomblades, which left a significant legacy in the industry. Additionally, more time is required, particularly regarding market maturity and the economic impact of blade decommissioning on various stakeholders as resource price regulation in the future can be different. In the near future, the results of various blade recycling initiatives will become apparent, primarily in terms of revenue after recycling as a lot of wind blades will be soon decommissioned.

The government, specially policy makers should intervene more effectively in the points suggested in the results section, as outlined in the diagram adapted by (Suárez-Eiroa et al., 2019). Specifically, standardization of laws in transport and European waste codes, or at least evaluate the various options outlined in this thesis based on stakeholder's practical knowledge to derive policies that address their needs. Concerns regarding design for circularity are essential in infrastructure and product feature considerations for future efforts. Currently, companies are making significant efforts to create more affordable products with revenue generation, aided by various recycling facilities and government support. This collaboration in product design should extend not only to recycling facilities but also to operators, ensuring proper usage knowledge for similar durability and productive energy output when employing new design on these blades.

6.2 Further Research

As mentioned earlier, many stakeholders were omitted, such as suppliers or transportation companies hired to handle blade logistics services. It is valid and also very interesting to understand potential barriers to CE from the perspective of these actors. Additionally, PaaS is a CE model that should be explored more deeply, especially with upcoming decommissioning projects and with other parts of the wind turbines. This would necessitate even closer monitoring of materials, even if their design has been modified to be more recyclable in the future.

It is acknowledged that many changes are needed for the future, and among these changes, the concept of CE plays a crucial guiding role. Therefore, exploring other CE models in more detail is necessary to draw more conclusions and find more ways to address EOL in this market. However, the practical support for making these changes and addressing EOL issues comes from specific strategies, frameworks, or initiatives within the industry. Exploring additional models can broaden the range of solutions tailored to this sector's needs. Similarly, in the case of PaaS, exploring it with a narrower scope would be beneficial. Considering the framework proposed by Beuren in 2017, it becomes clear that, beyond the factors already covered in this study, there are further aspects which require deeper analysis, such as the essential requirements of PaaS, located before development, implementation and monitoring in the framework. Future research in this area holds significant promise, and it might be worthwhile to explore the possibility of shifting the focus to permanent magnets instead of wind turbine blades.

In future cases, having only a company's business case and being able to speak with multiple individuals within the company would be ideal. This approach would provide perspectives not only from engineers but also from other roles such as sales, logistics, and even systems for implementing various CE-related processes.

This thesis has aimed to explore the different challenges and opportunities regarding 4 different factors highlighting a wide range of possible deficiencies in which the industry can jump in and tackle various problems. However further studies should scope down even more and portray one factor instead of four and address this issue in the eyes of more stakeholders. As an example, addressing the economic barriers regarding market maturity and price regulation initiatives with OEMs, wind operators, suppliers, resource extraction companies, policy makers, etc.

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Appendix

GDPR Consent Form

The following consent form is to make sure you have been given the information about the investigation and to give you the opportunity to confirm that you are willing to take part in this investigation project. Please mark with an (X) which of the following prompts applies to you:

	I have been **familiarized with the investigation project**, I have had the possibility to ask questions and I have received answers to these questions.
	I have been informed the **existence of a recording device during the interview(s)** and I give my consent for the private use of the researcher.
	I have been informed my **participation is voluntary** and I am on my right to withdraw at any time.
	As a researcher I give my consent to be **disclosed anonymously in the investigation**, only being identified by my position title but not my name or the organisation.
	I have given permission so the **content of the voluntary interview can be transcribed, analysed, and published** as research results of the investigation
	I have given permission for **collected data to be stored on secured university servers** for 10 years, according to Lund University guidelines.

Note: Your voluntary participation in this study is acknowledged. As a participant in interviews, you retain the autonomy to refrain from responding to specific questions. You have the right to decline or discontinue your involvement in the interview process without providing a justification. Additionally, you may express the desire to keep specific materials confidential.

Throughout the research process, up until May 17, 2024, you, as a research participant, possess the right to access your personal data, seek correction or deletion of such data, or limit the processing of your data. Furthermore, you have the option to file a complaint concerning the utilization of your personal data.

Please sign below to confirm your consent:

	Participant(s)	**Researcher(s)**
Name(s) & Last Name		
Signature(s)		
Date(s)		

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