# Towards Sustainable End-Of-Life Resource Management In Offshore Wind:

# Developing a Digital Product Passport Enabling Circular Descision-Making

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MSc. Construction Management and Engineering

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# Towards Sustainable End-Of-Life Resource Management In Offshore Wind:

Developing a Digital Product Passport Enabling Circular Decision-Making

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# Preface

Research is often compared to a marathon, requiring endurance, patience, and a lot of energy drinks. But, unlike a marathon, where you know the finish line is 26.2 miles away, research has a way of moving the goalposts. It's a journey filled with unexpected twists, late nights, and the occasional existential crisis over whether your data makes any sense at all.

This thesis is the culmination of such a journey—a mixture of determination, curiosity, and, yes, moments of wondering why I ever thought it was a good idea to dive into the intricacies of circularity in offshore wind turbine components. But like any good journey, it's been one filled with learning, growth, and the occasional surprising discovery (and not just the discovery of how much coffee I can drink in one sitting).

As you delve into this work, I hope you find the balance between academic rigor and practical relevance that I aimed for. This research would not have been possible without the support and guidance of many individuals. My supervisors from TU Delft and my first supervisor, Jelle Joustra, thank you for your constant support and encouragement. I appreciate the time and effort you have put into helping me engage with colleagues doing similar research and industrial experts to conduct interviews. Daan Schraven, thank you for being critical of my research and guiding me throughout the master's journey. Magchiel van Os, thank you for being approachable in the initial stages and providing guidance on the topics, especially suggesting my graduation company ECHT regie in transitie. I am glad to have been around my colleagues at ECHT, and a special thanks to Floris van der Plas, Nina Vielen-Kallio, and Mathijs Hoogvliet, who provided invaluable insights and direction for my research and much-needed distraction and encouragement— thank you.

A special note of appreciation goes to my mom, dad, and brother, who has always been my unwavering support system. Your encouragement, love, and belief in me have been the foundation upon which this journey was built. And to my fiancée, whose patience, understanding, and reminders to take breaks have kept me grounded throughout this process—thank you for being my constant source of strength and joy.

Finally, I dedicate this work to all who are brave enough to take on the challenge of making our world more sustainable, one turbine at a time. Let's keep moving those goalposts in the right direction.

Enjoy Reading.

*Rushabh Mutha*
*Delft, August 2024*

# Executive Summary


The Dutch Government has raised the offshore wind energy target from 11GW to 21GW by 2030, approximately 50GW by 2040, and approximately 70GW by 2050 (Agency, 2021). The trade-off between achieving sustainable energy sources and extracting raw materials for constructing these infrastructures gives rise to the efforts to transition towards a circular economy. This transition offers solutions to several societal challenges, one of which is resource security (PBL, 2023). Further, academic research emphasizes the necessity of a circular mindset from the beginning of life to achieve a high level of circularity and economic benefits at the end of life (Hall, Topham, & João, 2022; P. D. Jensen, Purnell, & Velenturf, 2020). However, reusing the components and materials of decommissioned wind turbines can act as a driving force for the future requirement of raw materials (Demuytere et al., 2024). In this regard, implementing circular strategies for the existing offshore wind turbines plays a significant role in the energy transition as well as the aim of having a fully circular economy by 2050.

However, circular strategies have limited applicability higher up the R-Ladder in the offshore wind industry due to various technical, economic, regulatory, and environmental challenges. The focus within science and industry has been either on developing circular strategies for the beginning of life or recycling materials to limit future ecological impacts (Hall et al., 2022; P. D. Jensen et al., 2020). The need to address end-of-life resource management for the existing offshore wind turbines is emerging but still needs a systematic approach for sustainable end-of-life decision-making (Delaney et al., 2021; Jadali, Ioannou, & Kolios, 2021; Vielen-Kallio, van Diest, Room, & Knol, 2021; Windemer & Cowell, 2021). Hence, to address the identified gap, the research developed a comprehensive circular decision-making framework that leverages a standardized data management system, specifically a Digital Product Passport. To achieve this research objective, the main research question is framed as follows:

*"In what ways can a decision-making framework for a standardized data management system, specifically tailored for the end-of-life phase of OWTs, contribute to enhancing circular practices by efficient resource management within the industry?"*

## Research Method

This research used a qualitative design-thinking methodology, specifically the *"Double Diamond Method"*. The Double Diamond Method is a design thinking approach that emphasizes problem-solving through a process of divergence and convergence in two phases, focusing on understanding user needs and generating innovative solutions through iterative design and testing (Council, 2024).

The first diamond comprises the *Discovering* and the *Defining* stages. The discovery will focus on conducting a systematic literature review—scientific and grey literature—and semi-structured interviews to collect data on topics such as the circular economy, offshore wind turbines, challenges, digital product passports, etc., based on the sub-research questions. Further, the data is systematically analyzed to define the design requirements, in other words, explicitly defining the requirements for circular decision-making through a Digital Product Passport.

The second diamond includes the *Developing* and *Delivering* phases. A DPP structure tailored for the end-of-life of offshore wind turbines and a circular decision-making framework are developed. Next, both developments are combined in a comprehensive tool called the *"EcoRush DPP"*. In the delivery phase, the circular decision-making framework and the EcoRush DPP are tested and validated with experts from ECHT regie in transitie using three test cases. Finally, the feedback received in the validation will be considered to some lengths and within possible boundaries.

## Results

The results of the applied research methodology are twofold; the first part covers the literature review results and the semi-structured interviews. The second part covers the development of the EcoRush DPP.

*Circular Strategies*
The EoL phase presents critical opportunities for implementing circular strategies such as (1) *Re-certify*, (2) *Reuse*, (3) *Repair*, (4) *Refurbish*, (5) *Remanufacture*, (6) *Repurpose*, (7) *Recycle*, and (8) *Recover*; in the order of high to low level of circularity which maximize resource recovery and minimize environmental impact.

*Circular Strategy Assessment*
Six overarching assessment themes have been identified, which can be utilized in the decision-making and assessing the relevance of the circular strategies. These are: (1) *"Typology Assessment"*, (2) *"Condition Assessment"*, (3) *"Performance Assessment"*, (4) *"Compliance Assessment"*, (5) *"Economic Assessment"*, and (6) *"Environmental Assessment"*. Economic and Environmental Assessments, although a critical aspect of decision-making, are out of the scope of this research because of their dynamic nature.

*Key Parameters and Data Attributes*
Next, the key parameters were mapped against the data attributes that are either available in a DPP or need to be added to the structure of the Digital Product Passport tailored for the end-of-life of offshore wind turbines. The key parameters and their respective data attributes are: (1)*Visual Inspection*, requiring Inspection Reports and Condition at EoL; (2) *NDT*, requiring Structural Integrity data; (3) *Material Composition*, requiring Material List, Critical Raw Materials, SVHC, and Quantities; (4) *Material Health*, requiring Material Degradation; (5) *Current Performance*, requiring Operational Reports and Current Performance metrics; and (6) *Future Performance*, requiring Maintenance Reports, Service Frequency, RUL, and Future Performance projections.

*Circular Decision-Making Framework*
As illustrated below, the identified circular assessments and their respective parameters are integrated into a decision-making framework. The path of the decision-making is derived from literature and interview analysis. This circular decision-making framework is integrated into the EcoRush DPP. Eventually, the digital product passport acts as a standardized data management system, aiding in circular decision-making.

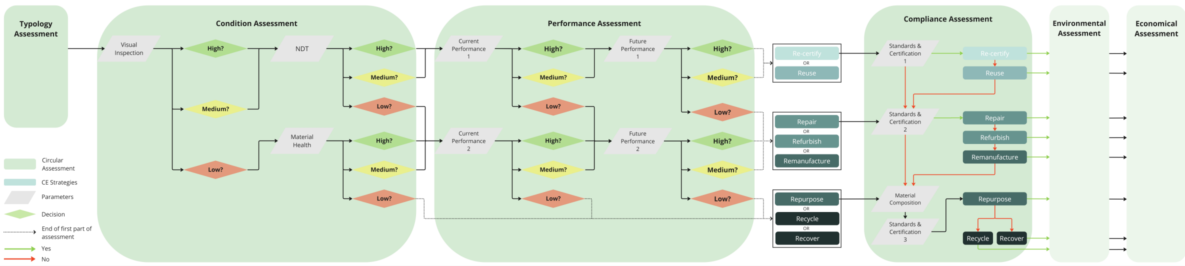


Figure 1: Circular decision-making framework.

*EcoRush DPP*
The image illustrated below is the standardized DPP structure for collecting data related to the EoL of an offshore wind turbine component. The data attributes in the DPP are divided into two categories: the mandatory data attributes necessary for EoL circular decision-making, and the second category has data attributes that add value to the component's second life.
The EcoRush tool aids decision-makers on the circularity aspect of a component based on the EoL data.

*EcoRush DPP Structure*

## Support Structure (SS001)

| | Data Attribute | Value | Unit |
|---|---|---|---|
| **(Required)** Key Parameters Circular Decision-Making | Size | | m(height) |
| | Weight | | kg |
| | Density | | kg/m3 |
| | Manufacturer | | Manufacturer |
| | Decommissioning Date | | Date |
| | Maintenance Records | | Documents |
| | Operational Records | | Documents |
| | Inspection Reports | | Documents |
| | Condition at EoL | | Visible wear & tear |
| | Structural Integrity | | High/Medium/Low |
| | Degradation Testing | | % of the component |
| | Use History/Current Age | | Year(s) |
| | Current Performance | | % Efficiency & reliability |
| | Servicing frequency | | Year(s) |
| | RUL | | Year(s) |
| | Future Performance | | % For ≥5 years. |
| **(Optional)** Material Properties | Bill of Materials | | Yes/No |
| | Material List | | Steel (tons) |
| | | | Concrete (tons) |
| | | | Rebar (tons) |
| | | | Coating (tons) |
| | | | Adhesives and Paint |
| | Recycled Materials | | Percentage (%) |
| | Critical Raw Materials | | Manganese (tons) |
| | | | Vanadium (tons) |
| | | | Nicke (tons) |
| | | | Chromium (tons) |
| | SVHC | | Cadmium (tons) |
| | | | Lead (tons) |
| | | | Arsenic (tons) |
| | | | Mercury (tons) |
| | Biodegradability | | Percentage (%) |
| | Combustible | | Percentage (%) |
| **(Optional)** Design & Production | GHG: Production Phase | | tons |
| | GHG: Transport | | tons |
| | GHG: Operational Phase | | tons |
| | GHG: Recycling | | tons |
| | Upgrade Potential | | Yes/No |
| | Design Flexibility | | Yes/No |
| | Disassembly Process | | Yes/No |
| | Ease of Disassembly | | High/Medium/Low |
| | Product Waranty/Certification | | Yes/No |
| | Environmental Regulations Compliance | | ISO 14001 |
| | LCA | | Yes/No |
| **(Optional)** EoL Data | Reusable Sub-Components | | Yes/No |
| | Residual Value | | € |
| | Incentives for Recovery | | Subsidies,etc |

| Company | Color-Code |
|---|---|
| North Sea Wind Ops | |
| Wind Maintenance Services Ltd. | |
| ECHT regie in transitie | |
| Vestas | |
| Green Supply Co. | |
| Wind Repair Solutions | |
| Remanufacture Renewables Ltd. | |
| Recycle Wind Resources | |

### Instructions

1. Ensure that all data entries are accurate and correspond to the specific parameters. Use the provided unit of measurement for consistency.
2. Regularly update the records/documents to reflect the latest inspections and servicing activities.
3. Use the color-coded system to identify the fields you are responsible for.
4. To navigate to a different system type or to navigate to a different component press the button System Overview or OWT001 respectively.
5. There is no data input in this sheet.
6. Review the data analysis in table Data Analysis.

## Data Analysis

| Parameter | Analysis |
|---|---|
| Visual Inspection | Inspection Report Missing |
| NDT | - |
| Material Health | - |
| Current Performance | Operational Report Missing |
| Future Performance | Maintenance Reports Missing |

## Circular Decision Making

| | |
|---|---|
| **Result** | **Necessary Reports Missing** |
| **Compliance Assessment** | |
| **Circular Strategy** | |

### Please Note

1. The circular strategie suggested above are based on the EoL data of the OWT. Further Environmental and Economic Assessment must be carried out.

## Reference to Value Ranges for Data Analysis

| Decision Making Parameters | Data Attribute | High | Medium | Low |
|---|---|---|---|---|
| Visual Inspection | Inspection Report | Yes | | No |
| | Condition at EoL | No visible damage/wear | Minor visible damage/wear | Significant visible damage/wear |
| NDT | Structural Integrity | No defects detected | Minor defects detected | Significant defects detected |
| Material Health | Degradation | <10% | 10-30% | >30% |
| Current Performance | Operational Records | Yes | | No |
| | Current Performance | 100-90% | 90-70% | <70% |
| Future Performance | Maintenance Records | Yes | | No |
| | Servicing Frequency | ≥2 | 1 | <1 |
| | RUL | ≥10 | 5-10 | <5 |
| | Future Performance | ≥80% | 80-50% | >50% |

*For further questions, scan the QR.*

OWT001

System Overview

Figure 2: *EoL DPP for the Support Structure. \textit{Fore detailed explanation refer to Section 4.8.*

## Discussion & Limitation

The EcoRush tool integrates circular decision-making in the offshore wind industry by providing a standardized data management system focusing on conditions, performance, and compliance assessments. By making relevant information accessible to different actors, it enhances stakeholder involvement and the effectiveness of decision-making processes.
The tool offers a structured approach that aligns with existing circular economy principles, thereby enabling the practical application of these principles in the offshore wind industry. However, the initial cost implications, the challenges associated with data collection, and stakeholder collaboration do not diminish the need to standardize data management or make EoL strategies for offshore wind turbine components more sustainable. The study's results help better understand the key attributes and variables needed for successful end-of-life resource management. They can be incorporated into future Circular Product Passports that promote circularity in the offshore wind industry.

Some limitations were faced while conducting the research. The literature review was limited by a few scientific publications discussing the intersection between circular economy and offshore wind at a large-scale commercial level. The dynamic nature of economic and environmental assessments warrants further research, making it difficult to put into immediate practice. Consequently, when a limited sample size is used in a validation process conducted within a particular organizational context, the external validity of the results obtained is reduced.
Nevertheless, it should be noted that despite problems with data collection and validation scope, the findings remain relevant and provide a systematic approach towards improving circular practices in managing end-of-life resources for offshore wind turbine components.

*I have included Appendix L, detailing the role of AI in my research process, and Appendix M, which provides a self-reflection on my entire thesis journey, offering insights into my personal and professional growth throughout this project.*

## Recommendation

ECHT regie in transitie and stakeholders in the offshore wind industry has to come together and establish comprehensive data collection protocols that will encourage cooperation among the stakeholders, ensuring uniformity and accuracy of data collected. Also, the beginning-of-life Digital Product Passport should be integrated with the mentioned data attributes to support end-of-life decision-making. In addition, greater integration of economic and environmental assessments within this framework, combined with extensive training and support for users, will ensure the effective application of the EcoRush DPP tool.

Future research is needed to concentrate on increasing the sample size and diversity of wind projects so that generalizations can be made from these results. Explore emerging real-time data tracking technologies such as IoT devices or blockchain systems to improve the accuracy and security of data collection activities. Moreover, a more holistic evaluation would entail conducting longitudinal studies using additional sub-components and systems within offshore wind farms. Other critical areas that require further investigation include regional variability assessment and the development of detailed economic and environmental assessment models. Moreover, optimizing the cross-functionality of offshore wind, offshore oil and gas, as well as onshore wind industries enhances circularity at the EoL.

ECHT regie in transitie and other researchers can improve the implementation and workability of circular decision-making in the offshore wind industry by considering these recommendations. This research helps build a strong basis for sustainable and efficient resource management practices by providing relevant insights into this subject and methods that can be applied across different sectors within the industry.

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# Contents

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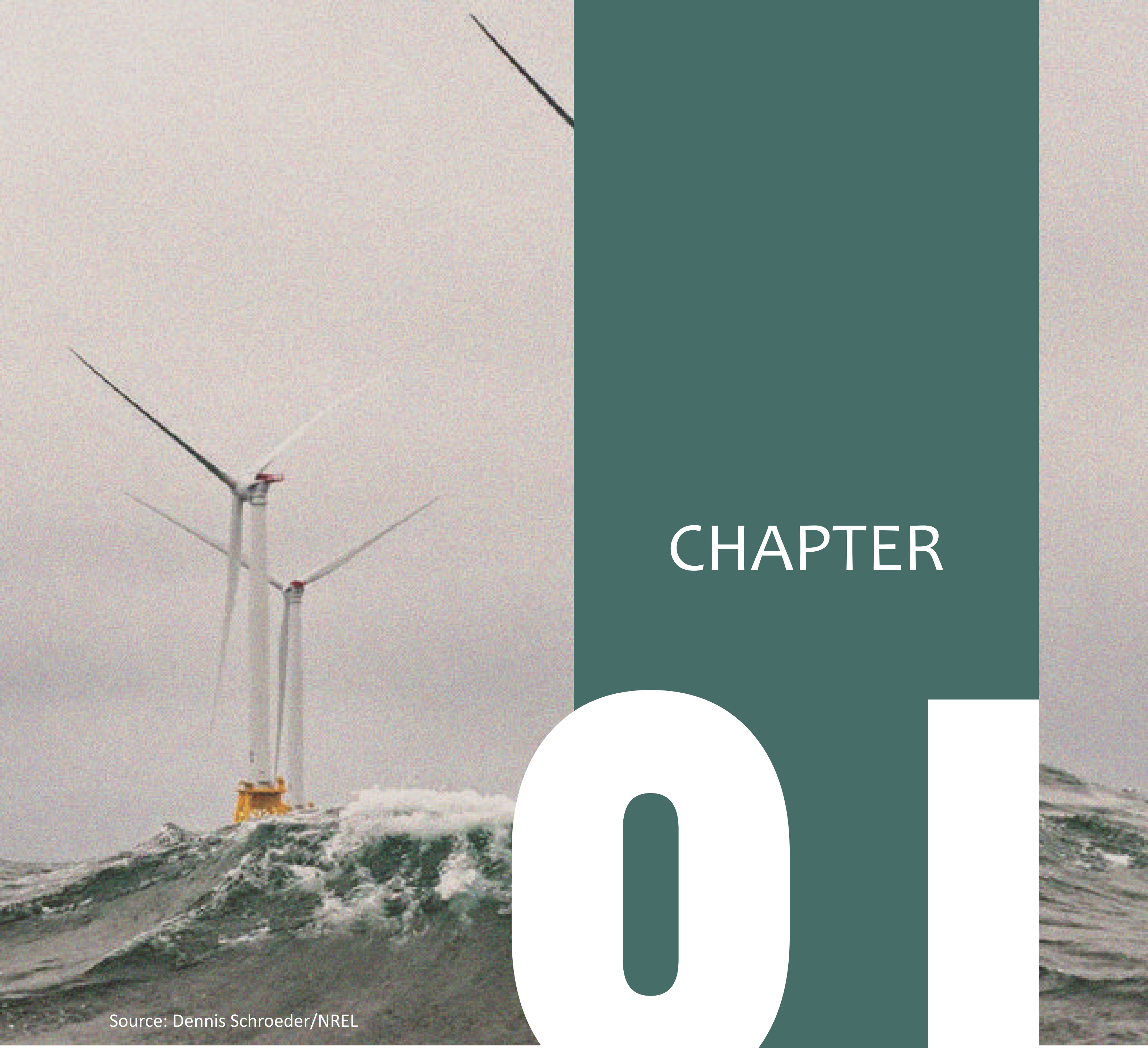
# Abbreviations & Definitions

## Abbreviations

- Offshore Wind Farm (*OWF*)
- Offshore Wind Turbine (*OWT*)
- Wind Turbine (*WT*)
- Tonnes (*t*)
- Mega Watt (*MW*)
- Rare Earth Elements (*REE*)
- End-of-Life (*EoL*)
- Beginning-of-Life (*BoL*)
- Circular Economy (*CE*)
- Rare Earth Element (*REE*)
- Digital Product Passport (*DPP*)
- Circular Product Passport (*CPP*)
- Material Passport (*MP*)
- Double Diamond Method (*DDM*)
- Substance of Very High Concern (*SVHC*)
- Return on Investment (*ROI*)
- Lifecycle Assessment (*LCA*)
- Non-Destructive Testing (*NDT*)
- Original Equipment Manufacturer (*OEM*)
- Supervisory Control and Data Acquisition (*SCADA*)
- Internet of Things (*IoT*)

## Definitions

- **Wind turbine**: A device that converts kinetic energy from the wind into mechanical energy, which is then converted into electrical energy through a generator. Wind turbines can be installed onshore (on land) or offshore (in bodies of water).
- **Offshore wind turbine**: A wind turbine installed in bodies of water, typically in the ocean, to generate electricity from wind energy. These turbines are usually larger than onshore wind turbines and are designed to withstand harsh marine conditions.
- **Circular economy**: An economic system aimed at eliminating waste and the continual use of resources. It contrasts with a linear economy with a 'take, make, dispose' production model. A circular economy focuses on closing the loops of product lifecycles through greater resource efficiency and sustainable practices.
- **Circular strategies**: Approaches and actions aimed at extending the lifecycle of products, components, and materials through reuse, refurbishment, remanufacturing, recycling, and repurposing. Circular strategies seek to minimize waste and make the most of available resources.
- **Circular practices**: Specific actions and processes implemented to achieve circular strategies. These practices include design for disassembly, materials recovery, product take-back schemes, and sustainable supply chain management.
- **End of Life**: The stage in a product's lifecycle when it is no longer usable for its intended purpose and needs to be disposed of, recycled, or repurposed. In the context of wind turbines, EoL considerations include decommissioning and recycling components.
- **Rare earth elements**: A group of 17 elements critical in the manufacturing of high-tech products, including wind turbines, due to their unique magnetic, luminescent, and electrochemical properties.
- **Standardized data management system**: A structured approach to collecting, storing, and analyzing data according to standardized protocols and formats. This system ensures consistency, accuracy, and accessibility of data across different stakeholders and applications.
- **Digital Product Passport:** A Digital Product Passport is an electronic record that contains comprehensive information about a product's lifecycle, including its origin, materials, manufacturing processes, usage, maintenance, and end-of-life handling. For this research, whenever the term DPP is used, it will be referring to an end-of-life DPP.
- **Circular Product Passport:** A Circular Product Passport is a document that details the design, materials, and processes involved in creating a product, explicitly emphasizing the principles of circular economy.
- **Material Passport:** A Material Passport is a document that specifies the types and quantities of materials used in a product, along with their properties and recyclability.
- **Assessment Criteria**: Assessment criteria for this research refer to precise guidelines used to evaluate the success/failure of circular strategy for an OWT component.
- **Data parameter**: A specific aspect or characteristic measured and recorded in a data management system. Parameters define the scope and scale of data collection and are essential for analysis and decision-making.
- **Data attribute**: A specific piece of information that describes or quantifies a data parameter. Attributes provide detailed insights into the parameters and help categorize and analyze data.



Source: Dennis Schroeder/NREL

CHAPTER

01

# INTRODUCTION

# 1

# Introduction

The way people live and work has had a significant impact on the environment since industrialization. Population growth worldwide is accelerating, which exponentially affects society's energy requirements. Carbon dioxide in the atmosphere has increased by almost 50% since pre-industrialization, leading to an increase in the global temperatures (Svensson, 2023), thus the need to switch from conventional energy sources (oil, gas, and coal) to environmentally friendly energy sources (wind, solar, hydrogen, and nuclear) has been recognized by social and economic organizations in a significant way (Elias & Victor, 2005).

Wind energy is considered one of the dominant renewable energy sources due to the availability of wind resources and the technological advancement in this sector (Esteban, Diez, López, & Negro, 2011). Later, there was a push for offshore wind energy due to the shortage of available land and the public's aversion to onshore wind farms (Orsted, n.d.). By 2050, the predicted global offshore wind capacity will rise to about 850GW compared to the 90GW capacity in 2040 (Energy, 2023). In Europe, The Netherlands is one of the leading countries in the development of offshore wind farms (OWF) (Statista, 2023) to achieve the climate goal of 55% reduction in CO2 emissions by 2030 (Agency, 2021). For instance, the Dutch Government has raised the offshore wind energy target from 11 to 21 gigawatts (GW) by 2030, approximately 50GW by 2040, and approximately 70GW by 2050 (Agency, 2021). Figure 1.1 illustrates the rapid growth of technological development globally to achieve these goals by increasing the number, size, and efficiency of offshore wind turbines (OWTs) in the coming years.

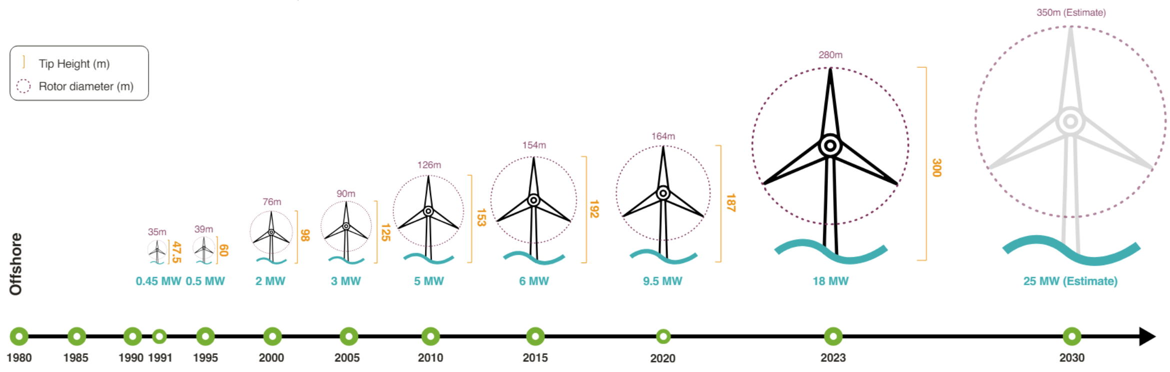



Figure 1.1: Trend of growth in OWT sizes. Source: GWEC (2024).

A trade-off exists between achieving sustainable energy sources and extracting raw materials for constructing these infrastructures. An OWF consists of multiple wind turbines (WTs) installed offshore. Wind turbines typically consist of a foundation, a tower, a nacelle, and a rotor with three blades, weighing approximately 650 tonnes and housing around 25,000 elements (Razdan & Garrett, 2015). The net material requirement to build a 100 MW wind farm can amount to more than 67850 tonnes of materials

(Razdan & Garrett, 2015). To meet the material needs, approximately 129-235 million tonnes (Mt) of steel, 8.2-14.6Mt of iron, 3.8-25.9Mt of concrete, 0.5-1.0Mt of copper, and 0.3-0.5Mt of aluminum will need to be extracted or recycled from existing raw material from 2020-2040 globally (Li et al., 2022). Additionally, the need for rare earth elements (REE) and other limited resources is high, posing severe recycling issues at the moment (Li et al., 2022). The immense waste streams and raw material extractions required by the development of OWFs contrast with the United Nations' goal of achieving sustainable management and efficient use of natural resources by 2030 (Sachs, Kroll, Lafortune, Fuller, & Woelm, 2022). Adding on to that argument, the EU has put forward a tool (CBAM) to be implemented in 2026 that will make companies importing carbon-intensive goods pay a fair price for the carbon emitted during the production of these goods/materials, making reusing and recycling a desired approach (Commission, n.d.).

As seen in Figure 1.2, the lifecycle of an offshore wind farm can be divided into five main stages: (1) Materials: Types and quantities of materials required to produce the components of the turbine; (2) Manufacturing: Making the components of the turbine; (3) Installation: Putting together the wind farm from components at the allocated site; (4) Operation & Maintenance: Maintaining and servicing the turbines over its lifespan; (5) Dismantling and End-of-Life (EoL): Decommissioning the wind turbine components at the end of functional life span (Vestas, 2024).

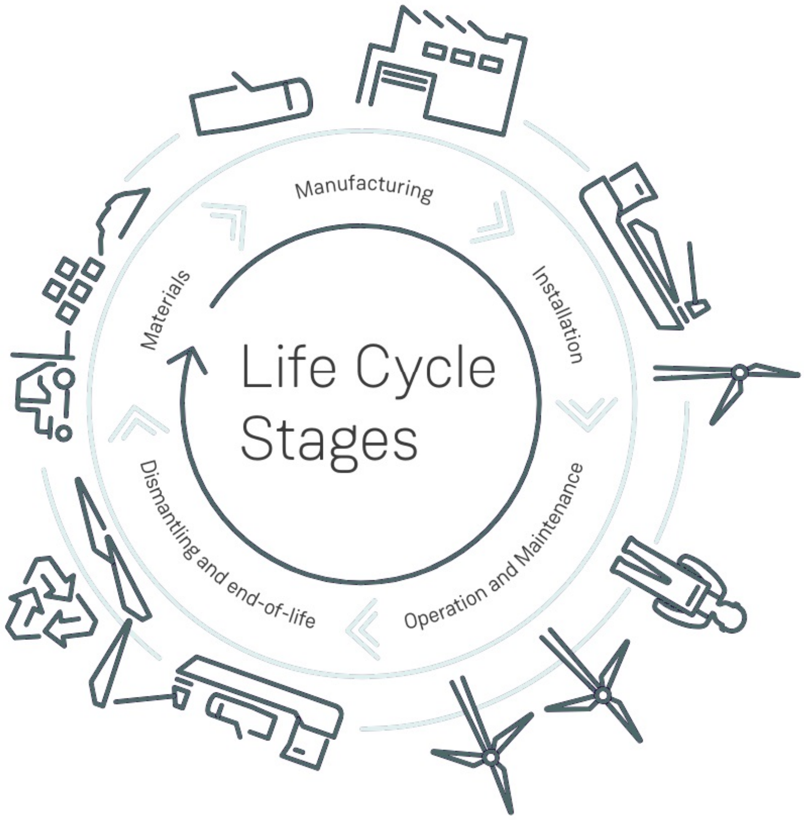



Figure 1.2: Circular lifecycle of an OWF. Source: Vestas (2024).

The global need for an energy transition is becoming increasingly urgent due to environmental concerns and the depletion of fossil fuel resources. Offshore wind energy has emerged as a crucial component of this transition, and as energy demands continue to rise, the capacity for offshore wind energy is steadily increasing. However, with the EoL phase approaching for many older wind turbines, there is an immediate need to develop sustainable EoL resource management strategies. These strategies must address both the extraction of raw materials to build new wind turbines and the reduction of waste accumulation because of decommissioning, thereby providing circular solutions for the wind sector as illustrated in Figure 1.2.

## Potential Of EoL Resource Management

The lifecycle of a project is estimated to be between 20 and 25 years (Topham, McMillan, Bradley, & Hart, 2019); thus, the wind sector is facing challenges regarding the decision concerning lifetime extension or decommissioning (Ziegler, Gonzalez, Rubert, Smolka, & Melero, 2018). Figure 1.3 shows how the projected capacity for installation and removal increases over time, indicating that decommissioning will become more crucial in allowing continued installation.

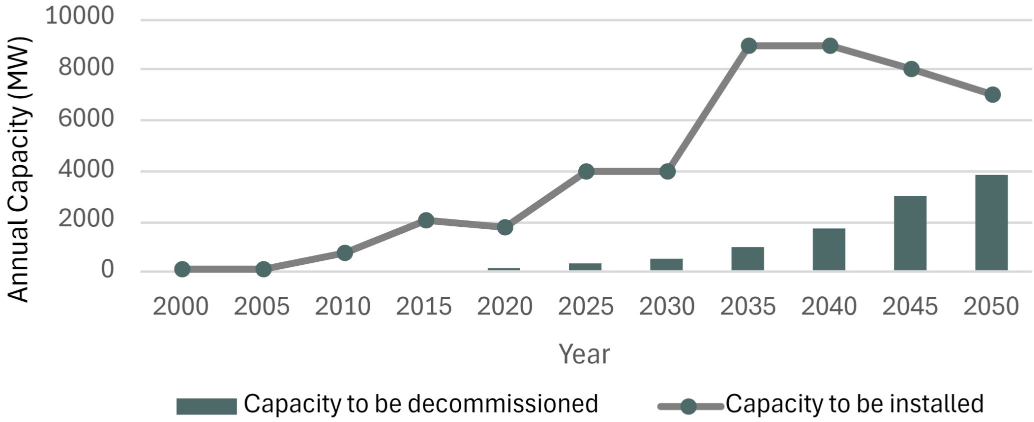



Figure 1.3: Projection of annual offshore wind capacity to be installed and decommissioned. Source: van der Meulen et al. (2020).

The process of halting operations and returning the site to its original condition for a wind farm at the end of its operational lifespan is decommissioning (Topham & McMillan, 2017). The decommissioning of OWTs may be a part of the overall offshore wind farm system's end-of-operational life, even though the wind turbines still can generate electricity (Fay Fang de, 2021). Thus, various operational components emphasize deciding whether to reuse or recycle the wind turbines' components in the initial decommissioning phases by evaluating the efficient use of the components post-decommissioning. An overview of the decommissioning process of an OWF can be illustrated in Figure 1.4.

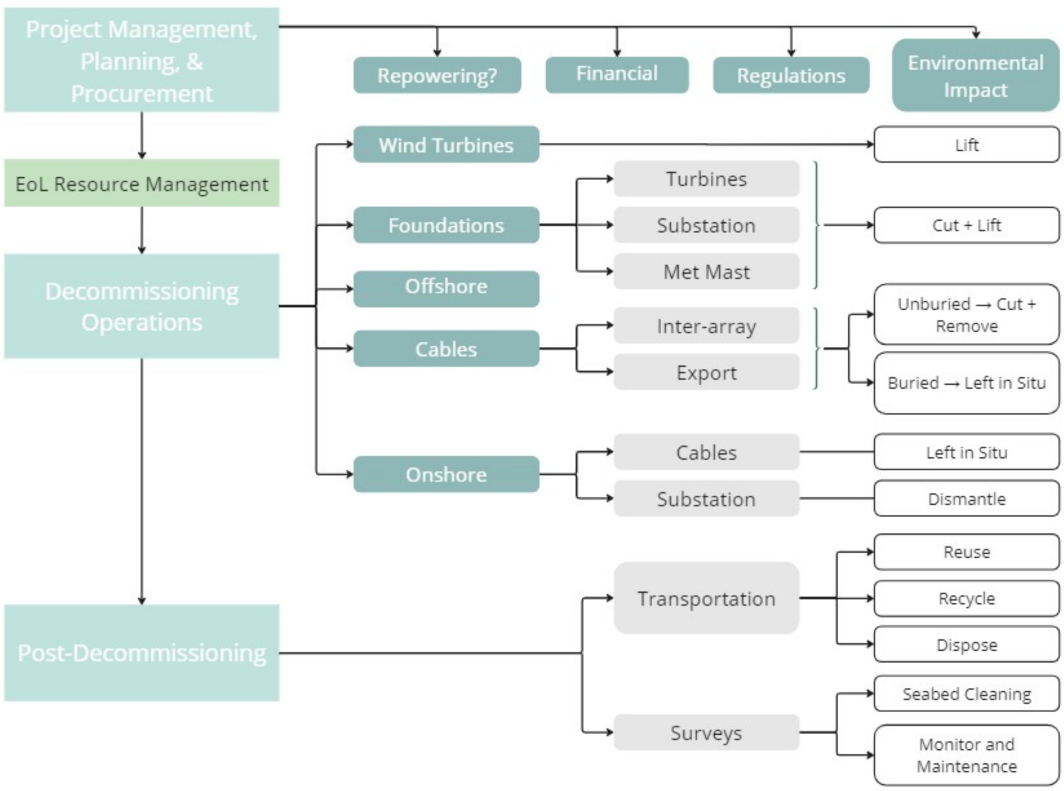



Figure 1.4: Decommissioning process. Adapted from: Topham and McMillan (2017).

Growing demand for materials and limited capacity for recycling requires the offshore wind industry for immediate and enduring sustainable resource management (Velenturf, 2021). The recycling of OWT materials is generally depicted as the primary strategy to limit future impacts. However, research suggests a far greater potential to reduce environmental impacts through improved application of circular strategies (Gallagher et al., 2019). The continuing challenge is to balance designing infrastructure with a longer shelf life and ease of disassembly to enable reuse and repairs (P. D. Jensen et al., 2020). As Hall et al. (2022); P. D. Jensen et al. (2020) emphasizes the necessity of a Circular Economy (CE) mindset from the beginning-of-life (BoL) to achieve a high level of circularity and maintain economic benefits. P. D. Jensen et al. (2020) highlighted that recycling was considered the main strategy to limit future environmental impacts of the offshore wind industry.

Furthermore, approximately 10% of the offshore wind capacity of the EU is approaching its EoL from 2030, using the materials and components from the decommissioned wind farms will act as a driving force to enable future material requirements (Demuytere et al., 2024). The sustainable decommissioning solutions necessary for component reuse are under-developed (Invernizzi et al., 2020). The implementation of circular strategies is limited due to the need for clear legal frameworks, previous experience, and lack of awareness in the supply chain (Winkler, Kilic, & Veldman, 2022). Also, most of the scientific literature is focused on the specific components such as the blades or the techno-economic assessments of EoL strategies (Jadali et al., 2021; Topham, Gonzalez, McMillan, & João, 2019). These challenges make the decision-making for the EoL resource management of an OWF a complicated process that leads to waste accumulation as well as extraction of new raw materials for upcoming offshore wind energy projects (Invernizzi et al., 2020; Topham, Gonzalez, et al., 2019).

CE is highlighted as a strategy for moving away from the current linear economy towards a circularity by minimizing the use of natural resource extraction and waste accumulation by optimizing environmental, social, and economic values throughout the lifecycle of materials, products, and components (Potting et al., 2017). Mendoza, Gallego-Schmid, Velenturf, Jensen, and Ibarra (2022) highlights the need to have a CE *"to create long-term material custody and generate greater resource and environmental savings than a product-based offering"*. To achieve the CE goals within the offshore industry, several solutions, such as developing an industry-wide digital data-sharing platform to enable circularity, Life Cycle Analysis (LCA), and Environmental Product Declarations, are commonly accepted by the stakeholders involved in the decommissioning process (Vielen-Kallio et al., 2021).

## 1.1. Knowledge Gap

CE is widely regarded as a groundbreaking approach to addressing climate change and creating sustainable ecosystems for the future. Circular strategies are not commonly and explicitly applied to offshore wind, and there is a need for a circular framework for offshore wind (Velenturf, 2021). According to Pego (2019), renewable energy is essential for a CE. However, experts on Energy and Marine Spatial Planning at the European Commission suggest that EoL resource management of wind infrastructure is a "fragile point' in environmental performance. A Scopus search on 01st April using "circular economy" and "offshore wind" returned 21 publications. The following paragraphs will explore the necessity of having a decision-making framework tailored for the EoL resource management of an OWT.

Lenzen and Munksgaard (2002) examined 72 LCAs of wind turbines, of which only 11 studies touched on the decommissioning phase. As a result, the availability of literature that explored the opportunities to implement circular strategies for EoL OWTs needs to be present J. P. Jensen and Skelton (2018). Gathering technical, economic, social, and environmental information and data through the lifetime of a wind farm is crucial to determining the functional quality of the components and evaluating the potential implementation of circular strategies (Mendoza et al., 2022). The circularity readiness of the business units and the manufacturing companies in the wind energy sector presents a strong inclination towards developing an industry-wide digital service that stores and shares circular and sustainable data in a centralized and controlled manner (Mendoza & Pigosso, 2023). Frameworks for the considerations of end-of-life strategies are emerging, but currently, there is no framework for the EoL resource management for the entire wind turbine (Delaney et al., 2021; Jadali et al., 2021; Velenturf, 2021; Windemer & Cowell, 2021). Delaney et al. (2021) suggest that to achieve the renewable en-

ergy target, it is necessary to re-power the existing wind farms with more efficient wind turbines while reusing the existing infrastructure. Jadali et al. (2021) develops a framework that supports selecting EoL scenarios that include service life extension, full re-powering, partial re-powering, and decommissioning. Where Velenturf (2021) explains how the different circular strategies can apply to offshore wind infrastructure's design, development, operational, and EoL management. Lastly, Windemer and Cowell (2021) develops a conceptual framework that investigates the impact of the EoL cycle and what are the key questions that need to be answered concerning the reversal of the adverse environmental effects due to the construction of wind farms.
Figure 1.5 clearly shows the environmental impact of different phases of a wind turbine. The negative impact of the decommissioning process corresponds to a positive environmental impact due to material and energy recovery. Planning for the decommissioning phase with reliable data is essential to retain the maximum value from EoL wind turbines (J. P. Jensen, 2019).

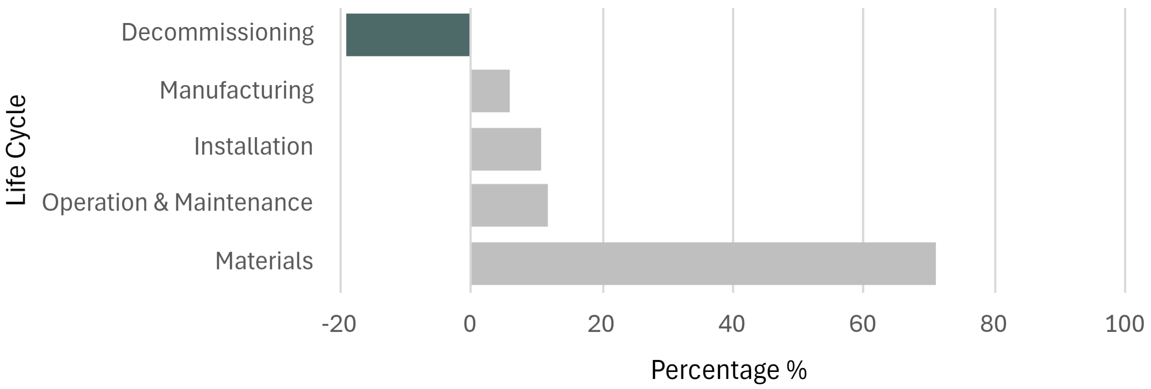



Figure 1.5: Percentage of the negative environmental impact of each life cycle stage. Source: Gamesa (2019).

Currently, the decommissioning process begins with dismantling individual turbines. The decision-making process of these OWT components includes multiple stakeholders, including wind farm operators, local and national authorities, and sometimes specialized recycling companies. Policies and regulations at both national and international levels play a crucial role in guiding these decisions, emphasizing the importance of sustainable practices and the potential for material recovery (Liu & Barlow, 2017). It is interesting to note that more needs to be published in the scientific literature about the data standards in offshore wind (Velenturf, 2021). There are no specific guidelines for the decommissioning process of an offshore wind farm due to a lack of prior experience; the decisions made across the industry may vary Velenturf (2021).
The need for more academic and industrial literature for developing CE innovations in the wind industry poses a significant limitation, specifically concerning the EoL resource management of wind turbines. Skjolde and Vinningland (2023); Vielen-Kallio et al. (2021) find that lack of standardization of turbine components and lack of information sharing are the most common barriers for stakeholders involved in EoL resource management of OWTs. To overcome the challenge of data sharing to improve CE innovations (Vielen-Kallio et al., 2021) suggests:

1. To determine the openness and accessibility to information and data.
2. To determine the incentive/driving factor and the challenges for the wind turbine manufacturers, wind farm owners, and operators to share data.
3. To define the data management parameters and requirements to analyze the circularity and sustainability of technologies, business models, and value chains for the EoL of a wind farm.
4. Create a standard or certificate to drive CE innovations.

With the rapid advancement and development of offshore wind energy and the urgent need for sustainable and efficient EoL resource management practices, a significant knowledge gap exists in the literature regarding the application of CE. Current research predominantly focuses on generic strategies for material recovery and recycling without adequately addressing the unique environmental, social, technical, and economic complexities inherent in OWFs (Velenturf, 2021). For instance, the development of a material/product passport is highlighted as a promising approach to facilitate the circular use of material and components (Braungart, McDonough, & Bollinger, 2007; Stahel, 2016), and a detailed framework for their development and implementation in the offshore wind sector remains scarce. This gap indicates a critical need for research focused on developing a circular decision-making framework that can be applied to a wind turbine component depending on the parameters, data attributes, and challenges of EoL decommissioning of OWF. The circular decision-making framework will act as a predecessor for implementing a standardized data management system in the EoL resource management of OWTs. Such a framework will support the sector in achieving its sustainability goals and enhance offshore wind projects' economic viability and environmental performance.

### 1.1.1. Problem Statement

As seen in the previous section, to develop and improve CE innovation in the offshore wind industry, it is necessary to have an industry-wide data management system (Mendoza et al., 2022). This standardized data management system needs to be critically assessed on the challenges and parameters that guide circular decision-making (Vielen-Kallio et al., 2021). Thus, a circular decision-making framework is essential for EoL resource management of OWT components, a predecessor for a standardized data management system. Therefore, the problem statement addressed in this research is:

*"Despite the growing recognition of the need for sustainable and circular practices in the offshore wind industry, there is a notable gap in the decision-making frameworks that integrate circular strategies specifically tailored for the EoL management of OWT components. This gap interferes with the efficient implementation of such principles, potentially leading to sub-optimal circular strategies for the components. The research aims to address this gap by developing a decision-making framework that precedes a standardized data management system, eventually identifying and applying the most appropriate circular strategies for OWT components at their EoL phase."*

This problem statement comprises four elements. Firstly, it addresses the current knowledge about the circular strategies used for various wind turbine components. Research on this topic will clarify the types of circular strategies that can be applied to the various components of a wind turbine.

Next, to efficiently implement a standardized data management system in EoL resource management, it is important to understand the challenges faced by the actors involved in the supply chain of the decommissioning process of an OWF. Research on this topic will clarify the challenges faced in the circular and sustainable decision-making process for the EoL resource management (Demuytere et al., 2024).

Lastly, this problem statement suggests the need for a holistic overview of circular strategies in combination with EoL resource management. This ultimately leads to developing a standardized data management system and a decision-making framework that can be used as a guiding tool tailored for OWF, bringing clarity to science and practice.

## 1.2. Research Objective

This research attempts to make a relevant contribution to the existing academic literature and practical implementation of circular decision-making tailored for the EoL of OWTs. Circular decision-making is accomplished by critically reflecting on the challenges faced in applying circular practices throughout the supply chain by identifying and incorporating key parameters necessary for capturing relevant data for the different components of an OWT.

*"This framework will facilitate the circular decision-making using relevant data across the entire EoL phase of OWT components, eventually aiding in deciding the relevant circular strategy using a standardized data management system ensuring the accuracy and applicability of information."*

With this objective, the research explores how a standardized data management system can actively contribute to efficient resource management practices, promoting CE through a practical decision-making framework during the EoL phase of OWTs.

### 1.2.1. Research Scope

The scope of this research is concentrated on the development and challenges faced in implementing circular strategies for OWTs, with a specific focus on their EoL phase and not the BoL, except where necessary for context and completeness. Key aspects of this research include:

1. Information Levels of Scale: The study will primarily focus on the component level of a wind turbine and will not delve into the further breakdown of the components into sub-components. Figure 1.6 illustrates the different levels of information scale, and for this research, the focus is on the component level. The research will not cover other renewable technologies or infrastructure components of an offshore wind farm, only the wind turbine as a whole. Necessary material details will be studied for contextual understanding.

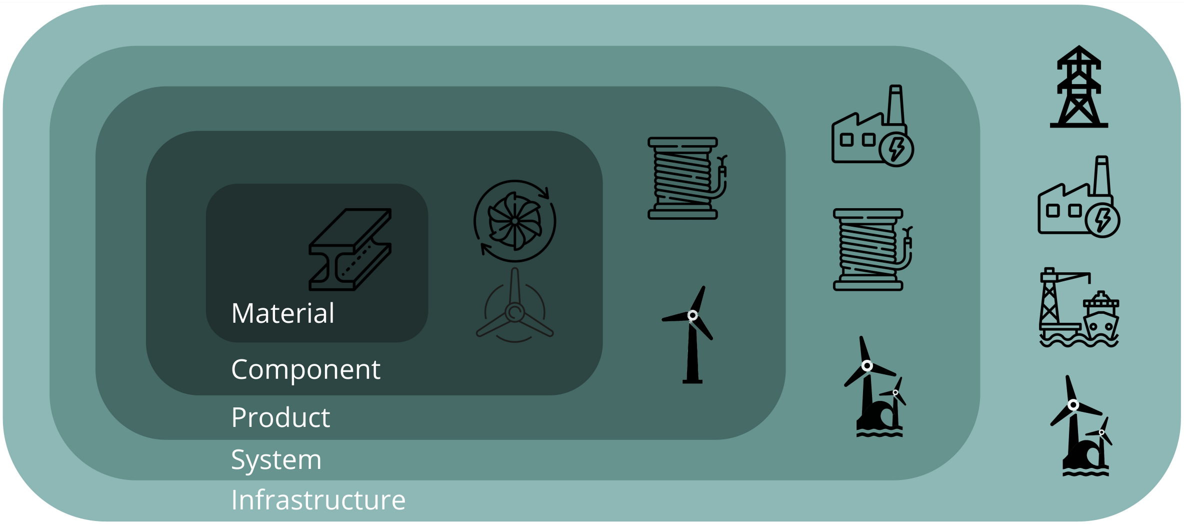



Figure 1.6: Information levels of scale. Adapted from: B. W. Byrne and Houlsby (2003).

2. Circular Practices: As mentioned in the introduction, several ways exist to achieve CE within the offshore wind industry. This research is limited to exploring circular decision-making through a standardized data management system, a Digital Product Passport.

3. Data management and decision-making: Emphasis will be placed on the assessments, parameters, and data attributes necessary to facilitate EoL circular resource management. The scope looks into the data management systems by standardized data management systems such as Material Passports or Digital Product Passports. The scope will not include exploring digital solutions and technologies for real-time data tracking.

4. Organizational and Operational Context: The research will explore the challenges of integrating circular strategies within the EoL decommissioning supply chain. This research will not explore ways to implement the standardized data management system into the business cases of any individual stakeholder of the EoL decommissioning.
5. Regional Context: The challenges and the application of the circular strategies will differ with the change in contextual regions, application, and geographical regulations. Thus, the circular decision-making tool will be developed based on the general overview of the offshore wind industry.
6. Economic and Environmental Assessment: A circular strategy's economic and environmental assessments are dynamic and cannot be generalized. The dynamic is because of the varying nature of the offshore wind farm site, secondhand use site location, weather conditions, etc. Thus, these two assessments will be a suggestion for the further development of circular decision-making and will not be explored in this research.

### 1.2.2. Research Questions

The objective of this research is studied through the following main research question:

*"In what ways a standardized data management system equipped with circular decision-making tailored for the end-of-life phase of OWTs, contribute to enhancing circular practices by efficient resource management within the industry?"*

The main research question generates knowledge about a standardized data management system and circular decision-making necessary to achieve a maximum level of CE in OWTs. Based on the information gathered through this research question, a standard structure for data management equipped with circular decision-making can be developed, enabling and enhancing EoL resource management of OWTs through a standardized data management system.

#### Null-Question

Before conducting the research, a 'null' question was answered. The 'null'-question is:

**SQ.0:** ***What existing circular strategies are applied in the offshore wind industry?***

To get a better understanding of the theoretical foundation of this research. That is, Circular Economy and Offshore Wind Industry.

#### Sub-Research Questions

The following sub-research questions have been established to address the main research question.

**SQ.1:** ***What are the various components of an OWT and their respective EoL circular practices?***

The first step of this research seeks to identify and analyze the components and materials used in OWTs. This step will help diagnose the existing circular practices applied to these elements. Given the availability of existing knowledge about these aspects, a literature review and document review would be carried out.

**SQ.2:** ***What are the key challenges faced in managing wind turbine components with regard to CE at their EoL phase by the stakeholders involved in the supply chain?***

The second step is to identify the key challenges encountered in the EoL resource management of wind turbine components and elaborate on what motivates the actors involved to adopt CE principles. Given the limited knowledge about these aspects in the current literature, data will be collected by conducting expert interviews.

**SQ.3:** ***What are the key parameters and data attributes that are required for the circular decision-making framework for a standardized data management system tailored for the EoL of OWTs?***

The third step is to explore the key parameters that will guide the decision-making process of the components that enter the component database. This step will eventually form the basis of the decision-making framework. To answer this question effectively, interviews will be conducted to capture the practical aspects of the question.

**SQ.4:** ***What are the implications of the identified circular strategies, key parameters, and data attributes for the EoL circular decision-making?***

Finally, the results from the preceding sub-questions are combined to develop a comprehensive tool for standardized data management and circular decision-making.

Figure 1.7 gives an overview of the sub-research questions that lead to answering the main research question. The next section will discuss the thesis's structure and how the sub-questions are dealt with.

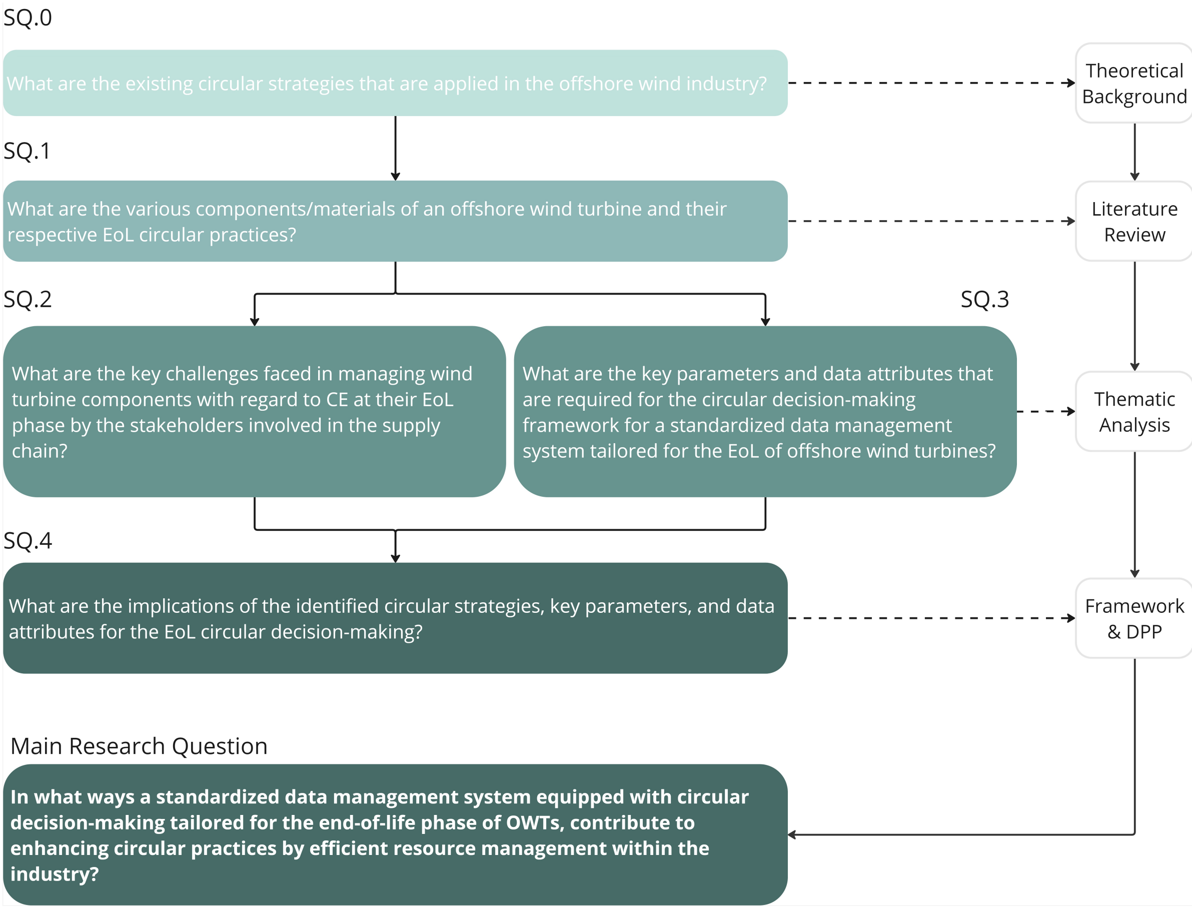



Figure 1.7: *Process of answering the main research question along with the research method for the sub-research questions.*

## 1.3. Thesis Structure

This research is divided into three phases and six chapters, as illustrated in Figure 1.8.

1. Introduction: Chapter one talks about the need for this research and lays down the basic structure for the report.
2. Theoretical Background: Chapter two provides the theoretical background on this research's key topics: Circular Economy and Offshore Wind.
3. Research Methodology: Chapter three elaborates on the research methodology used. Here, the Double Diamond Method (DDM) is used, and the various DDM steps for the research are explained.
4. Results & Analysis: Chapter four elaborates on the findings of this research for the previously defined sub-questions. The chapter is divided into four parts based on the four stages of the DDM. These sections aim to provide answers to the sub-research questions.
5. Discussion and Limitations: Chapter five critically discusses the research findings and limitations.
6. Conclusion and Recommendations: In chapter six, the conclusion for the main research question is provided. The elaboration of the future research recommendations accompanies this.

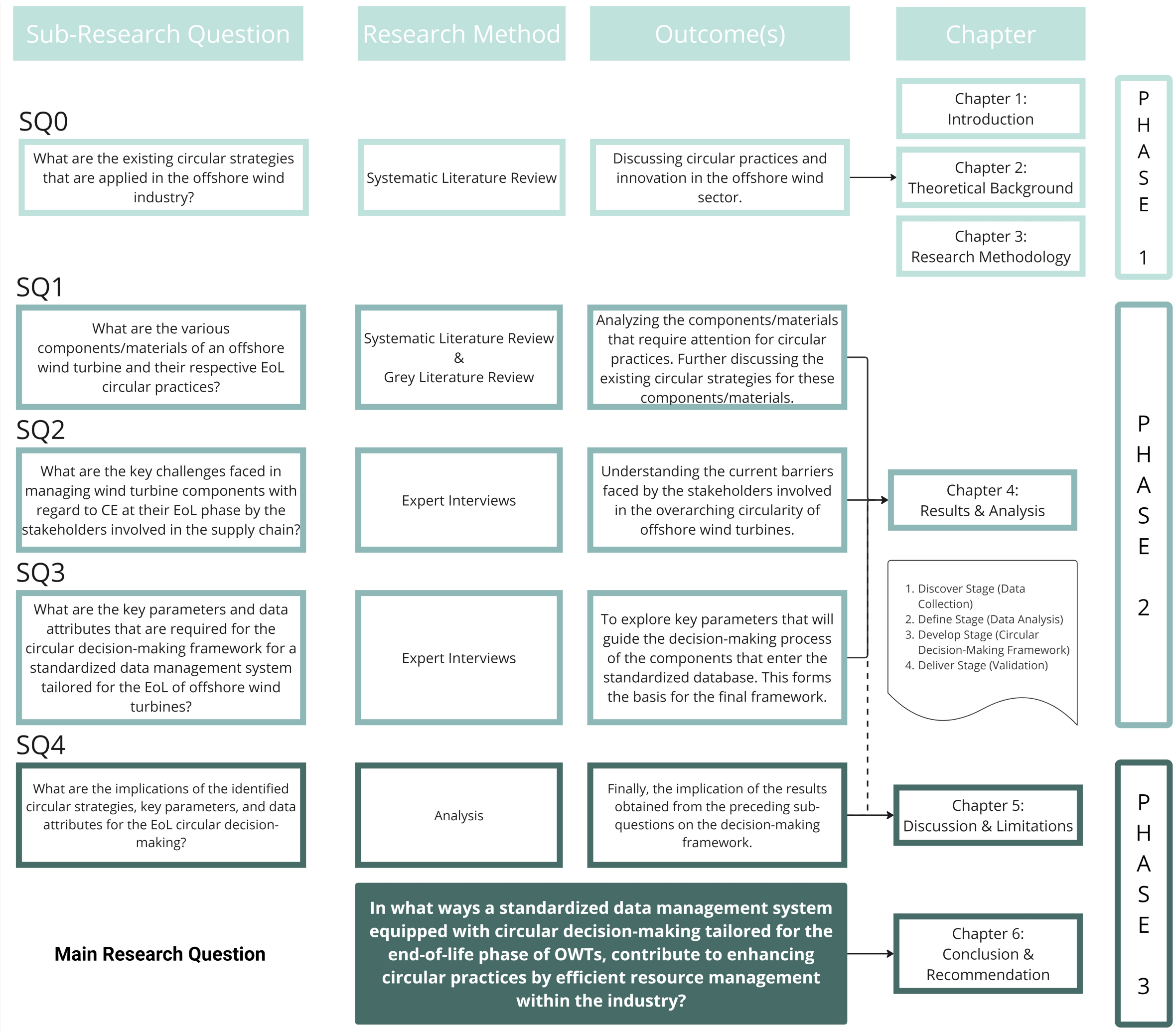



Figure 1.8: Coherence of the sub-research questions with the report structure.

*The following chapter will present the theoretical background for the research.*


Source: Offshore Wind Ørsted

CHAPTER

02

# THEORETICAL BACKGROUND

# 2

# Theoretical Background

*This chapter provides the theoretical background for the research by addressing the following sub-research question:*

- *SQ.0: What existing circular strategies are applied in the offshore wind industry?*

*This sub-question is addressed through a literature review by discussing circular practices and the related developments in the offshore wind sector.*

## 2.1. Circular Economy and Offshore Wind

By definition, *"**Circular Economy** refers to an industrial economy that is restorative by intention; aims to rely on renewable energy; minimizes, tracks, and eliminates the use of toxic chemicals; and eradicates waste through careful design."- MacArthur et al..* CE prioritizes waste avoidance over disposal and reuse over recycle (Potting et al., 2017).

According to EU legislation, all big businesses and listed companies must provide information about the possibilities and risks they perceive deriving from social and environmental challenges and the effects of their operations on the environment and human health using the CSRD (Finance, 2023). The CSRD includes several sustainability topics that companies select among the topics that are the most relevant to the stakeholders they are involved with through a process of double materiality. The double materiality analysis conducted in 2022 included >4000 survey responses, ~60 interviews, ten different stakeholder groups, 9+ countries by Vattenfall, apart from the current top 3 topics: Renewable Energy, Climate Change, and Affordable Energy; Resource use and Circularity are considered critical topics in the long-term as they contribute to fighting climate change as well as to combating future material bottlenecks (Ramsköld, 2022).

The materiality analysis conducted in 2023 concluded that Circular Economy is one of the most crucial material topics RWE (2023); Vattenfall (2023); Vestas (2023); Ørsted (2023a). The materiality analysis resonates with the sustainability reporting, including the promotion of circularity throughout the lifecycle of products through three strategic areas: Circular Design & Materials to reduce and optimize resource usage by rethinking the design of new renewable energy assets; Operational & Late-life Strategies: Extending the operational lifespan of wind farms by ten years, beyond the predicted lifespan by investigating opportunities for repair, refurbishing, and reusing key components; Resource Recovery & Recycling: Ensuring that materials are effectively recovered and recycled at the EoL cycle into new supply chains (RWE, 2023; Vestas, 2023; Ørsted, 2023a). Few offshore wind companies do not have circularity as one of their materiality topics but have a ‘Responsible Supply Chain’ that relates somehow back to circularity (Seaway7, 2023).

CE is an enabler for many of the Sustainable Development Goals (SDGs) set by the UN (Korhonen, Honkasalo, & Seppälä, 2018). The EU’s CE Action Plan outlines mandated and voluntary activities that enhance the Ecodesign framework and promote circularity (*Circular economy*, 2024). WindEurope's sustainable blade waste management hierarchy follows the European Waste Framework Directive (2008/98/EC) (Woo & Whale, 2022). Still, as seen, there were strategies for waste management for the wind turbine blades, and the rest of the wind turbine components were expected to be recycled. During the Climate Change Conference (COP28), 132 participating countries accepted the "Double Down, Triple Up" which translates into tripling up renewable energy and doubling energy efficiency by 2030 (COP28, IRENA, & GRA, 2023). With this growth rate, the challenge in the supply chain, where bottlenecks in production capacity and skilled workforce availability are expected to emerge in the medium and long term (5-10 years ahead), could slow down wind energy development. One of the critical growth opportunities to overcome the supply chain challenges is circularity (GWEC, 2024).

**Definition of Circularity for Offshore Wind**

*Circularity for the offshore wind industry can be defined as the reuse, re-purposing, recyclability, and recovery of wind farm components, including wind turbines, and the reduction of waste and environmental impacts generated in the wind project lifecycle in line with a CE approach.*

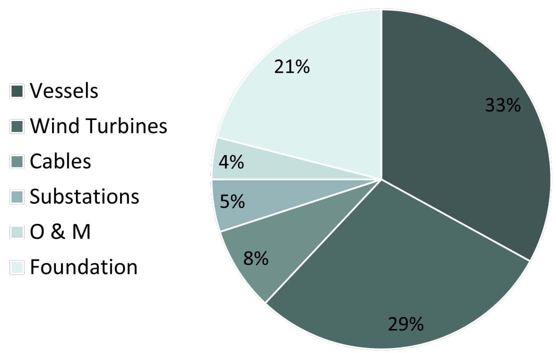



Figure 2.1: LCA offshore wind farm; Asset specific supply chain emissions. (This is an average and may vary according to the distance of shore, depth of waters, wind farm layouts, etc.). Source: Ørsted (2023b).

The current utilization of repaired and refurbished components is 14% and is expected to be 55% and 75% in 2030 and 2040, respectively (Vestas, 2023). To achieve a sustainable supply chain, tools for supply chain transparency and material databases are being explored, the ultimate aim is to transform into a circular business model (Vattenfall, 2023). These tools would aid in achieving the goals of being 100% circular in 2050 set by the EU and big business in the offshore wind industry (RWE, 2023; Vestas, 2023; Ørsted, 2023a). LCA is a scientific approach to quantify the environmental impact of a system's manufacture, installation, and transportation (Offshore wind farms) (Weinzettel, Reenaas, Solli, & Hertwich, 2009). LCAs improve data accuracy, which will reflect in the design choices and the type of material used (Ørsted, 2023b).

Figure 2.1 illustrates that transportation vessels, wind turbines, and foundations are the highest contributors to environmental emissions. The figure makes it clear which assets of the offshore wind industry the circular strategies must be focused on.

In an LCA calculation conducted by Vestas to measure the vital nature of the material flow of a product in the context of CE, the four main circular indicators were identified: (1) Material Input, (2) Product Lifetime, (3) Material Output, and (4) Disposal Efficiency; that eventually led to a circularity score of 0.68 (68% of wind turbine materials are managed in a closed loop and remaining 32% act in a linear manner) that is only including the recycling value of materials (Vestas, 2024).

The transition towards a CE within the offshore wind industry is necessary to mitigate environmental impacts and enhance the sustainability of renewable energy systems. However, managing the lifecycle of wind turbines, particularly in their decommissioning and EoL stages, is critical, as they present environmental and logistical challenges (Velenturf, 2021).

### 2.1.1. Circular Strategies

CE, by definition, is a perspective on the significance of high-value, high-quality material cycles and the transition towards a closed loop material flow, reducing the waste generation and raw material extraction (Korhonen et al., 2018). The level of circularity is measured in terms of the amounts of natural resources needed to produce new materials. It is also important to note that the consumption of fossil fuels for recycling materials to their initial forms and again using natural resources for these materials to be used in another functional application (Vielen-Kallio et al., 2021).
Circular strategies are various actions to implement CE in a process. These strategies are differentiated based on the level of circularity achieved. Potting et al. (2017) listed circular strategies to reduce resource and material consumption in the product chains. As shown in Figure 2.2, the R-ladder where the strategies differ in order from high circularity (low R-number) to low circularity (high R-number). Appendix D explains the circular strategies in depth.

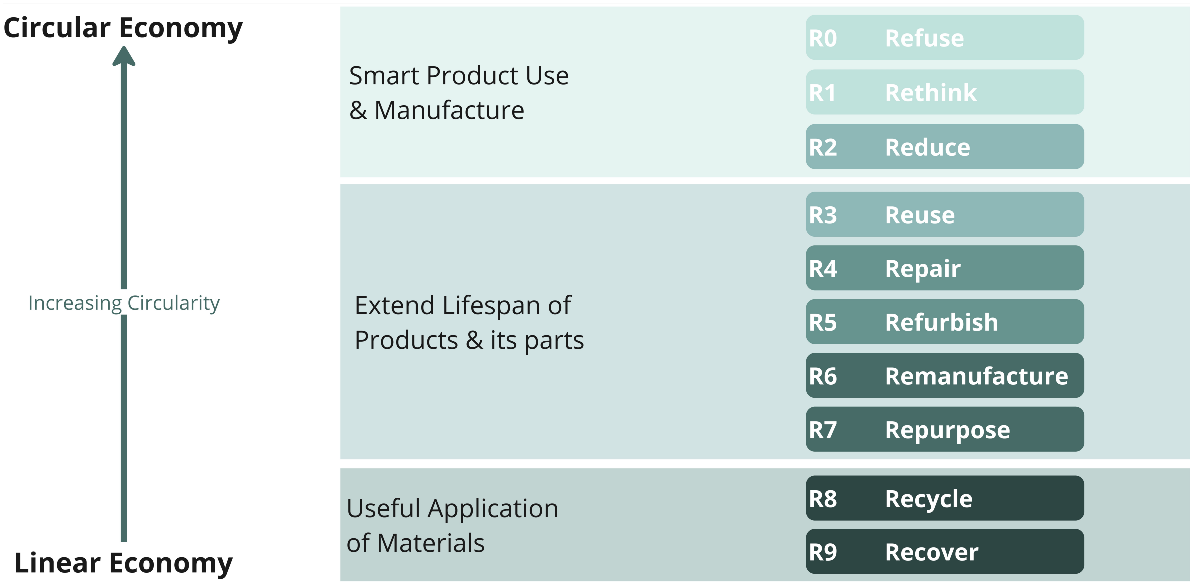



Figure 2.2: Circular strategies (R-Ladder). Source: Potting et al. (2017).

These circular strategies have different applications and require various types of information for their efficient application. The information needed to assess circular strategy can be categorized into six assessments. These assessments differ in their application from one circular strategy to another and require careful consideration while being evaluated. Following is a list of assessments based on general categorization from Appendix D:

1. **Typology Assessment:** Assess the function of the product/component before evaluating for circular strategies. This assessment is necessary because not all products can be processed for all circular strategies. The assessment includes assessing the technological feasibility of upgrades and available skills.
2. **Condition Assessment:** Assessing the condition of a product in terms of wear and tear, expiration, etc. (Geissdoerfer, Savaget, Bocken, & Hultink, 2017).
3. **Performance Assessment:** Measuring the current and future performance based on using the product as it is or with upgrades (Ijomah, 2002).
4. **Compliance Assessment:** Evaluating the regulatory aspect of the potential application of a circular strategy. This assessment is evaluated in the form of standards and regulations.
5. **Economic Assessment:** Evaluating the cost-effectiveness of applying a circular strategy regarding market demand, logistics, and actual costs needed.
6. **Environmental Assessment:** Evaluating the decrease in material consumption and reduction in waste generation against the emission of greenhouse gases in implementing a circular strategy.

### 2.1.2. Circular Strategies in Offshore Wind

70-80% of the environmental impact of turbine manufacturing is the result of material extraction and processing (J. P. Jensen, 2019). The analysis of J. P. Jensen (2019) shows that offshore wind farms are not generally developed with a CE in mind and fail to take the perspective of EoL resource management. A literature review by Velenturf (2021) shows that the majority of the publications are focused on material recycling and recovery, however as discussed in Section 2.1.1, recycling ranks relatively lower in the hierarchy of circular strategies such as repair, reuse, and re-manufacturing. Thus, there is a need to have a more holistic and integrated approach to improve the circularity in the wind energy sector (Velenturf, 2021). To improve the CE at the system level, technology and material innovations must be followed by the design and implementation of Circular Business Models (CBM) (Vegter, van Hillegersberg, & Olthaar, 2020). The transition to a sustainable CE requires systematic changes in how businesses function within and across their value chains (Pieroni, McAloone, Borgianni, Maccioni, & Pigosso, 2021). However, little attention is given to the broad understanding of CE in the wind energy sector (Mendoza & Pigosso, 2023). Besides the CBM, it is necessary to integrate circularity in the design phase, operations and maintenance phases, and the EoL management (Pigosso, Schmiegelow, & Andersen, 2018).

The circular strategies identified by Woo and Whale (2022) and Velenturf (2021) have a lot of similarities. Woo and Whale (2022) discuss the strategies to incorporate CE in the wind energy sector and relate them with the level of CE achieved. The strategies identified include the following: Re-power, Lifetime extension, Reuse, Re-purpose, Recycle, recover, and Dispose.
Velenturf (2021) designed a framework that includes eighteen circular strategies organized based on their application to materials, components, and infrastructure as illustrated in Appendix E. These strategies aim to narrow, slow, close, and integrate resource flows throughout the lifecycle of offshore wind infrastructure, from beginning-of-life to end-of-life and beyond (Velenturf, 2021). The strategies identified by Velenturf (2021) include the following: Design for Circularity, Dematerialize, Prevent Waste, Modularization, Maintain & Repair, Reuse & Re-Purpose, Refurbish & Re-manufacture, Disassemble, Lifetime Extension, Data & Information, Re-power, Re-certify, Decommission, Recycle, Re-mine, Recover Energy, Restore Site, and Landfill.
The relation of the general circular strategies identified by (Potting et al., 2017) and circular strategy identified for the OWFs by Velenturf (2021) can be illustrated in Figure 2.3.

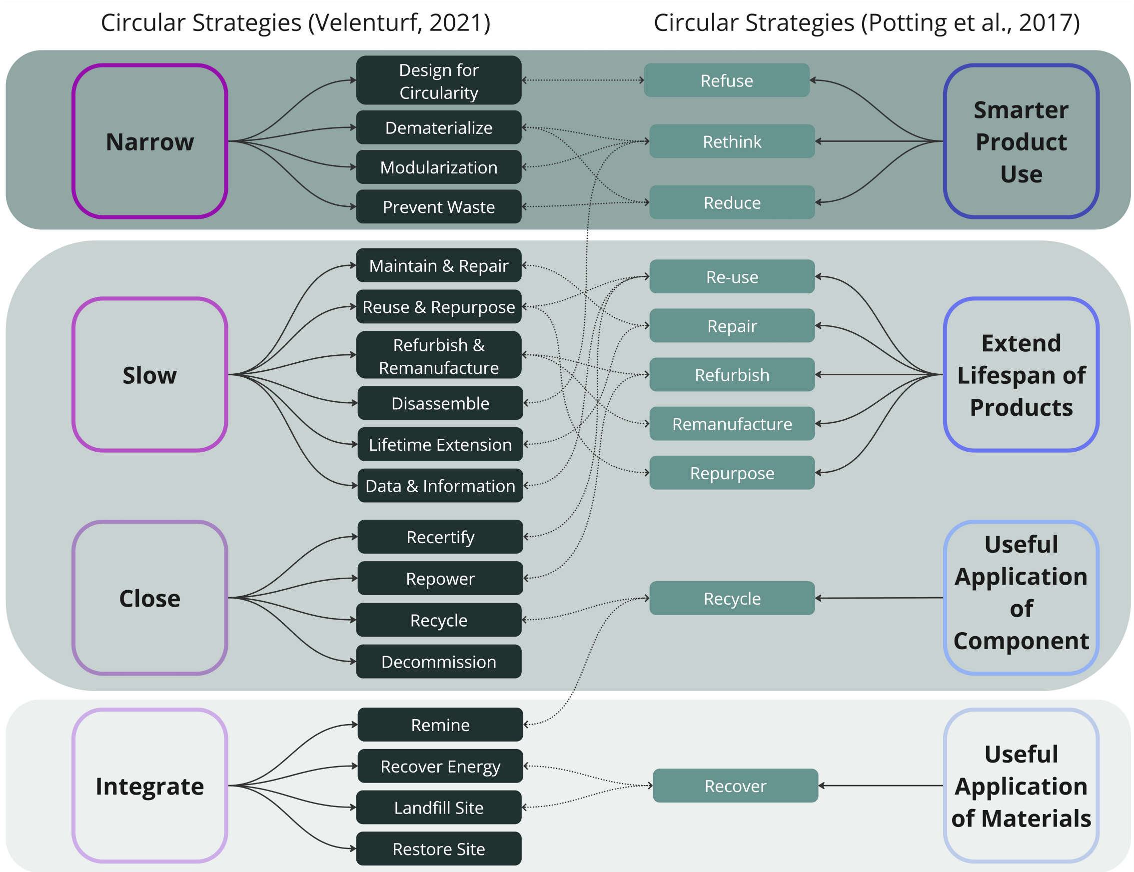



Figure 2.3: Existing circular strategies that are applied in the entire lifecycle of an OWF (left side) and the circular strategies that are recognized in The Netherlands (right side). Adapted from: Potting et al. (2017); Velenturf (2021).

The reason for conducting a relation analysis between the circular strategies identified by Velenturf and Potting is to bring together similar terms and ease further research. Another reason is to relate the circular strategies identified for the offshore wind industry and circular strategies identified for general purposes.

The success of a circular strategy is dependent on the lifecycle phase to which it is applied. The following is a discussion of circular strategies used in the different lifecycle phases of an OWF. It is important to note that technological developments in this sector are much faster, and the following discussion is based on the circular practices in the offshore wind industry as of May ’24.

**Beginning-of-Life Phase**
The design phase offers significant opportunities to incorporate CE in OWTs. Velenturf (2021) highlights that designing for disassembly and durability is crucial for the later stages of recycling and reuse. Additionally, dematerialization in offshore wind includes optimizing resource use by alternative materials or shape optimizations. However, no scientific articles have been published on the dematerialization in offshore wind (Velenturf, 2021). Disassembly plays a vital role in the component design phase, as strategies such as repair, reuse, re-manufacture, and recycling can benefit from this (Kerin & Pham, 2019). Still, it is not yet heavily investigated in the offshore wind industry (Velenturf & Purnell, 2017). Another waste prevention strategy is eliminating waste from production rather than dealing with waste once it has emerged (Reike, Vermeulen, & Witjes, 2018).

**Operational Phase**
Maintaining turbines in optimal condition during the operation and maintenance phase can significantly extend their operational life, reducing the frequency and demand for raw materials. Chen et al. (2021) discuss effective maintenance strategies, emphasizing predictive maintenance in reducing material waste and ensuring efficient operations. Extending the lifetime extension of a wind turbine is likely to be followed by more repairs and maintenance (Velenturf & Purnell, 2017). Repairs are followed by re-powering, a circular strategy that extends the service life of a wind turbine by either replacing the wind turbine components or the entire turbines with new, advanced machines (Bezbradica, Kerkvliet, Borbolla, & Lehtimäki, 2016).

**End-Of-Life Phase**
Lastly, the EoL phase of OWF presents critical opportunities to implement circular strategies that maximize resource recovery and minimize waste. According to Velenturf (2021), effective EoL management involves a range of strategies, including decommissioning, re-powering, and recycling components and materials. Decommissioning typically includes safely dismantling wind turbines and associated infrastructure, focusing on reusing and refurbishing parts where feasible. Ghisellini, Cialani, and Ulgiati (2016) emphasize the importance of recycling high-value materials such as metals and composites to reduce the environmental impact and recover valuable resources. Additionally, re-powering, which involves upgrading existing turbines with more efficient technology, can extend the operational life of wind farms and reduce the need for new installations (Kerin & Pham, 2019). Liu, Meng, and Barlow (2019) note that innovative recycling processes, such as those for composite materials used in turbine blades, are essential for improving the sustainability of EoL management. Furthermore, effective EoL strategies require robust data on the condition and performance of turbine components to inform decisions about reuse, refurbishment, and recycling (Velenturf & Purnell, 2017).

*Following chapter will discuss the research methodology followed for this research.*

Source: Interreg North Sea Region Decom Tools, EU

CHAPTER

03

# RESEARCH METHODOLOGY

# 3

# Research Methodology

*This chapter elaborates on the research methodologies employed to conduct the literature review and the interview analysis systematically.*

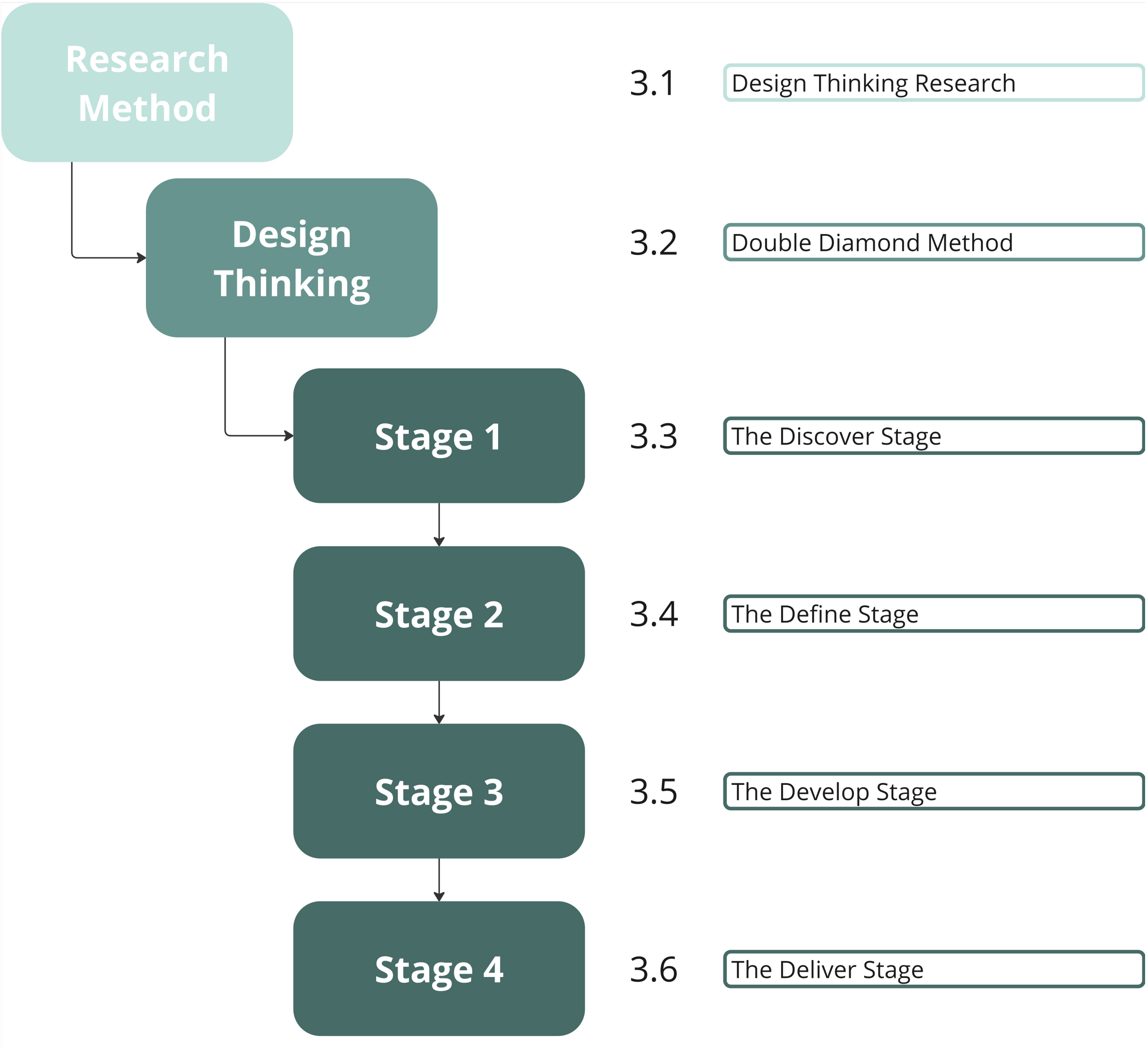



Figure 3.1: Overview of Chapter 3.

## 3.1. Design Thinking Research

This research aimed to develop a tool for circular decision-making through a standardized data management system. Thus, the researcher decided to use a design-thinking approach. Design thinking is a methodological technique similar to research methods used in engineering, where processes are developed to target specific goals or challenges. The definition of design thinking is as follows:

*"...an analytic and creative process that engages a person in opportunities to experiment, create and prototype models, gather feedback and redesign" - Razzouk and Shute*

Incorporating a design-thinking approach in the research methodology for assessing circular strategies in the offshore wind industry offers a creative and solution-focused way to tackle complex problems. As illustrated in Figure 3.2, design thinking involves understanding user needs, redefining problems, and creating innovative solutions through a human-centered design process (Braha & Reich, 2003). It can be particularly effective in developing and evaluating circular economy strategies by fostering stakeholder collaboration and generating user-centered solutions. There is a two-tiered concept for the design-thinking process that involves first identifying the problem and, secondly, a solution to the problem is designed in the form of a framework or a tool (Razzouk & Shute, 2012).

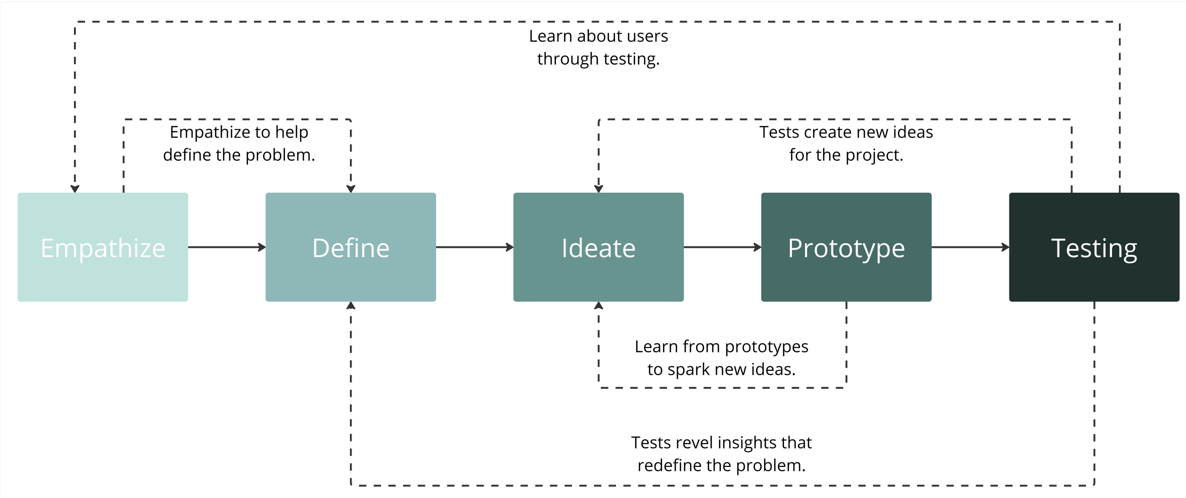



Figure 3.2: Design thinking process: A non-linear process. Source: Sharlip (2019).

The aim of the research could be achieved by gaining an in-depth understanding of the challenges and motivations of the different stakeholders involved in the EoL phase of OWTs and using this knowledge to develop a tool that would aid in the EoL decision-making for OWTs. In other words, how to incorporate CE in OWT decommissioning through a DPP system. Qualitative data collection and analysis to identify patterns and themes through an iterative process related to implementing circular strategies is explored. The design thinking approach used in this research is the 'Double Diamond Method'. This research approach was selected as it provided a structured approach for the development of the tool, emphasizing iterative exploration and refinements of ideas through expert feedback.

## 3.2. Double Diamond Method

The DDM is a design thinking approach that emphasizes creative problem-solving through a process of divergence and convergence in two phases, focusing on understanding user needs and generating innovative solutions through iterative design and testing (Council, 2024). Furthermore, it aligns with the research as it aims to explore scientific knowledge and aid actors in solving real problems (Spector, 2000).
According to Council (2024), the method emphasizes the diverging and converging nature and consists of four different stages as shown in Figure 3.3: (1) **Discover:** Involves identifying the real problem by the collection of qualitative data; (2) **Define:** Analyzing the qualitative data to gather insights to define the challenge; (3) **Develop:** Developing potential solutions and asking stakeholders for their opinions; (4) **Deliver:** Selecting and validating the solution that works for the stakeholders involved.

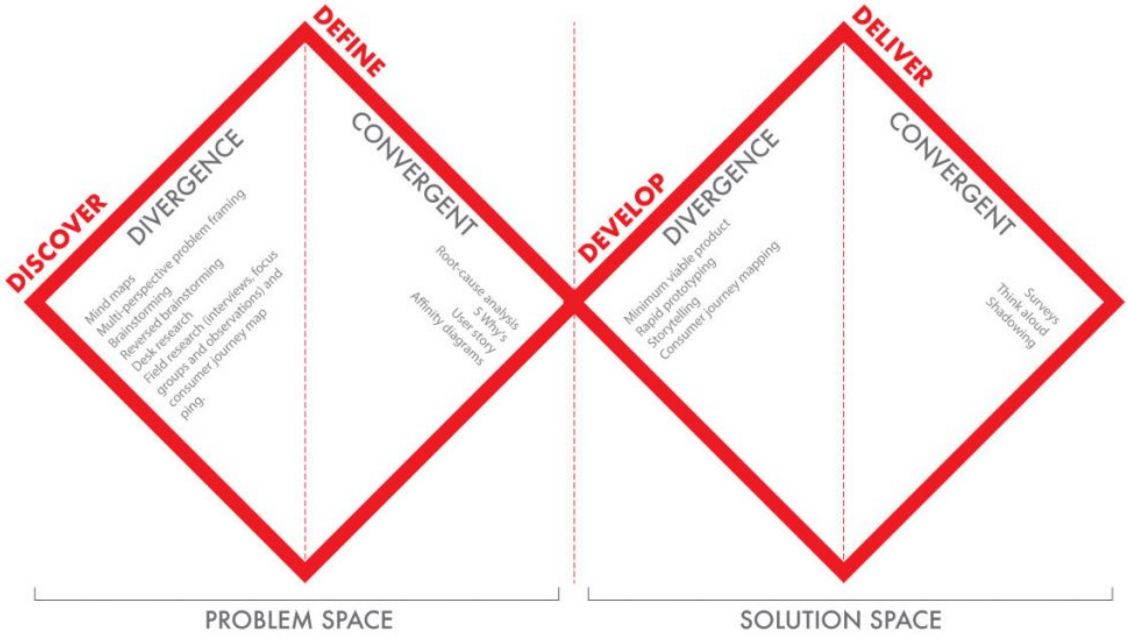



Figure 3.3: The Double Diamond design thinking process. Source: Elmansy (2023).

### 3.2.1. Application of DDM

The four main stages of the DDM for this research resonate with the different phases defined in Figure 1.8. This section will provide an overview of the various research activities for the selected research methodology to answer the research questions, as illustrated in Figure 3.4.

1. Discover (Phase 1): A literature review and semi-structured interviews will be conducted to collect data. This data collection process will be elaborated in this Section 3.3. To understand circular strategies, the challenges faced in implementing CE, and the data needed for circular decision-making related to the EoL of OWTs.

2. Define (Phase 2): The analysis of the data collected is presented in Section 3.4. The analysis will provide a list of relevant circular strategies, the key challenges faced in implementing circular strategy, and the key parameters and data attributes necessary for the EoL resource management of OWTs. The identified list is considered the “design brief” for developing the tool as it forms the basis for the circular decision-making framework and a tailored structure for a systematic data management system.

3. Develop (Phase 3): The solution to the problem will be explored in this phase. The circular decision-making framework and the DPP structure will be developed in Section 3.5. These will be integrated into a single tool, namely “EcoRush”. The process of development goes back and forth with the delivery stage. The inputs gained in the validation will be used to refine and polish the tool.

4. Deliver (Phase 4): The EcoRush tool developed in the Develop Stage will be validated through internal company validation in Section 3.6. The validation process is twofold: first, the validation of the circular decision-making framework, and next, the validation of the EcoRush tool with real-time data inputs.

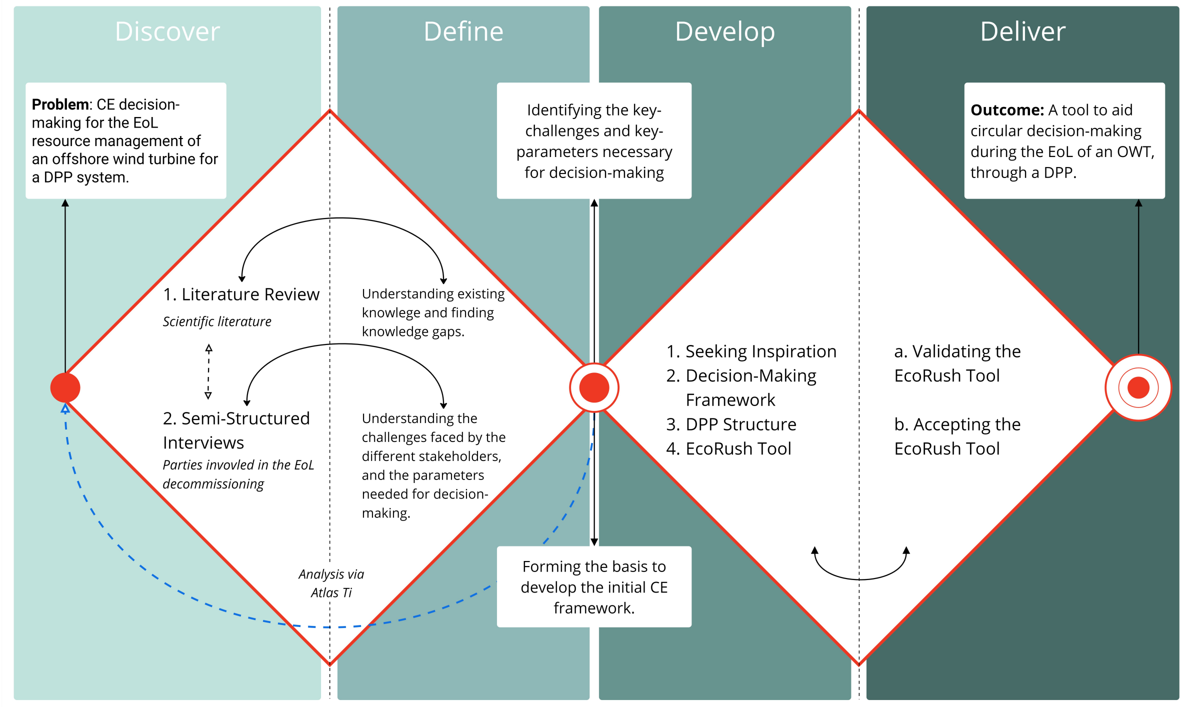



Figure 3.4: Adapted version of the DDM applied to the research, including the various activities carried out throughout the process. Adapted from: Elmansy (2023).

## 3.3. The Discover Stage

The identified problem in Section 1.1.1 for this research is an emerging research area and a need for practical application in the industry. The following section explains the data collection process to explore the identified problem in-depth and gain insights. The two types of data collection methods used for the research are namely: **(1) Literature Review** and **(2) Semi-structured interviews.**

Figure 3.5 illustrates the two types of data collection methods. This figure shows a systematic literature review of 66 scientific articles addressing SQ0 and SQ1. Next, nine semi-structured interviews provided data to answer SQ2 and SQ3. The literature review also forms the knowledge base for conducting the interviews.

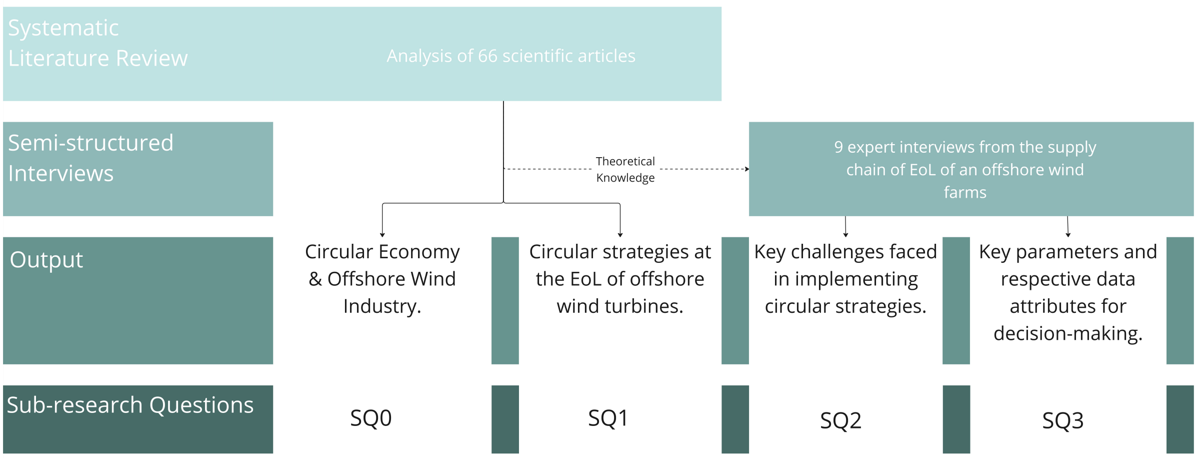



Figure 3.5: Illustration of the data collection method used and the coherence between Literature Review and Semi-Structured Interviews.

### 3.3.1. Systematic Literature Review

Existing knowledge is a crucial foundation for future research (Snyder, 2019). A method of collecting and synthesizing existing research to acquire existing knowledge is called literature review (Snyder, 2019; Tranfield, Denyer, & Smart, 2003). One should keep in mind that, while systematic literature reviews are a suitable method for mapping and reviewing material, they can still be subject to bias (Tranfield et al., 2003).

To understand the current circular strategies applied in the offshore wind industry and explore the concepts of standardized data management systems through a systematic literature review. The purpose is to create a theoretical framework implemented as a practical tool to enhance aspects of circular development in the offshore wind industry.
The systematic literature review was conducted according to PRISMA guidelines (Page et al., 2021), as illustrated in Figure 3.6. Before the literature review, selecting and combining keywords was conducted as detailed in Appendix A. The results of the identified keyword searches were examined in VOSviewer to choose the optimal keyword combination.

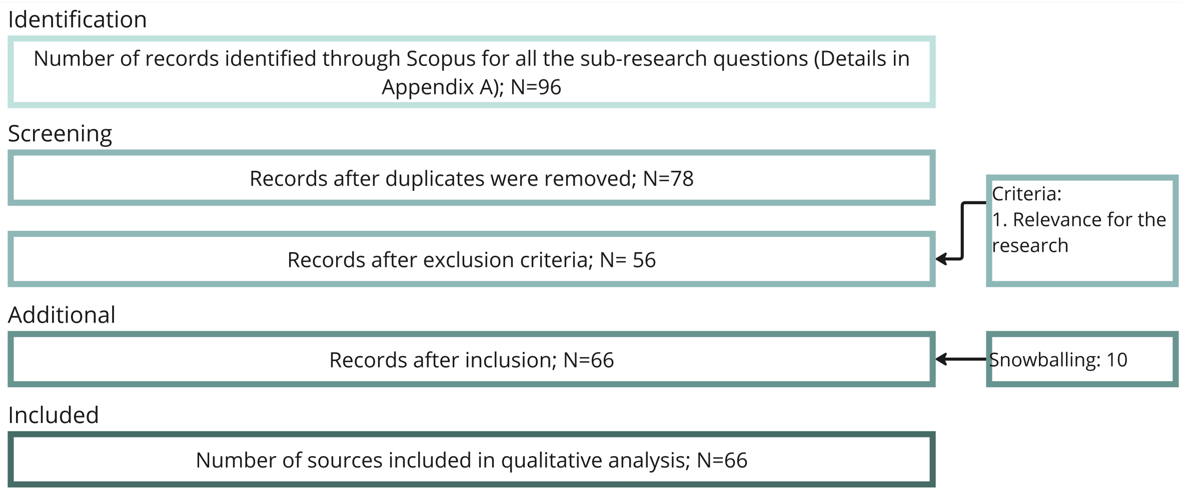



Figure 3.6: process of selecting articles for the systematic literature review, based on PRISMA guidelines. *Note: The systematic literature search was conducted on 01st April 2024.*

The Scopus search included filters for open access, the English language, and articles from 2010-2024. The articles were screened based on duplicates and also depending on the research topic. During this process, additional documents were found using the snowballing method. Eventually, the literature review included a total of 66 articles. One important finding was most of these articles were based on a general understanding of the offshore wind industry. The literature discussed heavily the EoL of wind turbine blades and not the other wind turbine components, such as the support structure, tower, and nacelle.

### 3.3.2. Grey Literature

Next to a scientific literature review, grey literature was also used as a part of data collection to gain insights, especially on the practical side of the research. By definition, grey literature is material on all levels of government, academics, business, and industry that cannot be identifiable by commercial publishers or scientific literature database (Rothstein & Hopewell, 2009).

CE and sustainability are hot topics of discussion for governments and the industry that go hand in hand regarding research development. Specifically for the industrial level, reports from companies with a significant impact on the offshore wind industry, such as Ørsted, Vattenfall, Vestas, Siemens Gamesa Renewable Energy, etc, were used. Most of these documents/reports are open source and can be retrieved from databases such as Google Scholar or by visiting the organizational websites. The research was conducted in collaboration with ECHT, and reports and documents provided by the company that were relevant to the study were also used.

As seen in Figure 3.7, key research areas were identified to make the search for grey literature manageable. It is important to note that the grey literature review procedure is not as thoroughly explained as the scientific literature review approach.

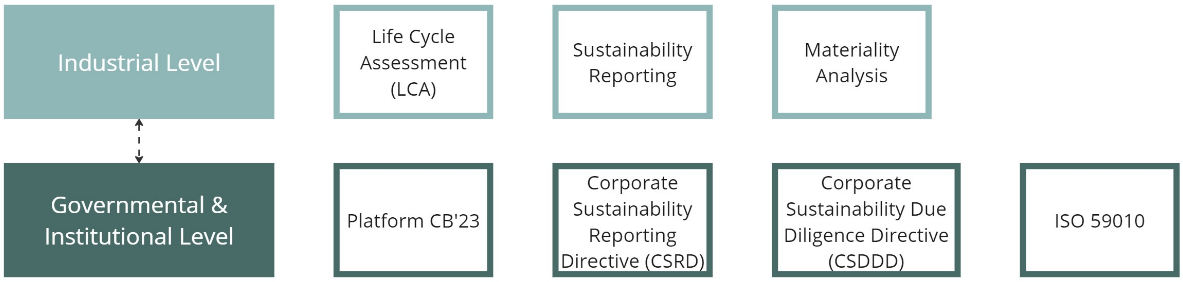



Figure 3.7: Key topics used to search for grey literature. *Note: This document/report search was conducted on 01st May 2024.*

There is research conducted on these topics at the **Industrial Level**:

1. LCA: An LCA is a method used to evaluate the resources used and environmental effects of a product's acquisition of raw materials, manufacture, and consumption, as well as waste management throughout its life span (Finnveden et al., 2009).

   Several companies have set up their LCA's reporting (Gamesa, 2023; Vestas, 2024; Ørsted, 2023b).

2. Sustainability Reporting: Companies pursuing different economic, environmental, and social interests try to meet these demands by being transparent and disclosing sustainability information to diverse stakeholders. Sustainability reporting is essential in determining corporate sustainability (Hahn & Kühnen, 2013).

   Companies also set benchmarks against their competition through sustainability reporting. Several companies deliver their sustainability reporting (RWE, 2023; Seaway7, 2023; Vattenfall, 2023; Vestas, 2023; Ørsted, 2023a).

3. Double Materiality Analysis: Materiality analysis aims to determine the most significant sustainability information for the companies and their stakeholders. Reports become more relevant, trustworthy, and transparent, enabling companies to better inform markets on their sustainability commitment (Calabrese, Costa, Ghiron, & Menichini, 2017).

   The materiality analysis is sometimes reported along with the sustainability reporting (Ramsköld, 2022; RWE, 2023; Seaway7, 2023; Vattenfall, 2023; Vestas, 2023; Ørsted, 2023a).

On a **Governmental Level**, organizations are trying to develop standards that will eventually aid the industry in becoming more circular and sustainable, such as:

1. Corporate Sustainability Reporting Directive (CSRD): Requires companies to report on the impact of corporate activities on the environment and society, and requires the audit of reported information (Finance, 2023; PricewaterhouseCoopers, 2023).

2. UPCM Guideline Materials Passport: The guideline may encourage the delivery of "minimum required circular information," which will allow an understanding of the degree of circularity of a given product or service based on circular data (Maakindustrie, 2023).

3. Platform CB'23: CB'23 is a Dutch nationwide agreement on circular construction that provides guidelines on topics such as Measuring Circularity, Passport for construction, Future Reuse, Circular Design, and Circular Tendering in the construction sector (Platform, 2024).

4. ISO 59010: ISO 59010 guides organizations wishing to transition their value creation models and networks from a linear to a circular framework. This standard focuses on business-oriented strategies to implement circular economy practices at organizational and inter-organizational levels (*ISO 59010*, 2024).

### 3.3.3. Semi-Structured Interviews

One of the qualitative approaches to collecting data (Ahlin, 2019) is conducting interviews. Structure interviews allow little to no room for deviation from the interview questions, whereas semi-structured interviews allow flexibility in their structure. Semi-structured interviews encourage participation and dialogue between the researcher and the experts from the field of study.
Validity is sometimes viewed as a threat to qualitative research since interviews are considered a more subjective data collection method. They typically do not provide statistics or quantification of replies. However, because semi-structured interviews collect firsthand, in-depth descriptions of practitioners' thoughts, behaviors, and responsibilities, they offer high validity (Ahlin, 2019).

The transition toward a CE necessitates effective collaboration between stakeholders in the EoL of OWFs. Gaining insights from the practice by conducting interviews was necessary for this research. The interviews aimed to find information that could not be found in the literature review. As illustrated in Appendix C, the stakeholders are identified through a stakeholder mapping for EoL OWFs. Next, Table 3.1 categorizes the stakeholders into four main categories and presents the stakeholders in each category.

Table 3.1: Table summarizing the stakeholder categories, the OWF decommissioning stakeholders, and the key roles. Adapted from: Spielmann et al. (2021); van Capelleveen et al. (2023)

| Categories | EoL Stakeholders | Key Role |
|---|---|---|
| The Owners' Chain | Wind Park Developer | The main responsibilities assigned to the actor in this category is to provide the existing data, legal responsibility, and circular ambitions for the entire supply chain. |
| The Governance Chain | Regulatory Authority<br>Consulting Companies<br>Research Institutes/Universities<br>Environmental Organizations<br>Certification/Inspection Body | The main responsibilities assigned to the actors in this category are verifying quality, integrity, and validating information. |
| The Financial Chain | Finances<br>Project Management | In the context of this research, the main responsibilities include managing the finances, evaluating the risks/opportunities, and managing the whole project. |
| The Production Chain | Manufacturer<br>Supplier<br>Logistics Company<br>Dismantling Company<br>EoL Resource Management Company | The main responsibilities assigned to the actors in this category are to provide documentation and information regarding the production, maintenance, and dismantling activities for other actors to benefit from this information. |

The purpose of these interviews is to learn about the key challenges faced in implementing circular practices in the EoL of an OWT, the key parameters and data attributes to access circular strategies, and the understanding of a DPP system. Interviewees were encouraged to share their perspectives about implementing circular practices to achieve maximum circularity, followed up with the key parameters that guide the decision-making, and finally, the second-hand market and the questions regarding understanding a DPP system. The questions were formulated to minimize interviewee bias by referring to interview strategies defined by Fitzpatrick (2013).

A guide was formulated before conducting the interviews. The interview was divided into three themes. The themes consisted of predetermined questions, keeping in mind to leave room for flexibility in the conversation. This guide can be found in Appendix B. The themes are elaborated more in the following paragraphs:

Theme 1 - **Role/expertise of the interviewee:** Role/expertise of interviewee within the organization concerning the research topic. The conversation followed up with their challenges and motivations in the EoL resource management of wind turbine components (Sharing a personal experience with an ongoing or previous project).

Theme 2 - **Understanding the key parameters in circular decision-making:** Exploring what are the key parameters and data attributes that need to be accessible by the decision maker of the EoL of components of a wind turbine. The parameters will form the basis of the framework that will guide the circular decision-making.

Theme 3 - **Second-hand market for wind turbine components:** As the focus of this research is to maximize the reuse of second-hand components, it is necessary to understand the perspective of the second-hand market for wind turbines. The conversation followed up with an understanding of a DPP discussing how this can help the supply chain in the second-hand market be more efficient.

The interviews were videotaped and transcribed to ensure the reliability and completeness of the data collected through interviews. The interviews were conducted with nine stakeholders from various stages of the EoL decommissioning of a wind turbine, as shown in Table 3.2. It was crucial for the research to include a variety of stakeholders as their various viewpoints provided unique insights into the procedure and helped to paint a complete picture.
To ensure the data collected covers all fields for this research and reduces biases as much as possible, the selection process of participants is crucial (Ahlin, 2019). Although the preference was to conduct the interviews face-to-face due to the availability of time and the convenience of interviewees, all the interviews were conducted online.

Table 3.2: Interviewees from organizations that participated in the research, their expertise, and the date of interviews.

| Organization | Country | Expertise | Interview Date |
|---|---|---|---|
| Windplanblauw | The Netherlands | Project Management (Wind farm developer) | 2024-07-05 |
| Sif-Group | The Netherlands | Decommissioning Resource Manager | 2024-06-14 |
| Lubbers Logistics | The Netherlands | Decommissioning Contractor | 2024-03-19 |
| University of Leeds | United Kingdom | CE expert Offshore Wind | 2024-06-13 |
| Suzlon | The Netherlands | OEM | 2024-06-05 |
| EoLO-HUBs | EU Consortium | Re-manufacturing and Refurbishing | 2024-06-20 |
| Continuum Group | Denmark | Recycling | 2024-06-17 |
| DNV-REWind | The Netherlands | Digital solution for sustainable wind farm decommissioning | 2024-06-12 |
| Business in Wind | The Netherlands | Second-hand Dealers | 2024-06-20 |

It is essential to guarantee the confidentiality of the personal information of the interviewees. Personal information is kept safe using the Human Research Ethics (HREC) committee guidelines of Tu Delft (Delft, n.d.). Since the interviews were videotaped and transcribed, guidelines were followed for storing and sharing the data. Appendix B presents the mentioned guidelines to safeguard privacy and data.

## 3.4. The Define Stage

The insights from the literature review and semi-structured interviews must be analyzed to understand the initially defined problem. The processing and filtering of the data collected will be the main emphasis of DDM's "Define Stage". It will ultimately result in the specification and requirements for the circular decision-making framework and a comprehensive DDP. The literature review forms the basis to conduct and analyze the interview data, as illustrated in Figure 3.8.

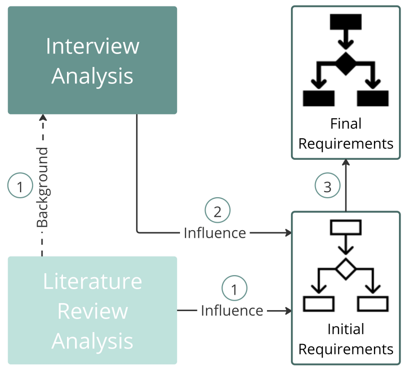



Figure 3.8: Illustration of how the literature review and the interview analysis influence defining the requirements for the tool.

### 3.4.1. Literature Review Analysis

A structured approach analyzes the literature review to ensure comprehensive and unbiased results. The literature review analysis will provide an overview of the circular strategies applied to the components of an OWT and the circularity assessments necessary to assess these circular strategies. SQ0 and SQ1 guide the analysis.

### 3.4.2. Interview Analysis

The data collected through interviews was analyzed to identify key parameters, and the challenges faced by the stakeholders in incorporating CE in the EoL phase will be identified. SQ2 and SQ3 guide the analysis.
According to Creswell and Poth (2016), the typical steps after conducting interviews are data analysis and interpretation, code application, code categorization, and pattern recognition. Table 3.3 presents the 6-step framework for a thematic analysis followed by an adapted 4-step framework, illustrated in Figure 3.9.

Table 3.3: 6-Steps of a thematic analysis. Source: D. Byrne (2022).

| Steps | About | Description |
|---|---|---|
| 1. | Familiarizing yourself with your data | Transcribing data (if necessary), reading and re-reading the data, and noting down initial ideas. |
| 2. | Generating initial codes | Coding the interesting features of the data systematically across the entire data set and co-relating the codes to each other. |
| 3. | Searching for themes | Collating codes into potential themes and gathering all data relevant to the potential themes. |
| 4. | Reviewing themes | Checking if the themes work about the coded extracts and the entire data set, eventually generating a 'thematic map' of the analysis. |
| 5. | Defining themes | Ongoing analysis to check the specifics of each theme and the overall story the analysis tells, generating clear definitions and names for each theme. |
| 6. | Producing the report | The final opportunity for analysis and relating to the research questions and literature review. Producing a scholarly report of the analysis. |

The adapted 6-step framework for the thematic analysis of the interviews conducted for this research is illustrated in Figure 3.9. As seen in the figure, the 6-step framework is adapted to this research as a 4-step framework because of the scope and the research time.

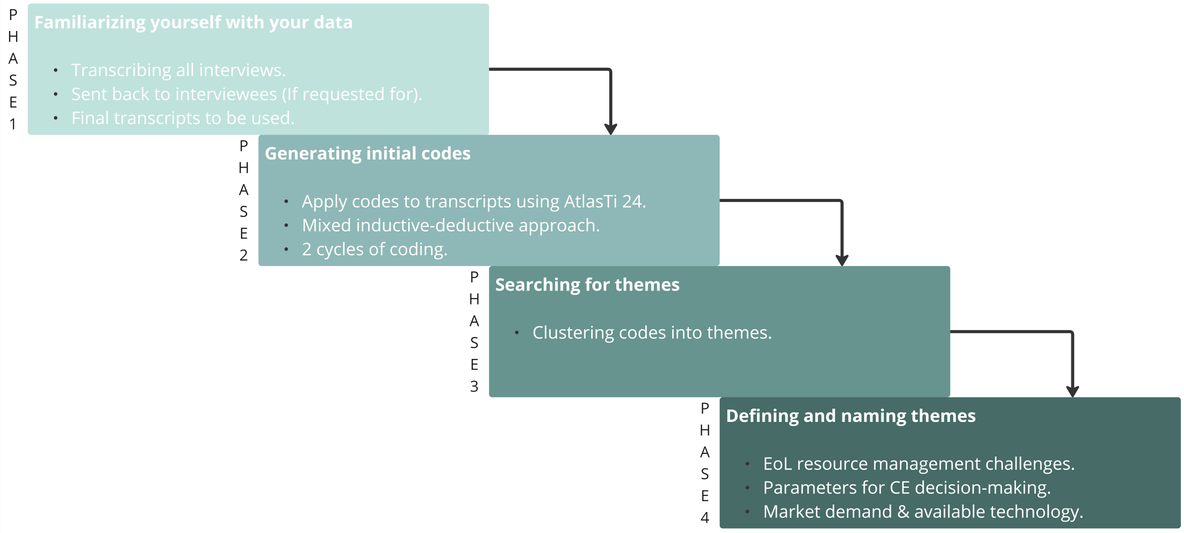



Figure 3.9: Adapted 4-step framework for thematic analysis of the interview data. Adapted from: D. Byrne (2022).

**Phase 1: Familiarizing with the data**
*Transcribing the interviews*

The interviews were recorded with the permission of the interviewees. The video recording was transcribed using automated transcript generation within Microsoft Teams. When something is fully transcribed, it indicates that every word said during the interview has been documented in writing. For instances where video recording was impossible, making notes is crucial at this point (Linneberg & Korsgaard, 2019). Results and conclusions cannot be drawn just from the transcripts. The original transcripts are filtered for excess words and expressions such as um, ohh, etc.

**Phase 2: Generating initial codes**
*Coding*

The next step was to analyze the interviews after the transcripts were ready to use. The interview data is analyzed using the program Atlas Ti-24. The texts from the transcripts are identified by assigning certain codes in Atlas Ti; therefore, an overview is created using all the data that has a code associated with it. The transcripts were carefully reviewed, vetted, and coded for the coding process. Codes were assigned to any information that might help answer the research question(s).

*Approach to Coding*

There are three different ways of coding: inductive-open coding, deductive-predefined list of coding, and a mix of inductive and deductive approaches. This research will use a combination of both deductive and inductive coding. The mixed approach leaves room for the researcher to discover surprises in the data.

Thus, the coding will take place in two cycles. The first cycle of codes starts with a deductive approach, where a codebook will be developed using an initial set of codes. The initial codes were identified by reviewing the transcripts, which led to an overview of common words, expressions, and quotes.
Next, adding these codes to Atlas Ti and canning for new codes is called the inductive approach. The process of looking for codes is carried out until no more codes can be defined.

**Phase 3: Searching for themes**
*Clustering*

The next step was to review and group codes related to a single theme after the second coding cycle. Creating a storyline or a broad framework can be helpful in this process. A ‘theme’ can be defined as:

“..a pattern that captures something significant or interesting about the data and research question”
-Baldew

The themes are linked with the fundamental concepts of the literature review.

**Phase 4: Defining and naming themes**
*Themes*

The outcome of the first three phases is presented in Table 3.4. These themes are used to analyze the interview and find patterns through the transcripts.

Table 3.4: Coding interviews via Atlas Ti.

| Theme | Code | Definition | Example |
|---|---|---|---|
| Challenges | Technical Challenges | Difficulties related to technical aspects of managing wind turbine components at their EoL phase. | Disassembly issues, recycling technologies, material composition, lack of maintenance records. |
| | Economic Challenges | Financial issues that affect the management of wind turbine components at their EoL phase. | High cost of decommissioning, limited market demand for second-hand components, investment in circular practices. |
| | Regulatory Challenges | Difficulties in meeting regulatory requirements and compliance standards. | Compliance with regulations, impact of legislation on business operations. |
| | Social and Environmental Challenges | Social perceptions and environmental concerns related to the EoL phase of wind turbine components. | Public perception, environmental impact, circularity ambitions. |
| Key Parameters | Component Condition | Assessment of the physical state and integrity of wind turbine components. | Structural integrity, current age, future lifespan. |
| | Operational History | Historical data related to the operation and maintenance of wind turbine components. | Maintenance schedule, operational performance. |
| | Material Properties | Information on the materials used in wind turbine components and their recyclability. | Material composition, recyclability. |
| | Traceability and Transparency | Methods for collecting, processing, and tracking data about wind turbine components. | Data collection, technology use. |
| Market Consideration | Transparency | The need for clear and accessible information throughout the supply chain. | Transparency in operations and data sharing practices. |
| | Second-hand Market | Factors affecting the use of second-hand components in the market. | Market demand, quality assessment of second-hand components, and product market fit. |

## 3.5. The Develop Stage

This stage is the start of the second part of the DDM. Here, the insights gathered and the analysis of the insights (design brief or the final requirements) aid in developing the DPP structure and circular decision-making framework. Subsequently, both of these are integrated to form a coherent tool. The tool must be checked to see if the requirements specified in the Define Stage are included. The check will add a verification to the tool. Throughout the development stage, the following steps will be taken as illustrated in Figure 3.10:

1. Inspiration from existing frameworks (Agra Neto et al., 2024; Jadali et al., 2021; Velenturf, 2021) are used to develop the circular decision-making framework tailored for the EoL resource management of OWT. The factors for the decision-making include the challenges of the stakeholders, the assessment criteria, and the circular strategies derived from the design brief.

2. To develop a standardized data management system, it is necessary to have a structured data collection platform. Thus, the next step in the development phase is to create a DPP structure that specifies data attributes needed for circular decision-making.

3. The circular decision-making framework and the DPP structure are cross-verified with the requirements specified in the Define stage.

4. The circular decision-making framework is incorporated into the DPP structure to facilitate standardized decision-making. This step accumulates to the formation of the EcoRush Tool.

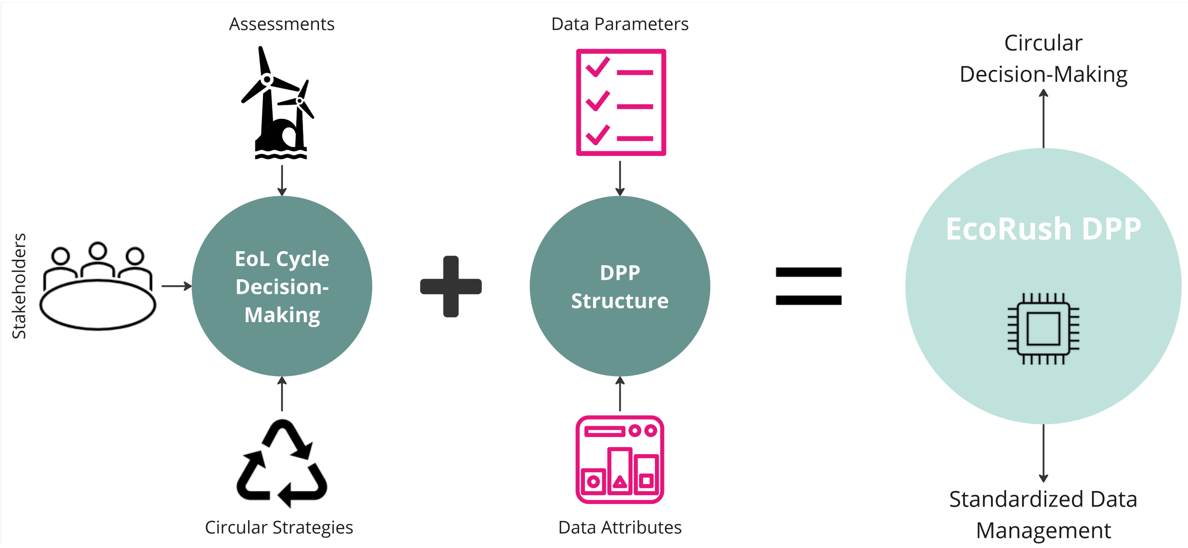



Figure 3.10: Overview of Development Stage, leading to the development of the EcoRush Tool.

## 3.6. The Deliver Stage

Finally, the last step of the DDM is the Deliver Stage. This section discusses the process of testing and validating the tool. The aim is to gather constructive feedback, make necessary adjustments, and confirm that the tool meets the requirements and expectations of its end-users. Validation is conducted in consultation with experts within ECHT regie in transitie.

The delivery stage is a threefold process as follows:

1. Circular Decision-Making Framework Validation: This step includes individual validation sessions for the circular decision-making framework (Figure 4.23) before implementing it in the EcoRush DPP. The purpose of conducting individual sessions was to gain in-depth feedback with reduced risk of bias. This process reflects the back-and-forth process of Develop and Deliver Stage of the DDM.
2. Testing the tool with Real Case Data: The data necessary for the circular decision-making will be collected and analyzed using the EcoRush DPP presented in Section 4.10. The tool will be tested through case data gained through the inspection reports of three different projects of ECHT regie in transitie (the names of these projects cannot be mentioned for confidentiality reasons). These projects are onshore wind turbines because of the limited available data for the OWT. Considering the research's timeline and data availability, the testing will be carried out for a single component, i.e., the Tower. The onshore wind turbine tower has significant similarities with the OWT Tower. This testing will provide guided steps to follow the decision-making framework. A similar approach can be followed to assess the circularity of the different components of an OWT.
3. Validating the results: This is a group validation session within the company where experts from various backgrounds will review the working of the decision-making framework regarding the three different cases through the EcoRush DPP tool. The session will be deliberately conducted in a group session as group discussion can foster collaborative problem solving, where a comment from one expert may trigger valuable insights or solutions from another. The comparison here will be based on the results obtained through the circular decision-making framework developed in this research versus real-life decision-making.

These three steps will validate the framework and deliver the final **Standardized Data Management System aiding in the EoL Circular Decision-Making**. The feedback received in the validation steps will follow the following protocol:

- General guideline: At the start of each step, the participating experts were given a summary of the development, the research progress, and the aim of the meetings.
- Step 1: The gained feedback will be incorporated into the decision-making framework. Since this framework is a critical step for the research, the feedback gained will be implemented during the development phase. Thus, the report will present the decision-making framework incorporating the feedback.
- Step 2: As previously mentioned, the testing will be carried out using the existing data of wind turbines and will be limited to the Tower of wind turbines. The wind turbine towers of three different projects will be used for the testing. A step-by-step guide will be provided to act as a reference for carrying out the testing for future components.
- Step 3: The feedback gained in this step will be based on several factors that may be out of the scope of this research. Thus, the input will be considered to some lengths and within possible boundaries.

*Following chapter will discuss the results and analysis of the research.*


CHAPTER

04

# RESULTS & ANALYSIS

# 4

# Results and Analysis

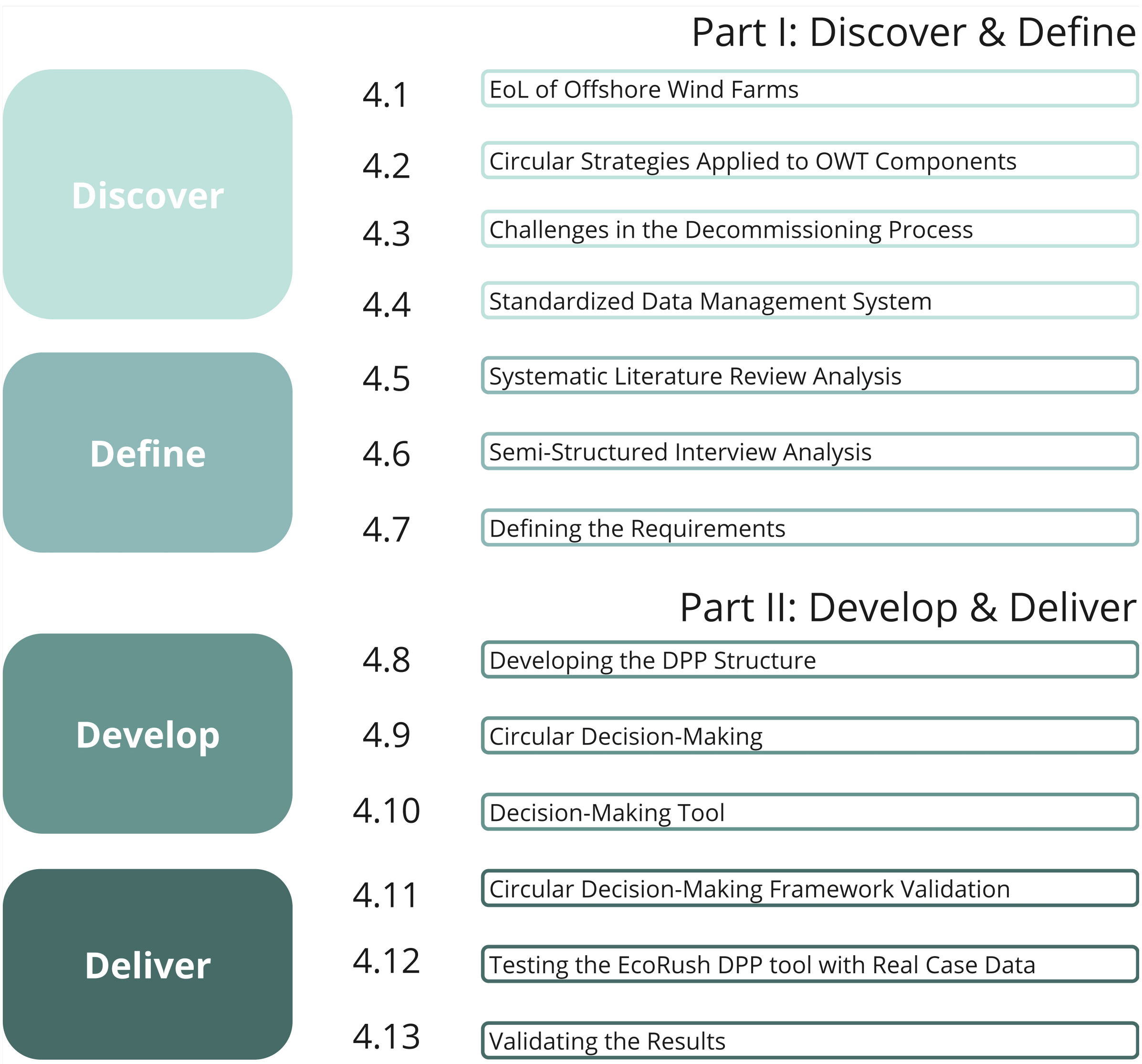



Figure 4.1: Overview of Chapter 4.

# Part I: Discover & Define

The first part of Chapter 4 focuses on the data collection through a systematic literature review and semi-structured interviews.

# Discover (Data Collection)

This section provides the data collection for the research to address the following sub-question:

- *SQ.1: What are the various components of an OWT and their respective EoL circular practices?*

To answer SQ.1, it is necessary to first look at the various EoL scenarios of an OWF as they define the type of circular strategies applied to the components of an OWT. Next, as the research is focused on EoL resource management, it is necessary to explore the challenges faced in the decommissioning process and barriers to incorporating circular strategies in the decommissioning phase. Lastly, examining the role of a standardized data management system regarding the EoL resource management of OWTs is essential.

## 4.1. EoL of Offshore Wind Farms

The EoL of a wind farm can be identified in two contexts: extending the project life or decommissioning and completing operational functions. The decommissioning phase can be systematically divided into six EoL scenarios as follows (Agra Neto et al., 2024):

1. Total decommissioning (deactivation):
   Example: Blyth Offshore Wind Farm, UK.
   The Blyth Offshore Wind Farm, which consists of two turbines and is one of the first offshore wind farms in the UK, was fully decommissioned in 2019. The project involved removing the turbines, foundations, and subsea cables and restoring the site to its original condition. The first turbine was set to be recycled and reused for spare parts, and the second was used for training purposes (Skopljak, 2019).

2. Total decommissioning with full re-powering:
   Example: Middelgrunden Offshore Wind Farm, Denmark.
   The Middelgrunden Offshore Wind Farm owners are considering a complete re-powering project where old turbines were removed and replaced with newer, more efficient models. The process of re-powering involved the complete decommissioning of the existing infrastructure followed by the installation of new turbines (Baltic, 2023).

3. Partial decommissioning with partial re-powering:
   Example: Hipples Wind Farm, Austria.
   In Austria, the Windkraft Simonsfeld project involved partial decommissioning, and specific older turbines were replaced with new ones. At the same time, some wind farm areas continued to operate with existing turbines.

4. Partial decommissioning with retrofit:
   Example: Tehachapi Pass Wind Farm, USA.
   Tehachapi Pass Wind Farm in California saw partial decommissioning with retrofit projects. Some of the older turbines were retrofitted with new technology to improve efficiency and extend their operational life, while other parts of the farm were decommissioned (Fried, 2012).

5. Partial decommissioning with re-powering and hybridization:
   This approach combines partial decommissioning with re-powering and hybridization by integrating new wind turbines and innovative ways to incorporate other renewable energy sources, such as solar. There is yet no practical example of this scenario.

6. Partial decommissioning with re-powering and retrofit:
   Example: Altamont Pass Wind Farm, USA.
   Altamont Pass Wind Farm in California underwent partial decommissioning, during which older turbines were replaced (re-powered) with more efficient models, and others were retrofitted to improve performance. This hybrid approach allowed for an optimized balance between new installations and upgrades to existing infrastructure.

The activities involved in the typical EoL for the resource management of the decommissioned components and materials are illustrated in Figure 4.2. Typically, EoL resource management is considered to start post-decommissioning, which is evident from Figure 1.4 and 4.2. The decommissioning plans about resource management methods do not consider the sustainable aspect of material recovery (P. D. Jensen et al., 2020). Initiatives are taken to develop the most efficient sustainable decommissioning methodology for OWF by (Topham & McMillan, 2017), further explained in Section 4.2.

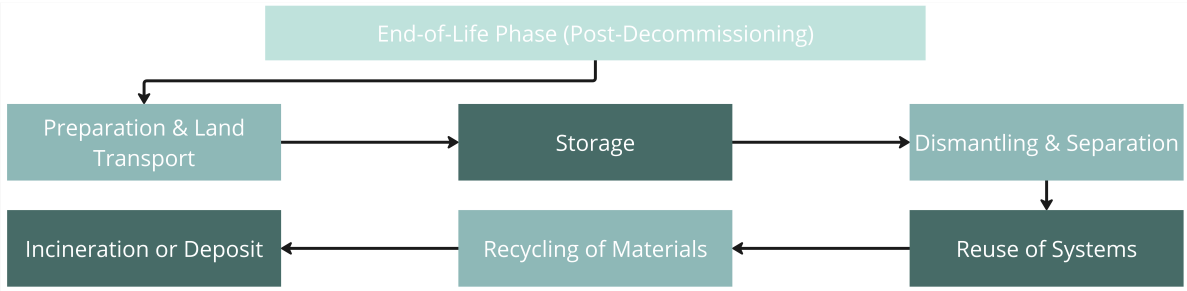



Figure 4.2: Activities involved in the EoL resource management. Adapted from: van der Meulen et al. (2020).

P. D. Jensen et al. (2020) argues the need to have a design considering decommissioning in mind. Partial decommissioning involves disassembling all components except those with longer planned service life, such as foundations, inter-arrays, and export cables (Hou, Enevoldsen, Hu, Chen, & Chen, 2017). Whereas complete decommissioning involves the removal of all the infrastructure, the purpose of which is to return the site to its most possible original condition (Hou et al., 2017).

Wind turbine components can be reused by *checking, cleaning, or repairing* in the same function or repurposed to be used in a different function. For example, using a turbine blade again as a blade would be reused, and using a turbine blade as a structural element in a bridge would be considered repurposed (Velenturf, 2021). Reusing a wind turbine component comes with the challenge of the component's reliability concerning its function. The reuse of wind turbine components is limited due to a lack of standardization across the industry. A step towards overcoming this challenge is to have standardized resource management to manage EoL resources efficiently (Velenturf, 2021). Developing a standardized solution for EoL resource management is challenging due to limited knowledge about the resource stocks and flows of components/materials (Chen et al., 2021).
Several factors influence the decision-making at the EoL. Agra Neto et al. (2024) identified factors that influence the decision-making of EoL of wind farms as follows:

1. External Aspect
   (a) National energy guidelines: These include the national energy planning considering energy demands, policies, and investment strategies.
   (b) Regulatory aspects and public policies: Land use authorization and public policies related to renewing power generation contracts or decommissioning.
   (c) Logistics and infrastructure aspect: This includes the electrical network and physical infrastructure to support the decision for the EoL.
   (d) Technological development in the sector: Technological developments are much faster, and thus, to cater to energy demands, there is a need to adapt to technological developments.
2. Internal Aspect
   (a) Economic aspect: The economic feasibility of the extension/reuse/repair of decommissioning the wind turbine components. Feasibility includes the operation and maintenance costs, the residual value of the components/materials, labor, and equipment needed for the decommissioning, and the price of complete or partial re-powering.
   (b) Environmental aspect: These include the carbon footprint of the decisions made during the decommissioning phase.
   (c) Operational aspect: The availability of specification data of the turbine component (number, dimensions, maintenance schedules, bill of materials, etc.) and the expiration of the current contracts.

Time and Costs have a significant impact on the decommissioning process. The most time-consuming activities are considered to be project management, planning, and procurement (Topham & McMillan, 2017), and including EoL resource management as an additional aspect of the decommissioning phase can be challenging.

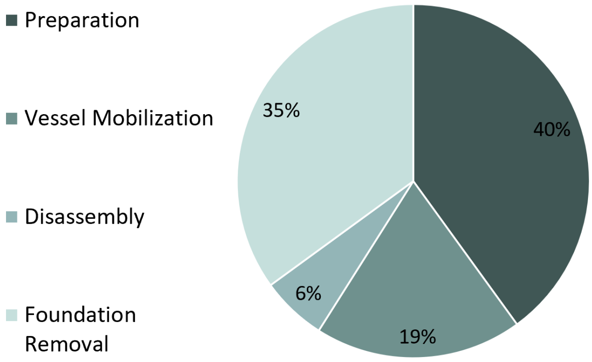



Figure 4.3: Approximate cost breakdown of OWF decommissioning. Source: Topham and McMillan (2017).

It is argued that efficient project management and planning can optimize resource reuse and recycling, thereby reducing waste and associated costs (Korhonen et al., 2018). However, efficient project management is in contrast to the existing decommissioning programs; due to the lack of experience, it is observed that time and cost estimation are optimistic according to Topham and McMillan (2017), and may pose a challenge while incorporating circularity in its operations. Figure 4.3 illustrates the breakdown of the decommissioning costs. The preparation phase, where the EoL resource management must be active, is the most expensive phase.

The offshore wind farm decommissioning is a complex process that involves multi-level and multi-functional collaboration and dependencies among stakeholders, e.g., approval holders, authorities, service companies, consulting companies, etc. Spielmann et al. (2021) identified three approaches for efficient collaboration among the stakeholders. The approaches are as follows:

- Sustainability Approach: Topics, objectives, and attributes relevant to the sustainability of OWF decommissioning;
- Stakeholder Approach: Deciding the stakeholder involvement in the OWF decommissioning based on their expertise, characteristics, and relevance to the project.
- Process Approach: The level of detail of each process is analyzed to assess sustainable performance.

The integration of all three approaches illustrated in Figure 4.4 will aid in achieving maximum sustainability goals in offshore decommissioning (Spielmann et al., 2021). The figure provides a guide to keep the decommissioning process sustainable while keeping the stakeholders and the technical process needed satisfied.

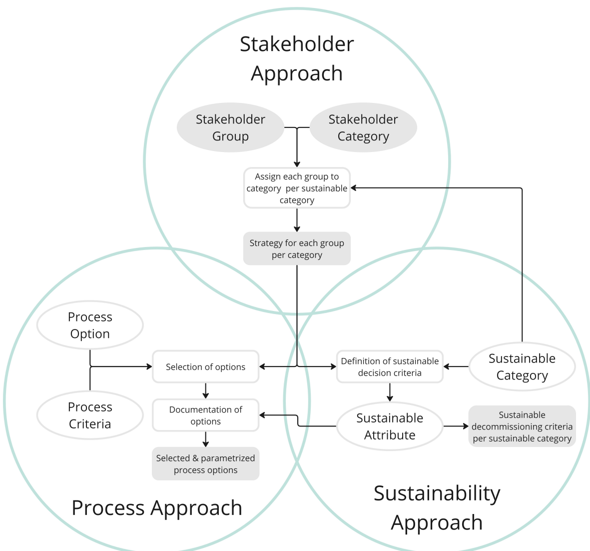



Figure 4.4: Integration of the three approaches (Stakeholder, Process, and Sustainable) to overcome challenges of OWF decommissioning. Source: Spielmann et al. (2021).

## 4.2. Circular Strategies Applied to OWT Components

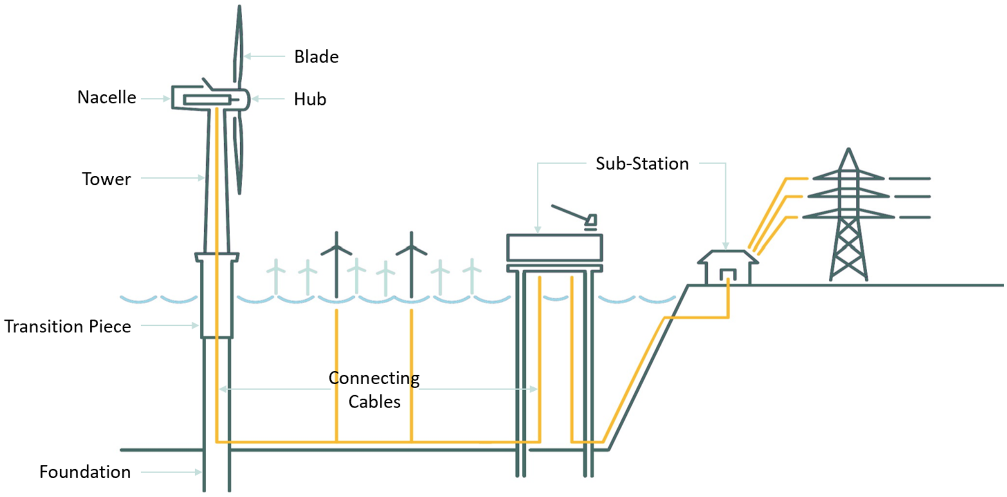



Figure 4.5: Components of an offshore wind farm on a system level.

Figure 4.5 illustrates an OWF system. Since the scope of this research is limited to the wind turbine components and not the entire offshore wind system, the following discussion will include the components of an OWT. To understand the circular strategies applied to the different components of an OWT, it is first necessary to summarize the various components of the turbine, their sub-components, and their material composition.
Approximately 30,000 parts, organized into the primary components including the support structure, tower, nacelle, and rotor, comprise an OWT (Vestas, 2024). Numerous mechanical and electrical parts, including the gearbox, main shaft, generator, control systems, etc, are housed inside the nacelle. In a typical OWF project, the components and the sub-components are manufactured by different sub-suppliers and purchased by the main contractor (Vestas, 2024).
Table 4.1 provides a comprehensive overview of the components, sub-components, and the material composition along with the indication of ease of recycling (Red= Not Possible; Yellow= Difficult; Green= Easy). From the table, it is evident that most of the turbines are recyclable, but recycling requires excessive energy and is highly cost-intensive.

Table 4.1: Components of an OWT along with their sub-components, material composition, and ease of recyclability.

| Component | Sub-Components | Materials |
|---|---|---|
| Support Structure | Transition piece | S355 Steel |
| | Foundation | S355 Steel |
| Tower | Tower | Steel |
| Nacelle | Yaw mechanism | Alloy steel gears/bearing + cast iron casing + copper windings |
| | Transformer | Iron, Copper, Aluminium |
| | Cover | GFRP |
| | Gearbox | Steel & Cast iron |
| | Generator | Iron |
| | | Copper |
| | | Magnet |
| | Shaft | Alloy steel |
| | Power Electronics | Silicon, Copper & Various Metals |
| Rotor | Blades | Composite |
| | Hub | Spheroidal graphite cast iron |
| Miscellaneous | Sensors | Various Metals & Plastics |
| | Computers and Controllers | Silicon, Plastics & Metals |
| | Cables | Copper, steel, lead, HDPE |

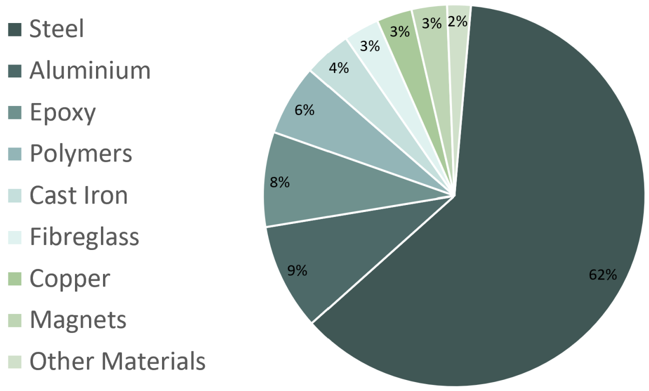



Figure 4.6: Approximate material composition of a wind turbine. Source: Gamesa (2023).

Wind turbine blades constitute 6% of the weight/ and the remaining weight of the turbine consists of components with a more complex composition. Figure 4.6 provides an average estimate of the type of materials in a typical wind turbine. Due to the challenges of recycling composite materials, most academic and practical research focuses on the wind blade component. Circular strategies applied to the OWT components besides WTB are addressed at the material level by focusing on strategies such as Dematerialization and Waste Prevention (Telsnig, 2022).

In a research case study of the RWE's offshore wind farm Trinton Knoll conducted by Svensson (2023), the decommissioning plan regarding sustainability is majorly focused on the WTBs and the towers prioritizing lifetime extension, second-hand use, waste management plans for decommissioning processes, and avoiding landfills. The optimal and sustainable decommissioning method includes minimum offshore activities, and activities like disassembly, repairs, etc, must be carried out onshore (Topham & McMillan, 2017). Following is the discussion on the component level of an OWT that will explore the definitions of the components, the optimal and sustainable decommissioning methods, and the current applied circular strategies. The whole OWT must be entirely removed from the site and disassembled onshore to achieve maximum sustainability during the decommissioning phase, which depends on factors like the size and weight of the turbine (Topham & McMillan, 2017).

### 4.2.1. Support Structure

The function of the support structure is to provide a steady base to the tower and other components of an OWT (Nyserda, n.d.). There are three types of foundations, depending on the site conditions:

1. Monopile Foundation: A prominent structural steel tube driven into the ocean floor, measuring around 10m in diameter. Zinc anodes are utilized to prevent corrosion, and the monopile's upper portion is painted. Monopiles are usually suited for water depths up to 50m (Vestas, 2024).
2. Jacket Foundation: A steel lattice structure that may be secured to the ocean floor using detachable suction buckets or pin piles driven into the earth. These structures might have four or three legs, straight or crooked. Zinc anodes are utilized to prevent corrosion, and the structure's uppermost part is painted. Suitable in areas where the risk of earthquakes is greater. Jacket foundations are suited for water depths up to 50m (Vestas, 2024).
3. Floating Foundation: A sizeable floating structure made of structure steel or a combination of concrete and structural steel moored to the seabed using steel mooring lines. This system suits water depths greater than 50m (Vestas, 2024).

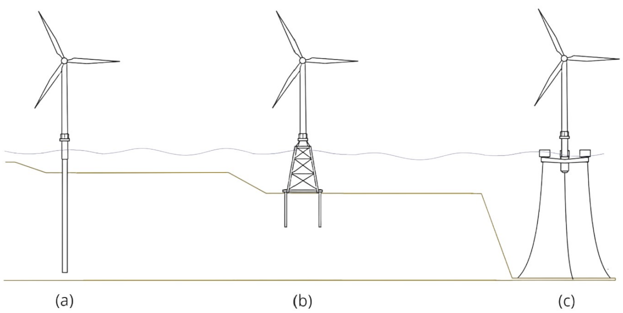



Figure 4.7: Types of OWT foundation. (a) Monopile, (b) Jacket, and (c) Floating. Source: Mandolini (2018).

The EoL management of a wind turbine's support structures, including the transition piece and foundation, is critical due to the substantial material use and potential environmental impacts associated with these components. The suggested decommissioning method for the support structure is to lift the transition piece along with the foundation (monopile and jacket foundation in this case), where the foundation is cut 1m below the mud line to minimize the environmental impact (Topham & McMillan, 2017).
There are three parameters to assess the structural reuse of steel components: (a) Deterioration, (b) Defects, & (c) Damage. These components can potentially be reused in a similar function (circular strategy: Reuse) or reused in a different function (circular strategy: Re-purposing) provided certification for reuse is issued (Coelho, Pimentel, & Sansom, 2021). This document must include test reports, inspection certificates, and a declaration of compliance.

### 4.2.2. Tower

The tower's function is to support the wind turbine's super-structure, mainly consisting of the Nacelle and the Rotor (Nyserda, n.d.).
The tower comprises two or more sections of tubular steel (Thomsen, 2014). COBOD (2024) developed a 3D-printed concrete tower enabling the construction of towers with increased heights to increase energy production and reduce costs. The circular strategies applicable in the Cobod innovation are (Telsnig, 2022): (a) Components reuse and re-purposing, (b) Recycle, and (c) Energy Recovery. Modvion (2023) developed a modular wind turbine tower that reduces the CO2 emissions by 90% during the production process, and with minor adjustments, it can be applicable in offshore wind projects too. The Modvion Wooden towers can be re-purposed in conventional buildings after the decommissioning process (Modvion, 2023). The circular strategies applicable in the Modvion innovation are as follows: (a) Dematerialization, (b) Prevent Waste, (c) Modularise, (d) Component reuse and re-purposing, & (e) Recycle (Telsnig, 2022). Both innovations consider the BoL of a tower, highlighting the transition towards using materials that can be more easily recycled or repurposed and have easier disassembly. Most EoL practices for the existing OWT towers are concentrated on recycling.

### 4.2.3. Wind Turbine Blades

The function of the blades is to convert the wind energy into mechanical energy (Nyserda, n.d.).
The size of these blades for onshore wind turbines is often over 52 meters, whereas they can be twice in size for OWTs (Office, n.d.). Countries such as Germany, The Netherlands, Austria, and Finland have already banned the landfill and incineration of composite waste (Chatziparaskeva et al., 2022), which has led the wind industry towards new sustainable EoL processes for wind turbine blades (Lund & Madsen, 2024). Telsnig (2022) identifies 20 initiatives that focus on the challenges faced in implementing CE for wind turbine blades. The most evident circular strategies applied to the WTB through the 20 innovation projects are as follows: (a) Dematerialization, (b) Prevent Waste, (c) Component reuse and repurpose, (d) Disassembly, (e) Recycling, and (f) Modularise Telsnig (2022). Most of the circular strategies are researched for the design phase of the WTB. However, the wind industry is still in the early stage of establishing sustainable EoL value chains for decommissioned WTBs, and systematic application of circular strategies is still missing in the academic and practical perspective Lund and Madsen (2024). The circular strategies applied to a WTB were mechanical recycling, thermal recycling, chemical recycling, cement co-processing, and structural re-purposing; a proposed roadmap for sustainable EoL value chains of WTB is illustrated in Figure 4.8. There are several alternatives for the second life of a WTB, but as the figure illustrates, several steps are involved between the decommissioning and the end use. The extensive process makes it difficult to develop a business case around the circularity of wind turbine blades.

Mechanical recycling is the process of cutting, shredding, milling, or grinding WTbs with mechanically powered technology (Rani, Choudhary, Krishnan, & Zafar, 2021). This technique either reduces the size of the resin and fibers before use or is directly used in secondary applications (Ramirez-Tejeda, Turcotte, & Pike, 2017). The recycling method is cost-effective and can accept huge volumes of WTB waste (Krauklis, Karl, Gagani, & Jørgensen, 2021). Mechanical recycling is also a pre-process for thermal- and chemical recycling and cement-co-processing (Rani et al., 2021). Several applications of mechanical recycled WTBs include filler in noise cancellation barriers (Fonte & Xydis, 2021), filler in asphalt or concrete replacing gravel (Rani et al., 2021), filler material in sheet molding (Rentizelas, Trivyza, Oswald, & Siegl, 2022), as dust in wood paint (J. P. Jensen & Skelton, 2018), or can be used in 3D-printed components.

Thermal recycling is when the polymers decompose under hot temperatures, high pressure, and no oxygen (Lund & Madsen, 2024). This incineration process is banned in many European countries as up to 60% of the blade waste is ash, which must be treated or land-filled (J. P. Jensen & Skelton, 2018).
Chemical recycling refers to recycling methods in which resin components in the WTBs are removed or depolymerized with chemical products, separating the fibers from the resin (Ribeiro et al., 2016). This process is considered to have lower environmental impact (Liu et al., 2019), but at the same time, includes downside from potential chemical hazards, and the efficiency depends on the material composition of the WTB (Ramirez-Tejeda et al., 2017).
Cement co-processing was considered the most suitable recycling method amongst the previous three recycling strategies (Paulsen & Enevoldsen, 2021). In this process, the mechanical recycled blades are partly incinerated to heat the cement kilns and partly used to replace raw materials such as sand and limestone in the cement mixture (Paulsen & Enevoldsen, 2021). This process not only helps improve the environmental footprint of the WTB waste but also the environmental footprint of cement manufacturing (Paulsen & Enevoldsen, 2021), as it benefits by replacing fossil fuels and virgin raw materials in cement manufacturing.

Structural re-purposing is a process for EoL decommissioned WTBs where the WTBs are cut into sections and re-purposed in several projects (Lund & Madsen, 2024). Examples of structural re-purposing include furniture (Joustra, Flipsen, & Balkenende, 2021), playgrounds (J. P. Jensen & Skelton, 2018), bridges (André et al., 2020), and housing projects in Mexico (Bank et al., 2018). The potential of re-purposing depends on material composition and the dimensions of the blade. Also, this process can handle a small number of WTBs and can be a good option for asset owners with a small portfolio of wind turbines (Lund & Madsen, 2024).

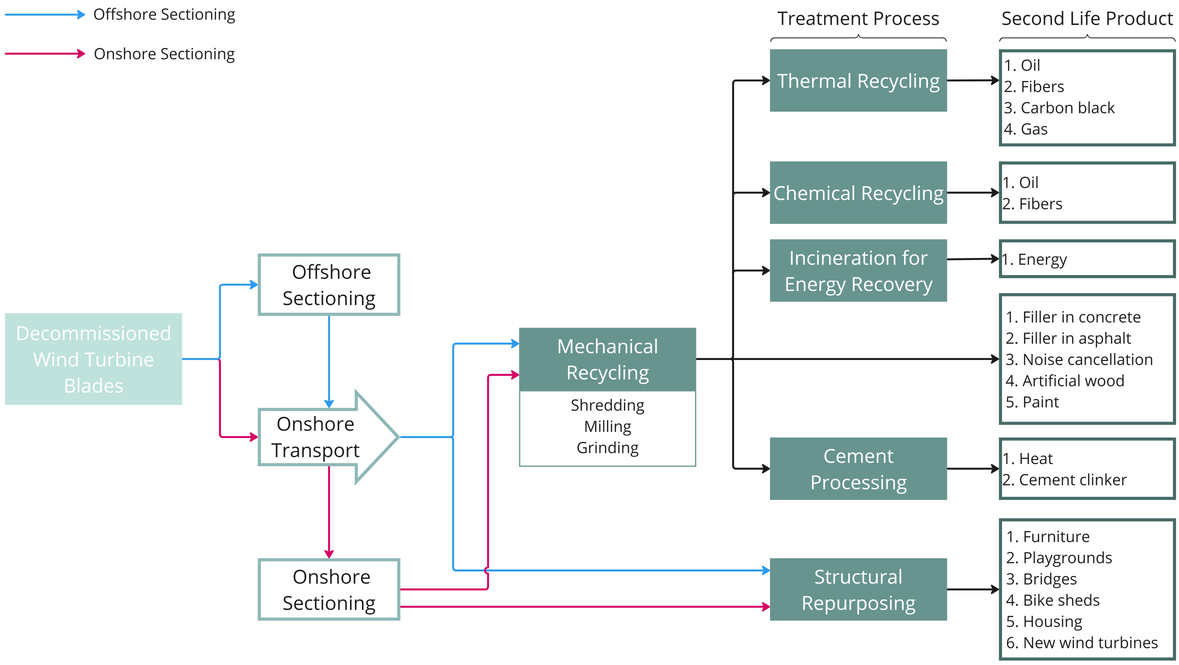



Figure 4.8: Sustainable EoL value chain roadmap for wind turbine blades. Adapted from: Lund and Madsen (2024).

### 4.2.4. Nacelle

The nacelle houses components such as the generator, gearbox, yaw mechanism, etc.; the primary function is converting mechanical energy to electrical energy (Nyserda, n.d.). In the offshore wind industry, circular economy strategies for decommissioned nacelles primarily focus on reusing, refurbishing, and recycling components to extend their lifecycle and reduce waste. Key strategies include refurbishing mechanical and electrical components, such as gearboxes, generators, and transformers, which can be tested, repaired, and upgraded for reuse in new or existing turbines (Liu & Barlow, 2017). The composite materials found in the nacelle cover present recycling challenges, and ongoing research aims to improve these processes, which are similar to the composites used in the wind turbine blades. A critical aspect of nacelle recycling involves recovering rare earth elements (REEs) from permanent magnets used in the generators.

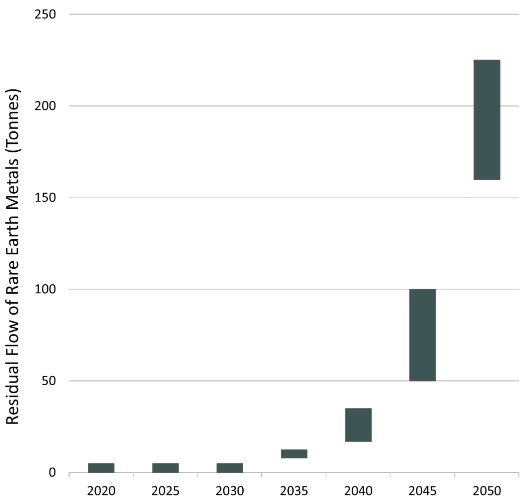



Figure 4.9: Residual flow of neodymium alloy permanent magnet (tonnes) resulting from the decommissioning in the Southern North Sea. Source: van der Meulen et al. (2020).

REEs are present in the magnets inside the wind turbine generator (Bjarke, Emiliano, Björn, & Sergei, 2023). Recycling REE is highly explored due to the benefits of recovering all magnet materials for reducing waste, reuse, and resource depletion (Bjarke et al., 2023). Additionally, technical circularity solutions include modular design, refurbishment, maintenance, and repair (Bjarke et al., 2023). The wind industry is exploring ways to design wind turbine systems using fewer or no REE (Graeme, 2022). There is a strong incentive for industry-wide collaboration to engage with policymakers and those organizing tenders to highlight the significance of circular strategies beyond recycling to meet the resource demands to build new wind farms (Bjarke et al., 2023). Figure 4.9 illustrates the estimated rate at which REE results from the decommissioning of OWF in the Southern North Sea only.

## 4.3. Challenges in the Decommissioning Process

The operational life span of a wind farm is finite, so optimizing the decommissioning process and using residual materials through both social and economic points of view is necessary (van der Meulen et al., 2020). The coherence between these stakeholders is paramount to overcoming the challenges during decommissioning.

Topham, Gonzalez, et al. (2019) identifies several factors that complicate the decommissioning process, including managing large volumes, a lack of experience, and a prolonged learning curve. Unlike the oil and gas sector, wind turbine decommissioning is only partially comparable, with unique challenges such as unclear specifications and an ambiguous decommissioning process.

The decommissioning process can be seen as an exchange of physical products and data among the stakeholders. These exchanges can be tracked by the combination of the identified EoL stakeholders by Andresen (2023), the procurement phase of decommissioning by Fay Fang de (2021), and the value chain by van der Meulen et al. (2020) as shown in Figure 4.10. It can be seen that OWF decommissioning is a complex process involving several back-and-forth interactions and data exchanges among the stakeholders.

In addition to the challenges faced during decommissioning, logistical requirements, and inadequate incentives create further obstacles to achieving circular EoL practices.

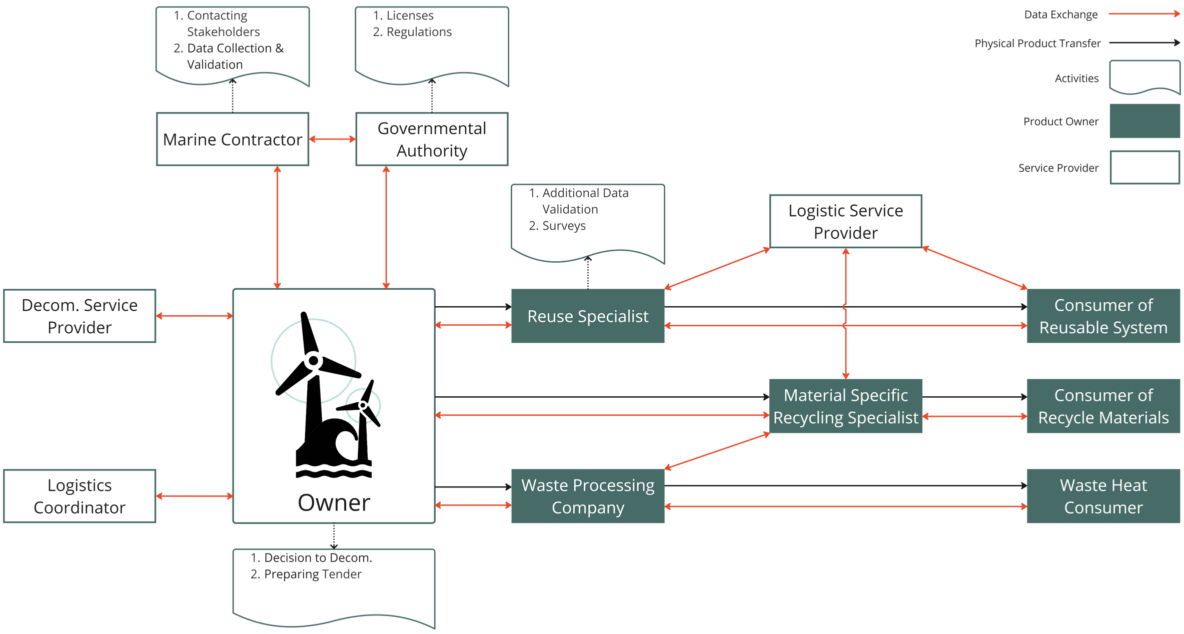



Figure 4.10: Data exchange and physical product transfer among the stakeholders involved in decommissioning an OWF. Adapted from: Andresen (2023); Fay Fang de (2021); van der Meulen et al. (2020).

The challenges faced by the stakeholders involved in the decommissioning process can be grouped into four categories: Technical, Economic, Regulatory, and Environmental (Topham, Gonzalez, et al., 2019). The components of the OWT have varied sizes, properties, compositions, etc., changing the severity of the challenges faced. Following is the discussion of the decommissioning challenges per component of an OWT accompanied by Figure 4.11 illustrating the severity matrix of the challenges.

1. Support Structure(Foundation and Transition Piece) *(SS)*: These components, typically made up of steel and concrete, are labor-intensive to remove and require specialized machinery, causing significant soil disturbance and potential environmental impact (Velenturf, 2021). Economically, recycling concrete is often not viable due to high separation and processing costs, although steel reinforcements within the concrete can be recycled, albeit through a resource-intensive process (P. D. Jensen et al., 2020). Regulatory challenges include wide variations in regulations regarding the removal and disposal of foundation materials, complicating the development of standardized EoL practices (Velenturf, 2021). Environmentally, managing leftover concrete and steel to avoid degradation is essential, with proper disposal methods and potential reuse in construction projects necessary to mitigate impacts Sachs et al. (2022).

2. Tower *(TO)*: OWT towers, primarily made of steel, require significant resources for dismantling due to their large size and weight but are generally easier to handle compared to blades and nacelles (Velenturf, 2021). Economically, while recycling steel from towers is relatively efficient, the costs associated with transportation and handling of large steel sections can be substantial, necessitating cost-effective recycling processes (P. D. Jensen et al., 2020). Regulatory challenges stem from regional variations in recycling and disposal regulations for steel, affecting the uniformity of EoL practices across different locations (Velenturf, 2021). Environmentally, improper disposal of steel components can lead to pollution and waste of valuable resources, making it crucial to ensure all steel is recycled or reused in a similar or a different function (Sachs et al., 2022).

3. Nacelle *(NC)*: The nacelle, housing critical components like the gearbox, generator, and control systems, contains a mix of metals, plastics, and Substances of Very High Concern (SVHC), making dismantling complex and requiring meticulous planning and specialized equipment to manage these intricately arranged components and SVHC (Velenturf, 2021). Economically, high costs are associated with the safe dismantling, separation, and recycling of nacelle components due to the presence of SVHC and mixed materials, necessitating significant investment in advanced technologies (P. D. Jensen et al., 2020). Regulatory challenges include varying requirements for the handling and disposing of hazardous substances, complicating the development of uniform EoL management practices (Velenturf, 2021). Environmentally, improper disposal of hazardous substances can lead to soil and water contamination, underscoring the need for strict environmental controls and effective decontamination processes (Sachs et al., 2022).

4. Rotor Blades *(RB)*: OWT blades, made from composite materials such as fiberglass and carbon fiber reinforced polymers, present significant dismantling challenges due to their size and weight, requiring specialized equipment and techniques (P. D. Jensen et al., 2020). Recycling these composites is difficult and costly, with current technologies leading to low recovery rates for high-quality materials (Sachs et al., 2022). Economically, the high costs associated with dismantling, transportation, and recycling can deter stakeholders from adopting sustainable EoL practices. This highlights the need for economic incentives to support cost-effective recycling technologies (Velenturf, 2021). Regulatory challenges arise from inconsistent regulations across regions regarding the disposal and recycling of composite materials, creating uncertainty and hindering the adoption of standardized practices (Velenturf, 2021). Environmentally, disposal of blades in landfills is unsustainable due to their long degradation time and potential for contamination. This necessitates innovative EoL methods such as repurposing or energy recovery to mitigate impacts (Velenturf, 2021).

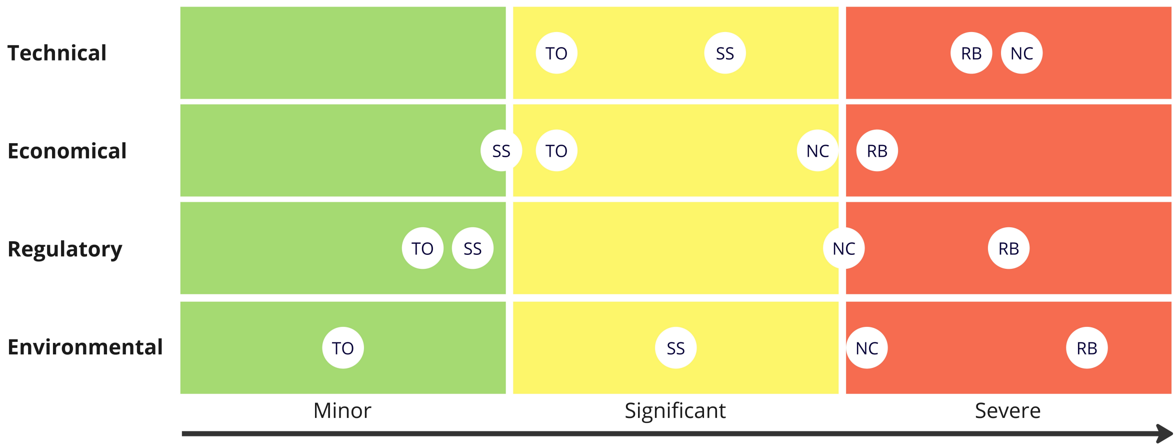



Figure 4.11: Decommissioning challenge matrix for the components of an OWT.

## 4.4. Standardized Data Management System

The previous section discusses the challenges faced in the decommissioning process. The high level of data exchange among the stakeholders involved in the decommissioning process is a critical element of the four groups of challenges. This exchange of data necessitates data management (Topham & McMillan, 2017). Data management treats data as a valuable asset consisting of collecting, organizing, and processing data to provide meaningful information (Fay Fang de, 2021). Effective data management requires high-quality data that is fit for use by the data consumer. High-quality data means the four data quality dimensions identified are prerequisites for this research are accuracy, coherence, timelines, and completeness.

There are several sides to developing data management strategies to enable circular practices in the offshore wind. These include, but are not limited to, the design and management of data systems; provision, linking, storing, converting, and sharing existing datasets; standards to guide all data collection and sharing aspects, etc. (Velenturf, 2021). In a research conducted by ECHT regie in transitie, to facilitate and stimulate the stakeholders in the wind industry to work together towards a more sustainable and circular wind industry, stakeholders displayed strong interest and willingness to make a structured information sharing platform (Vielen-Kallio et al., 2021).
*The authorities granting the tender for the Ijmuiden Ver Offshore wind farm in The Netherlands kept circular ambitions as one of the critical elements. Extra points were provided to organizations that consented to demonstrate circular practices in design, operation, maintenance, and decommissioning under the tender criteria. The points will be awarded when the permit holder agrees to provide insights into variables and methods described in the Circular Manufacturing Industry's Circular Product Passport Guide (RVO, 2024).*
Provision of the variable data is a process of collecting sufficient data from the manufacturers, suppliers, logistics providers, and OEMs and making it essential to have a standardized data management system. A standardized data management system would eventually ease data sharing within the industry, aiding in the circularity aspect of reusing and repurposing materials and components.

A standardized data management system must declare these variable data across the industry. Standardized data management will eventually improve communications between stakeholders regarding EoL and act as a guide to implement CE in the offshore wind industry (Vielen-Kallio et al., 2021). Figure 4.12 illustrates how a standardized data management system can collect data from various stakeholders in a single platform.

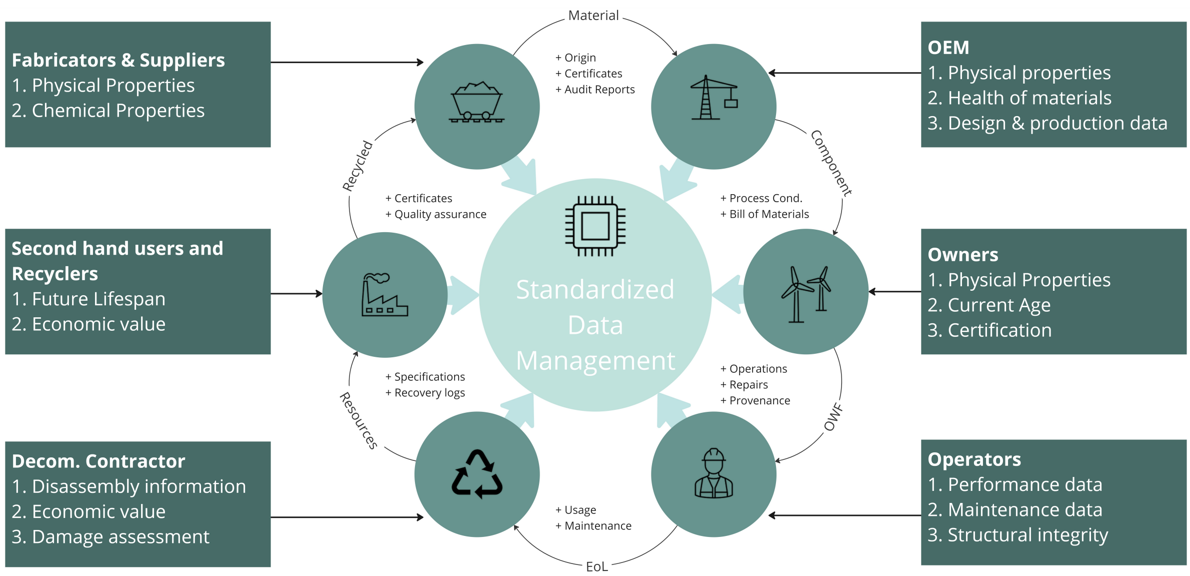



Figure 4.12: Role of stakeholders to provide information to the DPP in the EoL offshore wind industry. Adapted from: Maakindustrie (2023); Platform (2024); Stretton (2022).

Several terms can be used for a standardized data management system as follows:

- Circular Product Passport (CPP): CPP is a term used to describe a platform that stores information regarding the product throughout its lifecycle. This term is a local term used in The Netherlands.

- Digital Product Passport (DPP): A DPP aims to create a digital twin of a physical product and securely records operational, transactional, and sustainability-based data from across the product's lifecycle (Spindogs, 2024). A DPP is similar to a CPP in its function; the only difference here is DPP is an EU-based term.

- EoL DPP: An EoL DPP focuses on the data collected in the EoL of a product and provides strategies to manage the resources circularly.

- Dynamic DPP: The function of a dynamic passport is similar to a DPP. The only difference is that in a dynamic passport, real-time data collection is done using IOT devices, etc. Dynamic data is used to prepare for maintenance strategies and performance indicators.

- Material Passport (MP): An MP is a digital document that collects and stores information regarding a product's materials from the raw material stage until the finished product.

The research aimed to aid in the circular decision-making of EoL OWTs; thus, it was decided to explore a DPP system as it would provide a broad overview of these data management systems, and later, the research would tailor the DPP for the EoL resource management of OWTs.

### 4.4.1. Digital Product Passport

A DPP is a digital dossier that contains relevant information needed to manage a product's life cycle efficiently, particularly regarding its materials and components. DPP is a value-tracking tool that returns residual value to the market. It includes data such as the types of materials used, their quantities, locations, quality, condition, etc. (Hoosain, Paul, Raza, & Ramakrishna, 2021). This concept is derived from the principles of the CE, aiming to maximize the value of materials over time and facilitate their efficient recovery and reuse. Insights into the volumes, qualitative technical characteristics, and associated environmental, social, and economic values are crucial in enabling a more CE. This information is needed by the actors involved in the decision-making regarding the uptake of circular strategies regarding the level of circularity that needs to be achieved and the decommissioning process to be followed (Velenturf, 2019).

The European Commission envisions DPP as an enabling tool to enhance transparency and enable the applicability of CE across the entire value chain in several ways, including increased transparency and trust, more accessible access to detailed information, and the opportunity to make sustainable decisions with knowledge (Beanland, 2023). As a result, the DPP is a relevant digital technology in the EU's strategic plan for the transition to a CE (Beanland, 2023; Maakindustrie, 2023; RVO, 2024).

The volumes of OWT structures are so large that there is hardly any space and technique available for the sustainable processing of these materials (DecomCockpit, 2023). According to the analysis by P. D. Jensen et al. (2020), the current OWFs are not generally developed with a CE in mind. There is a lurking danger that recyclers will shred the entire turbine without considering the individual quality and reuse options of components for a second-life function. Throughout the lifespan of a wind turbine, not all materials wear out equally. Parts are also replaced during their operational life. Therefore, some wind turbines have relatively new parts when dismantled (DecomCockpit, 2023). To enable the circular reuse of these components, interested parties need to be assured about the components and their material qualities.

By documenting and preserving the value of components and materials throughout their lifecycle, DPP can help the offshore wind industry minimize their environmental impact and contribute towards a more sustainable EoL resource management (Stahel, 2016). The economic viability of an OWT at the EoL stage can also be enhanced by providing detailed data on the components, eventually creating financial incentives for the actors involved in decommissioning.

### 4.4.2. Data in a DPP

The specifications for DPP usually change depending on the product's intended use. Developing a DPP for circular resource management in the offshore wind industry requires a comprehensive understanding of the parameters that capture the lifecycle data of components and, if necessary, materials. Most product passports consist of parameters like Physical composition, Technical characteristics, Quality condition, Servicing history, Guidelines for maintenance, safety, recycling, and Valuation (van Capelleveen et al., 2023). Figure 4.13 illustrates the various data types collected in a DPP. For this research, it is necessary to consider all of the data categories. The data is collected through various attributes associated with the parameters, which will eventually help develop the DPP structure tailored for the offshore wind industry.

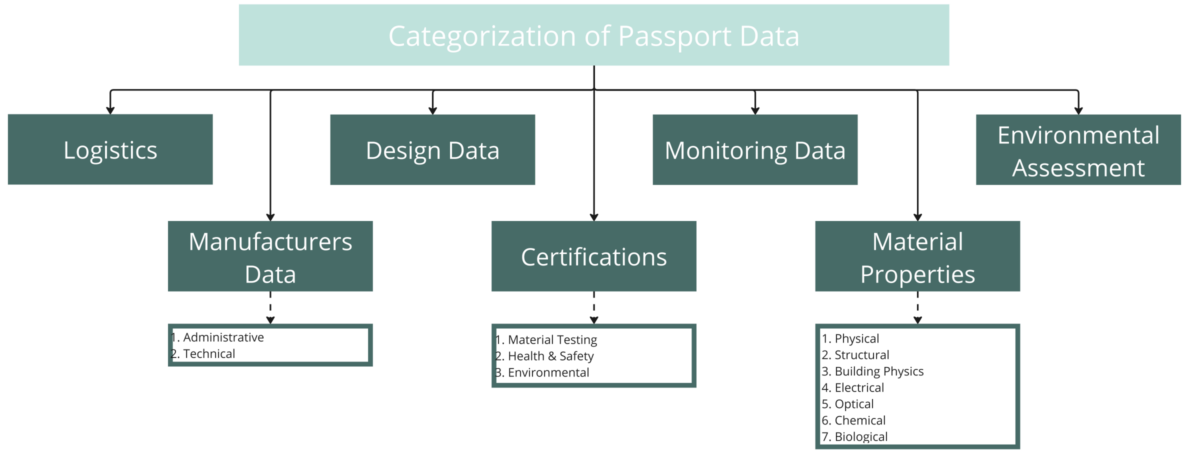



Figure 4.13: Categorization of parameters that are required for a DPP. Source: Holla (2021).

Following is a discussion of data attributes used to collect data to evaluate circular assessments. The data attributes will form the basis for circular decision-making and the EoL DPP structure tailored for the offshore wind industry.

### 4.4.3. Data Attributes for Circular Assessment

Section 2.1.1 discussed the assessments needed to evaluate circular strategies. This section explores data attributes in a DPP necessary for the evaluations. By identifying data attributes in the DPP, stakeholders can make informed decisions on the type of circular strategy for decommissioning.
Following is a list of data attributes in a DPP. Table 4.2 is adopted using various sources, as follows:

1. Maakindustrie (2023): The guideline offers guidance on what kinds of data can be returned in a materials passport and how to obtain circular data. The guideline is based on the different lifecycle phases of a product.

2. Braungart et al. (2007): This book provides foundational concepts of CE and lifecycle thinking, highlighting the importance of material properties, design specifications, and environmental impacts.

3. Allwood, Ashby, Gutowski, and Worrell (2011): This paper discusses material efficiency and the significance of various physical and chemical properties in determining material recyclability and reuse.

4. Ghisellini et al. (2016): This review provides a comprehensive overview of CE principles and their application in different industries, including critical factors for lifecycle assessment and environmental impact.

5. Charter and Gray (2008): This article explores the principles of remanufacturing, including necessary parameters like structural integrity, material properties, and cost analysis.

Table 4.2: Data attributes mapped against Circular Assessments

| **Data Attributes** | **Assessments** | | | | | |
|---|---|---|---|---|---|---|
| | Typology | Condition | Performance | Compliance | Economic | Environmental |
| Detailed Documentation | | X | X | X | X | X |
| Design Specifications | | X | X | X | X | X |
| Engineering Drawings | | X | X | X | | |
| Disassembly Guidelines | X | | | | X | X |
| Structural Integrity | | X | X | X | | |
| Service History | | X | X | | | |
| Maintenance Records | | X | X | | | |
| Operational Records | | X | X | X | X | |
| Visual Inspection | X | X | | | | |
| Non-Destructive Testing (NDT) | | X | | | | |
| Load Testing | | X | | | | |
| Quality Assessment | | X | X | X | X | |
| Material Composition | X | | | | X | X |
| Material Health | X | X | X | X | | X |
| Performance Testing | | X | X | X | X | |
| Functional Testing | X | | X | X | | |
| Operational Testing | X | | X | | | |
| Remaining Useful Life | | X | X | X | X | |
| Upgradability | X | | X | | X | |
| Technological Requirements | X | | X | | | |
| Regulatory Compliance | X | X | X | X | X | |
| Certification Documentation | X | X | X | X | | |
| Safety Standards | X | X | X | | | |
| Post-Repair Testing | | X | X | X | | |
| Risk Assessment | X | X | X | X | X | |
| Market Demand | X | | | | X | |
| Cost-Benefit Analysis | X | X | X | | X | |
| Lifecycle Assessment | | | | X | | X |
| Environmental Impact | | | | X | | X |
| Waste Reduction | | | | X | | X |
| Tools and Equipment | X | X | | | | |
| Recycling Pathways | X | | | X | | X |

The process of understanding the data attributes for the circular assessment would help in the data analysis of the interviews. The interviews are prepared to provide an overview of the key parameters necessary for circular decision-making in the industry. The key parameters will be linked to the DPP data attributes for a comprehensive circular assessment.

### 4.4.4. Challenges of a Standardized Data Management System

One solution is an industry-wide data collection and sharing system to enhance the circularity in the decommissioning phase. But as discussed in Figure 4.10, the data exchange among the stakeholders consists of several thousands of files and folders that can go up to more than a terabyte of data. The applicability of CE also depends on the quality and the accessibility of the correct data by the right stakeholder (Fay Fang de, 2021). Looking at the challenges faced while implementing a standardized data management system is essential. Critical challenges associated with such a system are as follows:

**Technical Challenges:**
The constant evolution of the turbine technology often leads to the installation of varied turbine designs over time, complicating the established standards. This variety can hinder the development of efficient post-decommissioning strategies, which ideally rely on homogeneity in material and design (Woo & Whale, 2022).

- One of the technological challenges is data governance, regarding the accountability for an organization's decision about its data assets (Khatri & Brown, 2010).
- Another challenge is the lack of standardization in the data collection and data exchange among different stakeholders across supply chains (Anastasiades et al., 2021; Kedir, Bucher, & Hall, 2021).
- Also to have appropriate incentives for all the stakeholders to provide data in a structured manner (Kedir et al., 2021).
- Next, there are no clear guidelines for the data ownership of the different components/materials in the supply chain (Ganter & Lützkendorf, 2019). Still, there is a downside to this as the confidentiality aspect of the companies makes them reluctant to share information in the supply chain Munaro and Tavares (2021).
- Lastly, the challenge to prevent counterfeiting and guaranteeing data quality Munaro and Tavares (2021).

**Economic Challenges:**

- The economic aspect of the capital and operating expenses associated with a standardized data management system needs to be justified upfront while benefits are realized by the different stakeholders (Munaro & Tavares, 2021).
- The lack of interest in CE-based material utilization is a second financial issue impeding these digital systems (Adisorn, Tholen, & Götz, 2021). This is also affected by a negative perspective of 'used' or 'second-hand' components (Munaro & Tavares, 2021).
- There is currently a limited market for second-hand components in their primary function as a part of OWF (van der Meulen et al., 2020). Establishing a business case around a standardized data management system without a stable demand is challenging.

**Regulatory Challenges:**
To create market conditions for an industry-wide standard for data collection and storage to be practical, several studies attribute to the role of governmental regulatory frameworks (Böckel, Nuzum, & Weissbrod, 2021; Ganter & Lützkendorf, 2019). As the possibilities of contracting or sub-contracting supply chains may go across borders, regulations may be challenging (Munaro & Tavares, 2021).

- Lack of comprehensive EoL legislation in regulatory frameworks across different regions. While some countries have well-established regulations that promote CE, others lack specific guidelines, creating inconsistent application of the system (Plan, 2020).
- The challenge of complying with local regulations across nations is challenging for a standardized data management system. The decentralized nature of many wind turbine installations further complicates monitoring and enforcement efforts (Woo & Whale, 2022).

*The next part of the report will present the analysis of the data collected.*

# Define (Data Analysis)

The following section will present the data analysis through a literature review analysis in Section 4.5 and a semi-structured interview analysis in Section 4.6.

## 4.5. Systematic Literature Review Analysis

This section presents the key findings from the literature review by analyzing existing scientific and grey literature. The analysis answers the following sub-research question:

- *SQ.0: What are the existing circular strategies applied in the offshore wind industry?*
- *SQ.1: What are the various components of an OWT and their respective EoL circular practices?*

The end goal of this research is to develop a decision-making framework with circularity and EoL as central concepts. The literature analysis will focus on identifying indicators that capture these concepts. The systematic literature review reveals that while significant progress has been made in applying circular strategies in the offshore wind industry, several challenges and gaps remain. Addressing these issues through standardized procedures, improved data collection, and analysis will be crucial for advancing sustainable and circular practices in the sector. A standardized data management system is one of the solutions for standardized EoL guidelines and streamlining circular strategies in the offshore wind industry. As mentioned in the scope of the research, the EoL resource management of OWTs will be assessed based on the data attributes and parameters used to develop a DPP.

### 4.5.1. EoL Circular Strategy

An initial literature analysis identified significant gaps and opportunities for integrating circular strategies in the offshore wind energy sector. The review identified several circular strategies currently applied in the offshore wind industry, categorized into three main stages of the wind turbine lifecycle: design and manufacturing, operation and maintenance, and end-of-life management. Implementing CBM that facilitates systemic changes across value chains (Vegter et al., 2020) is necessary. Integrating circularity into the design, operations, and maintenance phases and EoL management will require coordinated efforts in technology and material innovations alongside strategic planning and policy support (Pieroni et al., 2021).

In the coming decade (2025-2035), approximately 1500-1800MW of offshore wind capacity is expected to reach their EoL (Hou et al., 2017; van der Meulen et al., 2020). Despite the substantial environmental impacts associated with material extraction and processing during turbine manufacturing (J. P. Jensen, 2019), offshore wind farms have traditionally been developed without a comprehensive focus on EoL resource management. Woo and Whale (2022) and Velenturf (2021) identify a broad spectrum of circular strategies encompassing the entire lifecycle of an OWF. However, the predominant focus in the literature remains on recycling. This oversight highlights the necessity for an approach to CE that extends beyond recycling and recovery to include higher-order circular strategies such as repair, reuse, remanufacturing, etc. (Velenturf, 2021).
"Circular strategies" aim to implement CE in the value chain of a process to achieve less resources and material consumption (Potting et al., 2017). Identifying circular strategies and those relevant at the EoL of a product or a system is the first step towards efficient EoL resource management.

The process of analyzing the circular strategies relevant to the EoL resource management of a wind turbine is explained in Appendix F. There are four steps to this: (1)Target lifecycle phase, (2) Information level of scale, and (3) Level of circularity. The EoL circular strategies tailored for an OWF, according to the level of circularity they achieve (from high to low), are as follows:

1. High Circularity Level
    - **Re-certify**: Grouping strategies like Refuse, Rethink, and Reduce under Re-certify include minimizing resource use at the first stage of deciding the EoL scenario for an OWF. This approach ensures that components and materials are critically evaluated for their necessity and optimized for efficiency and longevity (Velenturf, 2021). By integrating this strategy, the overall waste generation decreases, leading to a significant reduction in environmental

impact (J. P. Jensen, 2019) and economically beneficial, allowing the wind farm owner to keep generating electricity.

- **Reuse (Direct Reuse)**: Offshore wind turbine components, such as blades and towers, that remain in good condition can be directly reused in other wind farms. This strategy conserves resources and energy that would otherwise be required for manufacturing new components (Woo & Whale, 2022).
- **Repair (Component Life Extension)**: Repairing damaged parts can extend the operational life of wind turbines. For instance, repairing gearbox or generator failures allows for continued use without needing complete replacement, thus conserving materials and reducing waste (Velenturf, 2021).

2. Moderate Circular Strategies
   - **Refurbish (Upgrading and Modernization)**: Refurbishing involves upgrading older components to meet current standards or improving their efficiency. This strategy benefits nacelle components and control systems, which can be updated with newer technology, enhancing performance while avoiding full replacement (Velenturf, 2021).
   - **Remanufacture (New Life for Old Components)**: Remanufacturing takes parts from decommissioned turbines and refurbishes them to a like-new condition. This strategy is viable for high-value components like generators and gearboxes, ensuring that valuable materials are used longer (Mendoza et al., 2022).
   - **Repurpose (Alternative Uses)**: Repurposing involves using decommissioned components for new applications. For example, turbine blades can be converted into pedestrian bridges or playground equipment, providing innovative uses for materials that would otherwise become waste (Velenturf, 2021).
3. Low Circularity Strategies
   - **Recycle (Material Recovery)**: Recycling focuses on recovering raw materials from decommissioned components. Although this strategy ranks lower in circularity, it is crucial for materials that cannot be reused or repurposed. Metals such as steel, copper, and rare earth elements from generators are commonly recycled, contributing to resource conservation (Liu & Barlow, 2017).
   - **Recover (Energy Recovery)**: In cases where recycling is not feasible, energy recovery from the incineration of non-recyclable materials can be considered. This strategy ensures that the energy content of the materials is utilized, albeit as a last resort (Velenturf, 2021).

Circularity Assessment
The EoL scenarios identified by Agra Neto et al. (2024); Jadali et al. (2021) can be directly linked with the type of circular strategy applied. The framework, as illustrated in Figure 4.14, highlights the need to assess the OWTs based on six circularity assessment levels as follows:

1. **Typology Assessment** (Data Availability): Refers to the extent and quality of data for the OWT components. Fay Fang de (2021) points out four data quality dimensions: accuracy, coherence, timeliness, and completeness necessary for a data management system. Similarly, accurate and comprehensive data is crucial for making informed decisions regarding the potential for extending the service life of components, planning repairs, and evaluating overall system health (Velenturf, 2021). This assessment includes:
   - Material Specifications: Detailed descriptions of the materials used in constructing the turbine components, including types, grades, and sources.
   - Component Specifications: Information on the turbine components' design, manufacturing, and assembly.

   For example, the tower requires detailed data on material composition and structural integrity assessments to determine whether it can be reused, refurbished, or recycled. The mechanical components of a nacelle need comprehensive performance and maintenance records to decide on potential re-certification or remanufacturing of its complex machinery.

2. **Condition Assessment** (Residual Life Evaluation): The remaining useful life of OWT components is assessed based on their current condition and historical performance. Understanding the residual life helps determine whether components can be reused, repaired, or need to be replaced, which is critical for optimizing the EoL strategy (J. P. Jensen, 2019). This assessment includes:

    - Condition Monitoring: Using sensors and diagnostic tools to monitor the health of components such as the gearbox, blades, and electrical systems.
    - Fatigue Analysis: Assessing the wear and tear on structural components like the support structure and tower.
    - Service Life Estimation: Calculating the expected remaining service life based on operational data and environmental conditions.
    - Historical performance: Information on the operational history and performance metrics of the turbine and its components.
    - Maintenance Records: Provision of documentation for all maintenance activities, repairs, and inspections conducted over the turbine's lifecycle.

    For example, rotor blades are subjected to high stress and fatigue; their residual life evaluation will determine whether they can be repaired or need complete recycling. Electrical components in the nacelle, like the generator and transformers, also need thorough residual life assessments to decide whether to re-manufacture or replace them.

3. **Performance Assessment** (Capacity of Service Life Extension): Assesses the potential to extend the service life of OWT components through maintenance, upgrades, or retrofitting. Extending the service life of components can significantly reduce the need for new materials and components, thereby supporting circular economy principles (Pigosso et al., 2018). This assessment includes:

    - Maintenance Strategies: Implementing preventive and predictive maintenance practices to prolong component life.
    - Upgrades and Retrofitting: Enhancing components with newer technologies to improve performance and durability.
    - Component Compatibility: Ensuring upgraded components are compatible with existing systems.

    For example, extending the service life of a nacelle can be achieved by upgrading the gearbox and generator with newer, more efficient models. The tower can also benefit from structural reinforcements and corrosion protection measures.

4. **Compliance Assessment** (Technical Feasibility): This assessment involves assessing the technical feasibility of various EoL strategies, including re-certify, reuse, repair, refurbishment, remanufacturing, and recycling. Ensuring that the chosen EoL strategy complies with existing standards and specifications is necessary.

    For example, the support structure and foundation are the structural elements that hold the whole wind turbine together. Before reusing a component in a similar or new function, it must be certified according to the standards. Nacelle components like the gearbox and generator can be technically feasible for remanufacturing, provided they meet the required standards.

5. **Economical Assessment:** Involves assessing the economic feasibility of various EoL strategies, including re-certification, reuse, repair, refurbishment, remanufacturing, and recycling. Ensuring that the chosen EoL strategy is economically feasible is crucial for successful implementation (Mendoza & Pigosso, 2023). This assessment includes:

    - Cost-Benefit Analysis: Comparing the costs of different EoL strategies, such as re-certification, repair, and recycling, against their benefits.
    - Market Demand: Evaluating the market demand for second-hand components.

- Return on Investment (ROI): Calculating the ROI for different EoL strategies to determine their economic viability.

For example, the economic feasibility of reusing or refurbishing the tower depends on the cost savings from avoiding new material production versus the cost of refurbishing and the expenses incurred during the process.

6. **Environmental Assessment:** Lastly, evaluating risks associated with the EoL management of OWT components, including the potential impacts of different disposal and recycling methods. Minimizing environmental risks ensures that EoL strategies contribute positively to sustainability goals (Ghisellini et al., 2016). This assessment includes:
   - LCA: Evaluating the environmental impacts of the components over their entire lifecycle.
   - Waste Management: Assessing the potential for waste reduction and efficient waste management practices.
   - Pollution and Emissions: Measuring the potential pollution and emissions associated with different EoL strategies.

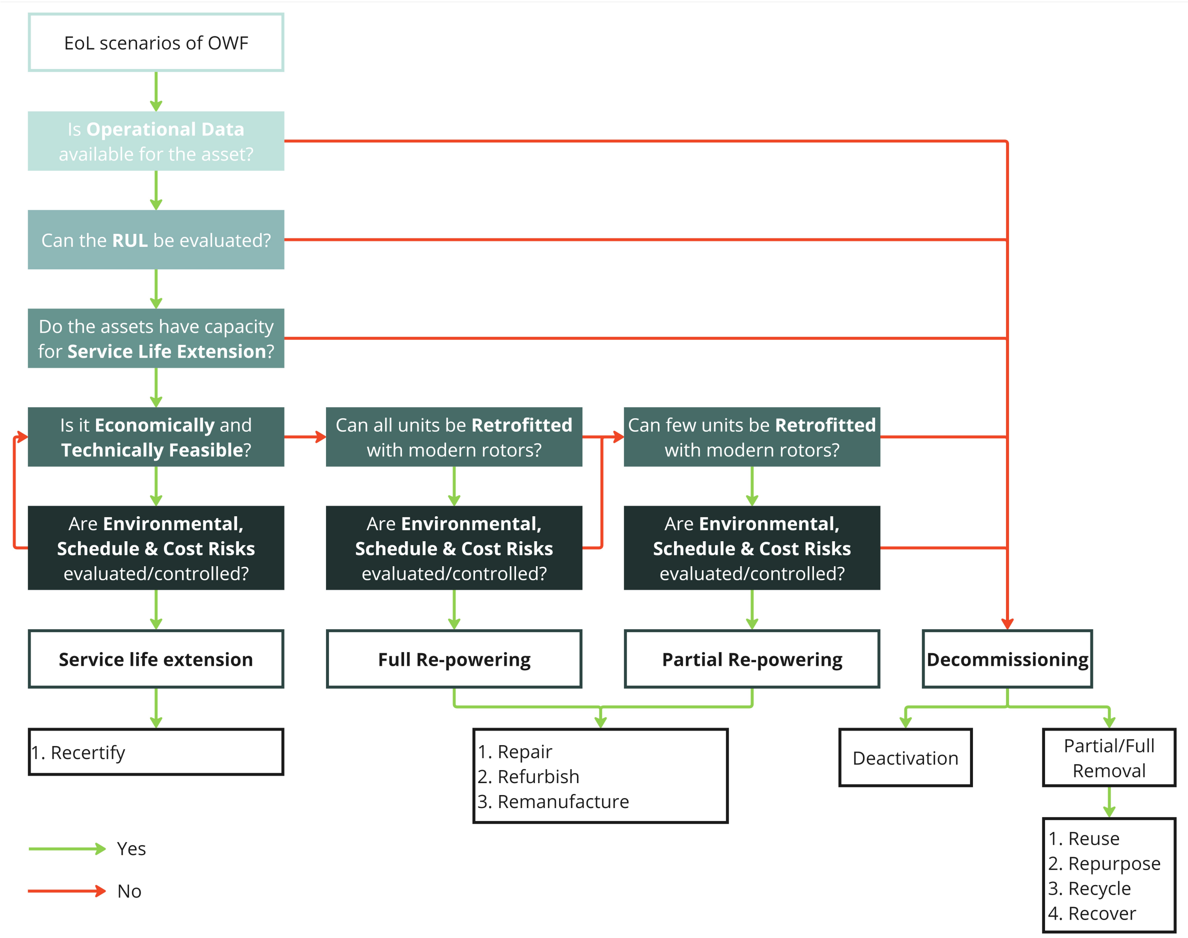



Figure 4.14: EoL scenarios for OWF and their decision support framework. Adapted from: Agra Neto et al. (2024); Jadali et al. (2021).

Figure 4.14 sufficiently answers *"SQ.0: What are the existing circular strategies that are applied in the offshore wind industry?" as it provides a complete overview of the EoL scenarios for the OWFs.*

### 4.5.2. Circular Strategies at the Component Level

The wind turbine comprises various components depending on the structural properties, material compositions, functions, etc. Thus, the circular strategies do not apply to the components similarly. Following is the discussion stating the applicability of circular strategies to the components.

1. Support structure (Foundation and transition piece): Support structures are typically made of steel and concrete and present various circular strategies. Circular strategies such as re-certifying, reusing, repairing, refurbishing, repurposing, and recycling are the most viable options, considering the components' material properties and structural strength. Although remanufacturing is a possibility, it is challenging due to the size and the changing site conditions. Lastly, recovery through incineration is not possible for these materials (Coelho et al., 2021).

2. Tower: The tower is primarily made up of steel. Like the support structure, the tower can use several circular strategies such as Re-certify, Reuse, Repair, Refurbish, Repurpose, and Recycle. Remanufacturing is considered a viable option but can be logistically challenging. And, recovery through incineration does not apply to steel components (Telsnig, 2022).

3. Nacelle (Mechanical Components): Re-certification is possible for functional components. Reuse is feasible, particularly for parts like gearboxes and generators. Repair and refurbishment are commonly practiced, extending the operational life of these components. Remanufacturing is also prevalent, especially for gearboxes and generators. While repurposing is less common, recycling presents a complex challenge due to the mixed materials and presence of SVHC in some sub-components. Energy recovery from incineration is possible for materials that cannot be recycled (Liu & Barlow, 2017).

4. Rotor Blades and Nacelle Cover: Rotor blades are one of the main components of a wind turbine, and the Nacelle cover is one of the sub-components of the Nacelle. Both are made of composite materials, such as glass and carbon fiber, posing significant circular challenges. Re-certification is possible if structural integrity is maintained, but reuse is generally not feasible due to material fatigue, wear, and tear. While minor repairs can be made, extensive restoration and refurbishment are limited. Remanufacturing composite materials is challenging and not widely practiced. However, innovative repurposing opportunities have been explored, such as converting blades into playground equipment or pedestrian bridges. Recycling composite materials is complex and not yet widely implemented, but incineration for energy recovery is considered a last resort before landfill disposal (Telsnig, 2022).

Table 4.3 provides an overview of an OWT's components and the difficulty level in implementing the circular strategy. Here, green is considered to be easily applicable, yellow is considered challenging, and red is considered not appropriate.

Table 4.3: Possibility of applying circular strategies to wind turbine components.

| Circular Strategy | Foundation & Transition Piece | Tower | Nacelle | Rotor Blades & Nacelle Cover |
|---|---|---|---|---|
| Re-certify | | | | |
| Reuse | | | | |
| Repair | | | | |
| Refurbish | | | | |
| Remanufacture | | | | |
| Repurpose | | | | |
| Recycle | | | | |
| Recover | | | | |

### 4.5.3. Key Parameters of a DPP for OWT

DPP tailored for the offshore wind industry must include detailed, accessible, and valuable information that can aid the integration of circular strategies in decommissioning, facilitating reuse, repairs, repurposing, or recycling of materials. In Section 4.4.3, the data attributes of a DPP necessary for circular assessments were explored. The data attributes were tailored for the OWTs by creating key parameters that combine comparable functional properties. Adapting from the extensive list of parameters identified by Heinrich and Lang (2019), the following is a list of parameters and their respective data attributes necessary for a DPP tailored for EoL of the offshore wind industry:

1. **Physical Properties:** The size, weight, density, etc. are crucial for transportation, handling, and integration into new or existing systems (Braungart et al., 2007). Data on the manufacturer, use, and maintenance helps determine the EoL and plan for decommissioning (D. R. Cooper & Gutowski, 2017).

2. **Material Composition:** The elements' or components' specific material composition will indicate if a material can be processed without downgrading quality and its estimated durability in various applications (Bakker, den Hollander, van Hinte, & Zijlstra, 2014). Health and safety precautions for chemically hazardous materials must be documented for proper handling or disposal (Bakker, den Hollander, et al., 2014). Highlights whether a material is biodegradable or easily reintegrated into the manufacturing cycle. Detailed information on the type and quantities of materials used in each component is essential for the recovery and recovery processes (Bakker, Wang, Huisman, & Den Hollander, 2014).

3. **Health of materials:** Depending upon the type of material, the actual service time versus the designed lifespan, and structural integrity help in the EoL decision-making of a component—detailed inspection reports to evaluate current functionality and safety. Information on the environmental and health impacts of materials used is crucial in safely handling, recycling, or disposing of materials (Zink & Geyer, 2017).

4. **Design and production:** The availability of technology, documentation, or certification to keep the data in a DPP up-to-date (Kjaer, Pigosso, Niero, Bech, & McAloone, 2019). These parameters include technological feasibility, upgrade potential, and design details, allowing EoL decisions on re-pursuing or remanufacturing the component.

5. **Regulatory Framework:** Certification ensures that the design and production process during the BoL meets regulatory and quality standards. Bill of Materials aids in lifecycle analysis and planning of logistics (McAloone & Pigosso, 2017). Information on compliance with environmental regulations is necessary for managing the EoL of turbine components legally and responsibly (Ranta, Aarikka-Stenroos, Ritala, & Mäkinen, 2018).

6. **Disassembly Information:** Understanding the process allows for efficient recovery of reusable components and minimizing waste (McAloone & Pigosso, 2017). Details on how to disassemble components, which tools are required, and the ease or complexity of disassembly. This is vital for recycling and re-manufacturing Braungart et al. (2007).

7. **Economic Value:** Estimated resale value of materials and components, which can incentivize the recovery of materials and inform financial viability of the EoL process (Linder, Sarasini, & van Loon, 2017).

Table 4.4 presents a sample DPP tailored for the offshore wind industry. The table consists of the parameters and their respective data attributes. The DPP parameters and data attributes are adapted from Maakindustrie (2023) and the draft version of the ISO 59040: Circular economy - Product Circular Data Sheet *ISO 59010* (2024).

The table shows that the DPP holds information regarding the applicability of circular strategies to the components, and this research plays a vital role in evaluating the circular strategy. Depending on the system level of information, the data in the DPP must be available for all types of systems. For this research, the scope is limited to OWT components only.

Table 4.4: Digital Product Passport tailored for the offshore wind industry (Note: the data provided in the DPP approximates the data available of a Vestas V90 offshore wind turbine).

| Parameter | Data Attribute | Value |
|---|---|---|
| Physical Properties | Size | 90 x 90 x 100 m |
| | Weight | 120,000 kg |
| | Density | 7.85 g/cm³ |
| | Manufacturer | Vestas |
| | Date of Manufacture | 2010-05-20 |
| | Maintenance Records | Available |
| | Use History | 10 years |
| Material Composition | Material List | Steel, Fiberglass, Copper, Rare Earth Metals |
| | Percentage of Recycled Materials | 30 % |
| | Critical Raw Materials | Neodymium, Dysprosium |
| | Hazardous Substances | None |
| | Biodegradability | Non-biodegradable |
| | Durability | 20 years |
| | Type and Quantities | Steel (80,000 kg), Fiberglass (20,000 kg), Copper (5,000 kg), Rare Earth Metals (1,000 kg) |
| Health of Materials | Service Time | 10 years |
| | Structural Integrity | Good |
| | Inspection Reports | Available |
| | Environmental Impact | Moderate |
| | Health Impact | Low |
| Design & Production | Technological Feasibility | High |
| | Upgrade Potential | Medium |
| | Design Flexibility | High |
| | Bill of Materials | Available |
| Regulatory Framework | Certifications | ISO 9001, ISO 14001 |
| | Environmental Regulations Compliance | Compliant |
| | Lifecycle Analysis | Conducted |
| Disassembly Information | Disassembly Process | Detailed |
| | Tools Required | Standard |
| | Ease of Disassembly | Moderate |
| | Reusable Components | Yes |
| Economic Value | Resale Value | 20,000 $ |
| | Financial Viability | Positive |
| | Incentives for Recovery | High |
| Circular Strategies | Re-certify | No |
| | Reuse | No |
| | Repair | Yes |
| | Refurbish | Yes |
| | Remanufacture | No |
| | Repurpose | Yes |
| | Recycle | Yes |
| | Recover | No |
| End-of-Life (EoL) | Decommissioning Date | 2030-05-20 |
| | Condition at EoL | Moderate |
| | Recommended EoL Strategy | Refurbish |
| | Residual Value | 10,000 $ |

It is necessary to explore the link between the EoL of OWTs and the circular strategies through a DPP for effective implementation of circularity. The EoL circular strategies of an OWT are assessed based on a circular decision-making framework. Finally, Figure 4.15 illustrates the transition from the EoL of an OWT to a circular strategy transitioning to a circular economy in the wind energy sector. By adopting a comprehensive circular framework, the offshore wind energy sector can reduce its environmental footprint (Mendoza & Pigosso, 2023).

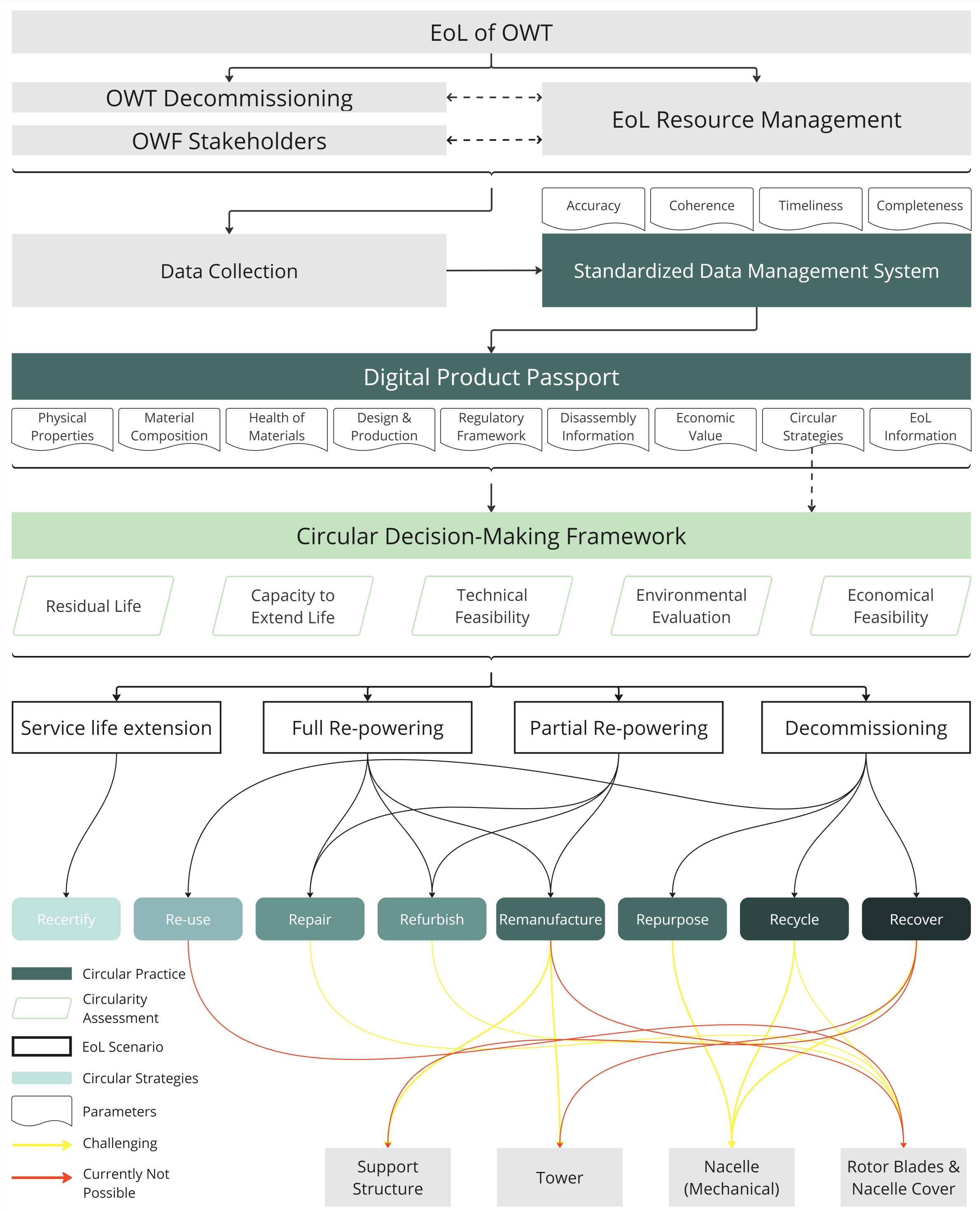



Figure 4.15: An overview of the literature review analysis illustrating the circular decision-making framework and how it will be used for the EoL resource management of OWF.

Table 4.3 and Figure 4.15 sufficiently answers *"SQ.1: What are the various components of an OWT and their respective EoL circular practices?"* as they provide an overview of the EoL circular strategies for the components of an OWT.

## 4.6. Semi-Structured Interview Analysis

Policymakers, industry professionals, and wind farm operators often lack adequate knowledge of circular EoL resource management and their associated challenges and opportunities (Woo & Whale, 2022). Yet, many stakeholders, including the public and the environmental organization, influence the EoL decision-making (Andresen, 2023). This knowledge gap hampers effective decision-making in adopting appropriate circular practices.

Semi-structured interviews were conducted to gain practical insights into the research problem. There were nine interviews, all actively working in the offshore wind industry, as shown in Table 4.5. This section presents the key findings from the semi-structured interviews. The analysis answers the following sub-research question:

- *SQ.2: What are the key challenges faced in managing wind turbine components with regard to CE at their EoL phase by the stakeholders involved in the supply chain?*
- *SQ.3: What are the key parameters and data attributes are required for the circular decision-making framework for a standardized data management system tailored for the EoL of OWTs?*

The interviewees involved will have different perspectives depending on their expertise. Thus, throughout the analysis, it is essential to refer to the type of interviewee and the following abbreviations will be used to reflect the expertise/perspective. To protect the interviewees' identities, the interviews' identities and original interview transcripts are not attached to this report.

Table 4.5: Interviewees list along with their abbreviation used to address them in the report.

| Organization | Expertise | Abbreviation |
|---|---|---|
| Windplanblauw | Project Management (Wind Farm Developer) | [WP_OW] |
| Sif-Group | Decommissioning Resource Manager | [SF_RM] |
| Lubbers Logistics | Decommissioning Contractor | [LL_DC] |
| University of Leeds | CE expert Offshore Wind | [UL_CE] |
| Suzlon | OEM | [SU_BM] |
| EoLO-HUBs | Re-manufacturing and Refurbishing | [EH_RR] |
| Continuum Group | Blade Recycling | [CG_BR] |
| DNV-REWind | DNV: Offshore standards governing body; REWind: Digital solution for sustainable wind farm decommissioning | [DR_DS] |
| Business in Wind | Second-hand Dealers | [BW_SD] |

As explained in Section 3.4.2, the interviews were analyzed using an adapted version of the thematic analysis framework described by Braun & Clarke. The general idea of the analysis is threefold, considering the perspective of EoL resource management in the offshore wind industry that needs to be gained. This section will focus on the key takeaways for each of the themes.

Firstly, the challenges involved in the decommissioning phase were explored through a literature review; next, the challenges faced in incorporating sustainable and circular practices in the decommissioning phase will be explored through the interviews. Next, to understand the key parameters that are necessary for circular decision-making at the EoL will be explored through the second theme of the interview analysis. Since there isn't a standard decision-making criterion, this theme would also look for the standard practices by the actors involved in the EoL decision-making for OWT components. Theme 2 would additionally provide inputs to developing a DPP to which parameters can be added to the existing structure of a DPP. Since the research aim is to promote the reuse of OWT components, it is necessary to consider the parameters from the perspective of the market's supply and demand. Theme 3 aims to provide insights on additional parameters to the previous theme necessary for a practical implication of the circular decision-making framework.

- **Theme 1: Challenges for circularity**
- **Theme 2: Key circular decision-making parameters**
- **Theme 3: Market consideration**

### 4.6.1. Theme 1: Key Challenges for Circularity

Since the decommissioning and EoL operations and challenges are unknown, predicting the required type and degree of activity is difficult. The lack of knowledge among stakeholders in the offshore supply chain and waste processing industry creates uncertainty about dependencies, costs, and benefits (van der Meulen et al., 2020). All stakeholders must have access to the data to document their actions and aid in the decision-making process regarding the EoL resource management in a circular manner (van Capelleveen et al., 2023). The EoL management of wind turbine components presents several challenges that complicate the integration of CE principles in the wind energy sector. The technical, economic, regulatory, and environmental challenges vary from component to component as explored in Section 4.3. However, the challenges explored through the interview analysis addressed the challenges faced in implementing circularity practices in the EoL phase.

The first set of interview questions was based on the interviewee's general background. This was followed by sharing their experience in decommissioning offshore wind turbine projects. From here, the discussion was directed towards exploring challenges they have experienced or will experience related to the research topic.

**Key Takeaways Theme 1: Challenges for Circularity**

1. Technical challenges identified through the interviews reveal a landscape where the lack of infrastructure, standardization, and advanced testing methods significantly hampers the potential for circularity in the offshore wind industry.
2. The high logistics, infrastructure, and compliance costs, coupled with insufficient market demand and inadequate financial incentives, create a formidable barrier to the widespread adoption of circular strategies.
3. Inconsistent regulations across jurisdictions create barriers to the effective implementation of circular strategies for offshore wind turbine components.
4. The environmental impact of energy-intensive recycling processes and the disposal of non-recyclable materials pose significant challenges to achieving true circularity.

**Technical Challenges**

Technical challenges arise due to the complex and varied nature of the OWTs. There is a shortage of established facilities for efficiently collecting and pre-treating wind turbine components before recycling (Woo & Whale, 2022). This absence of infrastructure hinders the seamless flow of materials and adds logistical complexity to the EoL process. Following are the quotes retrieved from the interview transcripts:

*"...Logistics and pre-processing costs are critical factors affecting EoL management of wind turbines..." [EH_RR]*

*"...The first reaction of the owners is to get rid of the turbines, yet repowering is being explored in one of the projects for decommissioning..." [WP_OW]*

*"...Asset owners prefer to have a single point of contact for the decommissioning and EoL resource management of the OWTs..." [SF_RM]*

*"...The lack of standardization in turbine design across different manufacturers poses a challenge, as different materials and designs require different handling and processing techniques..." [SF_RM]*

*"...The difficulty in assessing the remaining useful life of components due to varying degrees of wear and tear affects their reusability. Advanced non-destructive testing methods are often required to accurately evaluate the condition of materials..." [BW_SD]*

*"...Handling hazardous materials such as composite blades requires specialized disposal methods to prevent environmental contamination..." [SF_RM]*

*"...Retrofitting existing infrastructure to accommodate new recycling technologies is technically challenging and costly. The existing facilities are not always compatible with the requirements for handling new materials and processes..." [CG_BR]*

One of the primary issues is the lack of established facilities for efficiently collection and pre-processing wind turbine components before reusing them. The absence of streamlined processes means that many wind turbine owners opt for the quickest solution—often getting rid of the turbines without fully exploring CE strategies such as repowering or refurbishing. This inclination to "get rid of" turbines underscores a broader issue: the need for greater awareness and incentives to explore sustainable alternatives during the decommissioning phase.
Standardization emerges as another significant technical challenge. The interview data reveals that different turbine manufacturers' varied designs and materials complicate the recycling and repurposing processes. Without standardized designs, each turbine may require a unique dismantling and material processing approach, further straining the already limited recycling infrastructure. This lack of standardization increases the complexity of EoL operations and hinders the scalability of CE practices across the industry.

Assessing the RUL of components due to varying degrees of wear and tear is complex, further complicating the potential for reuse and repurposing. Advanced non-destructive testing methods are often necessary to accurately evaluate the condition of materials, adding another layer of technical and financial burden to the EoL management process.
Finally, the challenge of retrofitting existing infrastructure to accommodate new recycling technologies cannot be overstated. The cost and technical difficulty of upgrading facilities to handle new materials and processes present a significant barrier to adopting more advanced CE practices. As noted by one interviewee, existing facilities are often incompatible with the requirements for handling newer, more complex materials, highlighting the need for investment in technological innovation and infrastructure development.

**Economic Challenges**
Economic challenges are one of the driving factors in the business operation of any industry. The current supply of decommissioned turbine components is relatively low, limiting the financial viability of large-scale recycling and repurposing facilities (Woo & Whale, 2022). As a result, it is challenging to establish sustainable and profitable businesses to process this material stream. Implementing circular practices requires substantial investment in new technologies, infrastructure, and workforce training. Many stakeholders, especially smaller companies, may lack the financial resources to make such investments (Vielen-Kallio et al., 2021). Following are a few quotes retrieved from the interview transcripts:

*"...Transporting large blades and other components can be prohibitively expensive, especially when dealing with offshore installations where specialized vessels and equipment are required..." [EH_RR]*

*"...The economic viability of reusing components heavily depends on the availability of a market willing to purchase these refurbished parts. Without sufficient demand, the costs of refurbishing and storing these components can outweigh the potential benefits..."[BW_SD]*

*"...When you're looking at the most challenging part of the decommissioning project, it's actually the organization execution of that project because you can recycle everything if you want, but it's gonna cost you quite a lot right now. Most companies are more driven by the financial side than the circularity side..."[DR_DS]*

*"...one of the main drivers are the economic benefits, business case-driven, subsidy driven..."[WP_OW]*

*"... If I need to make compromises for end-of-life use, then I'm actually paying the bill for 25 years to gain it..." [SU_BM]*

*"...The lack of financial incentives from the government makes it difficult to justify the high costs of circular practices. Companies often need subsidies or tax breaks to make circularity economically viable..." [CG_BR]*

*"...The introduction of stringent regulations regarding circular economy practices is a double-edged sword. While it promotes sustainability, it also increases the compliance burden on companies, making it more costly and time-consuming to meet these new standards..." [LL_DC]*

*"...The initial setup costs for recycling facilities are very high. This includes not just the physical infrastructure but also the training and development of skilled personnel..." [UL_CE]*

The economic challenges in managing the EoL phase of offshore wind turbines are multifaceted, affecting the industry, society, and government. For the industry, the high costs of transporting large components, especially from offshore sites, make circular strategies like reuse and recycling economically burdensome. Companies are often driven by immediate financial considerations rather than long-term sustainability goals, as the market for refurbished components is underdeveloped and often unprofitable without significant investment. Since the interviews were conducted with industry experts, there was a strong inclination toward financial incentives for adopting circular practices.

From a societal perspective, relying on financial incentives such as subsidies highlights a broader issue: without adequate market demand and support, the costs of circular strategies can outweigh their benefits. This creates a situation where society bears the cost of unsustainable practices due to economic constraints despite the potential environmental benefits. For governments, while regulations aimed at promoting circularity are necessary, they also increase compliance costs for companies, which can stifle innovation and investment in sustainable practices. There is a need for a balanced approach where regulatory frameworks provide clear incentives for circularity while mitigating the financial burden on the industry. To address these challenges, coordinated efforts between industry stakeholders, society, and government are crucial in creating an economically viable pathway for circular practices in the offshore wind sector.

**Regulatory Challenges**
EoL management lacks standardized regulations or government incentives that would promote and support circular strategies. Consequently, companies struggle to justify investments in recycling or other circular approaches (Woo & Whale, 2022). There is yet uncertainty about the future regulation for OWF decommissioning that adds complexity for parties to commit to sustainable decommissioning practices (Topham & McMillan, 2017). Regulatory Challenges recorded during the interview are as follows:

*"...Varying regulations regarding the disposal and recycling of wind turbine components complicate the decommissioning process, as companies must navigate different legal requirements in each country they operate in..." [SF_RM]*

*"...The introduction of new regulations, such as mandatory digital product passports for tracking the lifecycle of components, could significantly impact the industry. While these regulations aim to enhance transparency and traceability, they also require companies to adopt new systems and processes, which can be both time-consuming and costly..." [EH_RR]*

*"...Current policies often focus more on safe disposal rather than on promoting the reuse or recycling of components..." [BW_SD]*

The regulatory landscape is fragmented and often inconsistent across jurisdictions, creating uncertainty and hindering the adoption of circular practices for offshore wind turbine components. Existing regulations tend to focus on safe disposal rather than promoting reuse or recycling of components. Compliance with varying legal requirements across different countries adds to the complexity and cost for companies. Harmonizing regulations across regions can streamline processes and reduce compliance costs, making it easier for companies to adopt circular practices in the EoL management of offshore wind turbine components.

**Environmental Challenges**

Circularity is considered one of the ways to reduce carbon emissions, but in doing so, other environmental factors must be taken into account. The interviews highlighted a few aspects of the environmental effects of decommissioning:

*"...Offshore decommissioning involves complex logistics that can lead to increased carbon emissions due to the use of specialized vessels and heavy machinery..."[EH_RR]*

*"...The disposal of non-recyclable materials, such as certain composites used in turbine blades, poses a significant environmental challenge. These materials often end up in landfills if not properly managed..." [BW_SD]*

*"...The energy-intensive processes required to recycle materials, such as melting down metals or chemically treating composites, can result in significant emissions and resource consumption. Balancing the environmental benefits of recycling with these potential negative impacts is a key challenge for the industry..." [SF_RM]*

The environmental impacts of decommissioning activities, such as increased emissions from transportation and energy-intensive recycling processes, are significant in the offshore context. Additionally, the disposal of non-recyclable materials poses environmental risks, undermining the principles of circularity. Circularity is considered a sustainable practice, but the allied carbon emissions to recycle, reuse, repower, etc., must be considered while assessing the circular strategies.

### 4.6.2. Theme 2: Key Decision-Making Parameters

Limited information is available about the remaining useful life and quality of second-life wind turbine components (Woo & Whale, 2022). This uncertainty creates risks for stakeholders seeking to reuse or repurpose these materials (Fay Fang de, 2021). A lot of data is lost during the life cycle of a project, and if not managed systematically throughout the lifecycle, the decommissioning phase can be challenging (Topham & McMillan, 2017). Based on the interview analysis, several key parameters and data attributes are essential for developing a circular decision-making framework tailored for a standardized data management system at the EoL phase of OWTs. These parameters help determine the feasibility and potential for reuse, recycling, or repurposing of turbine components. The findings are categorized into four main areas: component condition, operational history, material properties, and traceability.

The second set of questions focused on the technical parameters for deciding the reusability of an OWT component. It was followed by a discussion of the existing technologies that standardize these parameters.

**Key Takeaways Theme 2: Key Decision-Making Parameters**

1. Component Condition: Decommissioning components' condition is crucial for reuse or recycling. Visual inspections are the first step, assessing physical state, wear, and damage. The next step is advanced NDT methods, providing insights into components that cannot be visually measured. These tests accurately assess an OWT component's structural integrity and operational safety.

2. Operational History: The operational history of components is crucial for evaluating their remaining useful life and suitability for repairing, remanufacturing, or repurposing. Incorporating this data into a data management system, including SCADA data, maintenance logs, and operational history records, can improve the accuracy of assessments and decision-making processes for component reuse and recycling.

3. Material Properties: Stakeholders faced challenges in the EoL resource management due to insufficient knowledge of component material composition. Improper documentation of material usage creates safety hazards. Circular decision-making should include detailed information on component properties, including composition, amount of recycled materials, and presence of SVHC.

**Component Condition**

The condition of components is a fundamental factor in determining the potential for reuse or recycling. A thorough assessment of the physical state, wear and tear, and any existing damage is essential to make informed decisions about the future use of these components. Following are the quotes from the interviews that capture this topic:

*”...We always do an inspection before we buy, and if we sell a turbine, of course, the client also gets this inspection report by a third party in which, for example, the gearbox is really inspected from A to Z...” [BW_SD]*

*”...Visual inspections can only reveal so much. For a comprehensive assessment, we rely on both visual and advanced diagnostic tools to gauge the true condition of the components...” [UL_CE]*

*”...The future lifespan of the component is crucial; for instance, if a gearbox is just five years old, it is still good for reuse...” [EH_RR]*

*”...Advanced non-destructive testing methods are often required to accurately evaluate the condition of materials, adding to the complexity and cost of the decommissioning process...” [SF_RM]*

*”...Assessing the structural integrity of blades is particularly challenging due to their composite materials. Techniques like ultrasonic testing are essential but add to the overall cost...” [CG_BR]*

The condition of components during decommissioning is a fundamental factor in determining their potential for reuse or recycling. From the interviews, it was evident that the first step to check the condition of a component is to have a visual inspection. Visual inspection thoroughly assesses the physical state, wear and tear, and any damage visible to the naked eye. Visual inspection saves extra effort for testing the components, saving on costs. Detailed inspection reports and maintenance records accompany visual inspections. Stakeholders are strongly inclined towards having a platform where all the documentation and reports are integrated into a data management system.
Advanced non-destructive testing methods to determine a component’s structural integrity and material health are essential to satisfy the standards and certifications for second-hand use. These tests are necessary as they offer insights into the components that cannot be visually measured. This approach accurately assesses OWT components’ remaining useful life and suitability. The cost and time needed to conduct an NDT are comparatively higher than visual testing, but second-hand users can expect certification of the component’s structural integrity.

**Operational History**

The operational history of components provides valuable insights into their past, current, and future performances. Detailed records of a component’s usage, maintenance, and environmental conditions are crucial for evaluating its remaining useful life and suitability for repurposing or recycling. The quotes retrieved from the interviews for this topic are as follows:

*”...Nowadays more and more we’re also obtaining and we are very interested in obtaining Supervisory Control and Data Acquisition (SCADA) data. This data gives us a really good overview of the turbine’s past life, including weather conditions it has faced and how it has operated...” [BW_SD]*

*”...The load history and structural aspects of components are crucial for assessing their remaining useful life and suitability for reuse...” [EH_RR]*

*”..Access to detailed operational history allows us to create a comprehensive profile of the component, which is critical for making decisions about its future use...” [UL_CE]*

*”...If we have access to detailed operational history, it helps in making more informed decisions about the potential for repurposing or recycling components...” [SU_BM]*

*”...Regular maintenance records are vital for understanding the condition of components. Turbines with well-documented maintenance histories are easier to evaluate and repurpose...” [LL_DC]*

The operational history of components provides valuable insights into their performance and any stress they may have undergone. Detailed records of a component's usage, maintenance, and performance conditions are crucial for evaluating its remaining useful life and suitability for repairing, remanufacturing, or repurposing. Each component of an OWT is designed for a finite operational life, and few of the components are replaced earlier than others. This makes it essential to retain components that have been replaced and can be used as replacement components in another OWT.
In conclusion, incorporating detailed operational history into the data management system is critical for making informed decisions about the EoL of OWT components. This includes collecting and analyzing SCADA data, maintenance logs, and operational history records. A standardized approach to recording and sharing this data can significantly enhance the accuracy of assessments and decision-making processes for EoL resource management.

**Material Properties**
Material properties of a component are the most essential aspect of any circular assessment. Detailed knowledge of the materials used, their durability, and how they can be processed is critical for effective circular decision-making. Following are a few quotes retrieved from the interview transcripts:

*"...Understanding the material properties of different components, such as the type of composites used in blades, is essential for determining the appropriate recycling or repurposing methods..." [EH_RR]*

*"The diversity of materials used in turbines requires a tailored approach to recycling. Each material type has unique properties that must be understood to optimize recycling methods." [UL_CE]*

*"...We are developing processes to use reclaimed glass and carbon fibers from wind turbine blades, which requires a thorough understanding of the material properties to ensure quality and performance in new applications..." [SF_RM]*

*"...The properties of materials, especially in older turbines, can vary significantly, making it crucial to have detailed information on these properties to decide on the best circular strategies..." [DR_DS]*

*"...One of the circularity aspects that we focus on is the quantity of recycled materials used in the manufacturing process..." [DR_DS]*

In the interviews, the discussion about material properties mainly revolved around the recyclability of wind turbine blades. Stakeholders have faced several challenges in decommissioning and EoL resource management due to insufficient knowledge of the material composition of the components. Many OWFs that are currently or will be decommissioned were built more than two decades ago, and improper documentation of the material usage created safety hazards during decommissioning or EoL resource management. Another parameter is to collect data regarding the quantity of recycled materials used to manufacture new components.

Circular decision-making must include detailed information on each component's material properties, such as its composition, amount of recycled materials, and presence of SVHC. This information should be integrated into the data management system to identify suitable circular strategies. Advances in material science and recycling technologies should be continuously monitored and incorporated into the framework to ensure the effective processing of different materials.

### 4.6.3. Theme 3: Market Consideration

The successful implementation of circular practices for OWT components depends on technical and regulatory factors but is strongly driven by market dynamics.

The final set of questions focused on understanding the market's readiness, transparency/traceability, and the second-hand market's demand and supply conditions is crucial. The following subsections explore these market considerations in detail, based on insights from the interview analysis.

**Key Takeaways Theme 3: Market Consideration**

1. Market considerations are critical for successfully implementing circular practices in the offshore wind industry.
2. The interviewees stressed the significance of transparency and traceability in offshore wind turbine components, highlighting the need for standardized data collection and digital product passport systems to ensure accountability and sustainable practices.
3. Strict quality standards and increased awareness are needed to create suitable market demands for secondhand components. The second-hand market can play a significant role in the wind industry's circular economy, providing a sustainable alternative to new component manufacturing and reducing waste.

**Transparency & Traceability**

Transparency and traceability in the handling and processing offshore wind turbine components are crucial for building trust and ensuring accountability in CE. Implementing systems that track components throughout their lifecycle can significantly enhance the effectiveness of circular strategies by providing detailed information on their origins, usage, and handling. The quotes retrieved from the interviews for this topic are as follows:

*"...Clients require full transparency of what we do with the components, especially the blades. We need to provide detailed documentation on the destination and processing of each component..." [BW_SD]*

*"...A decision-making framework that helps in providing the optimal CE strategy for a specific component would be beneficial, ensuring traceability from decommissioning to final reuse or recycling..." [EH_RR]*

*"...Having a standardized data collection system, can greatly enhance traceability and support circularity in the wind industry..." [SU_BM]*

*"...Traceability is crucial for building trust with stakeholders. Implementing a digital product passport system can provide comprehensive data on each component's lifecycle..." [CG_BR]*

*"...Transparency in the supply chain is essential for promoting circularity. Systems that track components from manufacture to end-of-life can provide valuable insights for decision-making..." [LL_DC]*

*"...Implementing traceability systems ensures that all parties involved are accountable for the handling and processing of components, which supports circular practices..." [UL_CE]*

The interviewees emphasized the importance of transparency and traceability in handling offshore wind turbine components, highlighting their role in building trust and ensuring accountability for EoL resource management. Clients increasingly demand detailed documentation, particularly for high-profile components like turbine blades, to ensure alignment with CE principles. This underscores the need for robust systems that track components throughout their lifecycle.

A recurring theme is the need for standardized data collection and the implementation of digital product passport systems. These systems would provide comprehensive lifecycle data and support informed

decision-making. Such systems would facilitate transparency and ensure traceability from decommissioning to final reuse or recycling, addressing the current lack of uniformity in data management across the industry.
The emphasis on traceability is particularly significant, as it fosters trust among stakeholders by ensuring that all parties are accountable for their role in the component's lifecycle. Implementing these systems is essential for promoting sustainable and responsible practices in the offshore wind industry.

**Second-hand Market**
The second-hand market for wind turbine components is crucial in promoting circularity. Understanding the supply and demand dynamics and the barriers to market growth can help develop strategies to enhance the market for refurbished and reused components. Following are the quotes retrieved from the interview transcripts:

*"...The OEMs are now manufacturing turbines with a hub height, for example, more than 150m. There are projects where the height allowance of the wind turbines height allowance is 100m. Thus, using the existing smaller turbines is a market that I find quite interesting..." [WP_OW]*

*"...The market for second-hand components is still developing. The demand for refurbished parts is not yet robust enough to justify large-scale investments in recycling infrastructure..." [BW_SD]*

*"...There is a second-hand market for especially wind turbine blades, gearboxes, and generators, but it's mostly for onshore turbines..." [EH_RR]*

*"...The second-hand market for wind turbine components is still nascent. Increasing awareness and building a robust market for refurbished parts is essential for promoting circularity..." CG_BR*

*"...One of the main barriers to the growth of the second-hand market is the perception of lower quality and reliability of used components. Building trust and ensuring quality standards are crucial..." [LL_DC]*

*"...There is potential for a thriving second-hand market, but it requires significant investment in infrastructure and technology to assess and refurbish components to meet industry standards..." [UL_CE]*

The market for used wind turbine parts is essential to the industry's progress toward circularity. The interviewees highlight several obstacles to this transition. One important finding is that there is still a lack of development in the market for refurbished parts, particularly for offshore turbines, with insufficient demand to support large expenditures in infrastructure development for refurbishment and recycling. This reveals a significant obstacle to market growth, especially for parts primarily sold in the onshore sector, such as generators, gearboxes, and blades. However, participant [WP_OW] pointed out the second-hand market can be explored by exploiting the restriction applied to the wind farms in a specific region.
Another challenge is the assumption of the degraded quality of used components. Establishing and upholding strict quality standards is one way to overcome this assumption and cultivate trust with prospective customers. It will take coordinated efforts to increase awareness of the infrastructure required to evaluate, restore, and certify these parts under industry standards.

In conclusion, the second-hand market has the potential to play a significant role in the wind industry's circular economy by providing a sustainable substitute for the manufacture of new components and assisting in the overall reduction of waste, provided that appropriate investment is made and quality assurance is prioritized.

*The following section defines the requirements for the circular decision-making tool based on the literature review and interview analysis.*

## 4.7. Defining the Requirements

The systematic literature review and the semi-structured interviews were analyzed in the previous sections. The analysis identified the need to develop a decision-making framework using EoL offshore wind DPP data to support selecting a suitable circular strategy for the OWT components. The next step in the report is to use the results from the analyses to form the requirements that address the identified problem.

Identifying the requirements for circular decision-making will form the basis for answering the following sub-research question:

- *SQ.4: What are the implications of the identified circular strategies, key challenges, and key parameters for the EoL circular decision-making framework of an OWT?*

The requirements to address the identified problem based on the literature review and the interview analyses are as follows:

### EoL Circular Strategies

The circular strategies identified for the EoL resource management of an OWT are presented and explained in detail in Appendix F. These circular strategies will further develop the concept using the logic of achieving the highest level of circularity based on Potting et al. (2017), as illustrated in Figure 4.16.

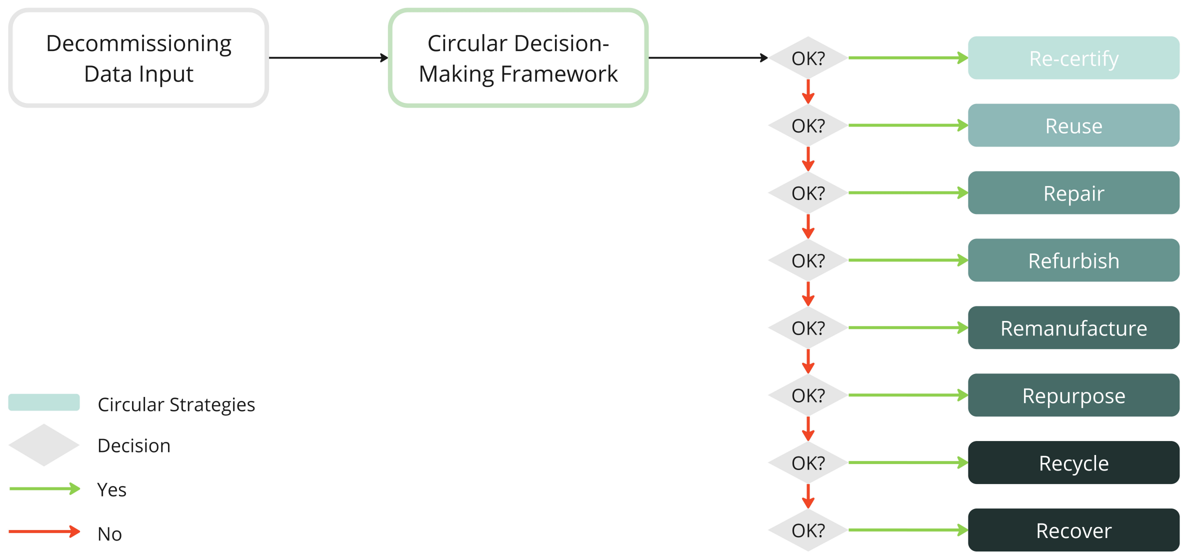



Figure 4.16: The circular strategies logic used to develop the decision-making framework.

The framework illustrated in Figure 4.16 demonstrates the flow of decommissioning data through a circular decision-making framework to determine the most appropriate circular strategy for OWT components.

When applied effectively, these circular strategies can significantly enhance the sustainability and resource efficiency of the offshore wind industry. The next challenge here is *to assess the circular strategy.* By incorporating comprehensive data inputs and assessments, stakeholders can make informed decisions that align with circular economy principles, ultimately contributing to a more sustainable energy future.

## Circularity Assessment and Key Assessment Parameters

The circularity assessment framework illustrated in Figure 4.17 provides a structured approach to evaluate the potential for applying circular strategies to OWT components. The assessments are categorized into six main types: Typology Assessment, Condition Assessment, Performance Assessment, Compliance Assessment, Economical Assessment, and Environmental Assessment. Each assessment requires specific parameters that guide the decision-making process toward evaluating the circular strategies.

*The economic and environmental assessments are vital for implementing a circular strategy. However, because of their dynamic nature, they can vary significantly based on regional aspects, policy frameworks, and organizational policies. Thus, no generalization can be made for these assessments, and they are kept out of the scope of this research.*

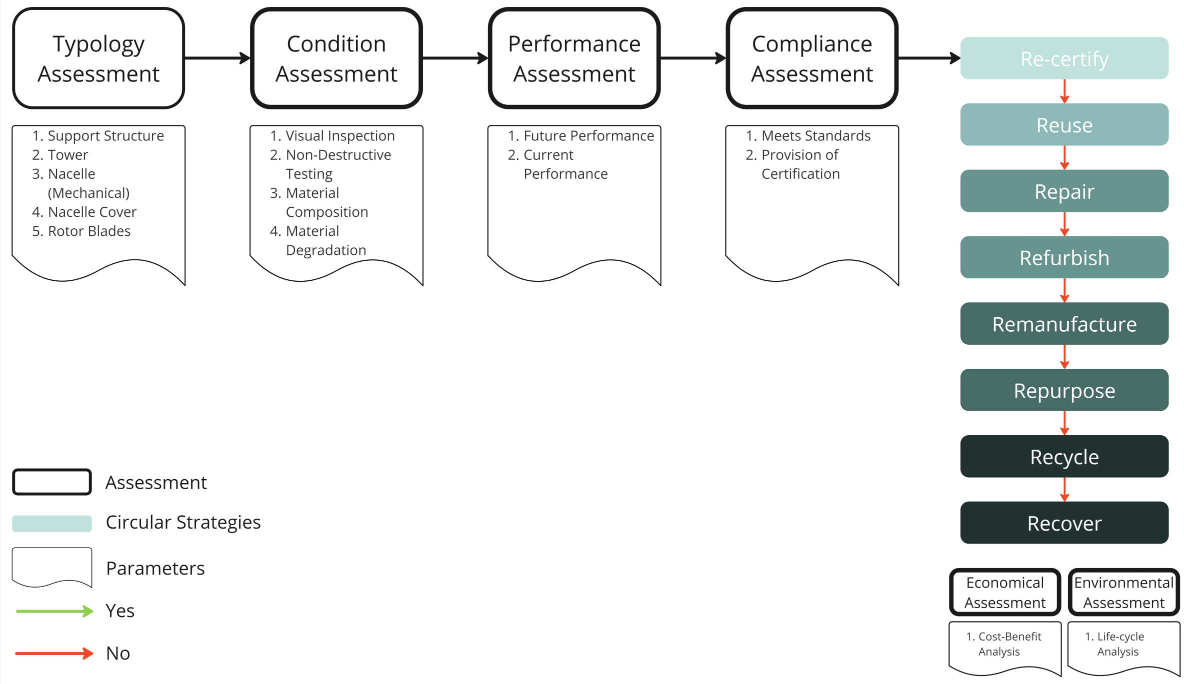



Figure 4.17: Assessments necessary for circular decision-making.

The circular decisions are assessed based on the following six assessment criteria. The extended list of parameters identified during the literature review in Table 4.2 was narrowed down to the key parameters necessary to assess circularity. The key parameters were identified through the process of interview analysis. It is crucial to explore how the key parameters will be evaluated. A DPP tailored for the EoL of OWT provides comprehensive data about each component, as shown in Table 4.4. Thus, the data attributes available in the DPP must be connected to the key parameters.

### Typology Assessment

The Typology Assessment is the initial stage where the type of OWT component is identified. This categorization is crucial as the compatibility of the components varies for the circular strategies. To determine the applicability of the circular strategies to the components, refer back to Table 4.3. The key parameters include:

- Support Structure
- Tower
- Nacelle (Mechanical Components)
- Nacelle Cover
- Rotor Blades

**Condition Assessment**

Evaluating the condition of components in OWTs is a crucial first step in determining the most suitable strategies for managing these components when they reach the end of their operational life. Various important parameters must be considered to perform this assessment effectively, each requiring specific data attributes to ensure a thorough evaluation.

1. Visual Inspection: Involves detailed examination of the component's external and, where possible, internal surfaces to identify any visible signs of damage, wear, corrosion, or other forms of deterioration. This step is essential for establishing a baseline understanding of the component's physical condition. The data attributes needed are as follows:
    - Inspection Reports: Detailed documentation of the visual inspection findings, including photos, annotations, and descriptions of any observed defects.
    - Condition at EoL: A summary of the component's overall condition at the time of inspection, which serves as a key input for deciding whether the component is suitable for reuse, repair, or other circular strategies.
2. NDT: NDT techniques, such as ultrasonic testing, radiography, or magnetic particle inspection, are used to evaluate the internal integrity of the component without causing any damage. NDT is critical for detecting subsurface flaws, cracks, or other structural issues that are not visible during a standard visual inspection (Zetec, 2019). The data attributes needed are as follows:
    - Structural Integrity: The results of NDT assessments that reveal the presence or absence of internal defects provide a clear understanding of the component's structural health.
3. Material Composition: Understanding the material composition of the component is crucial for determining its recyclability, potential for reuse, and the presence of any hazardous substances that may complicate processing (Mendoza et al., 2022). The data attributes needed are as follows:
    - Material List: A detailed inventory of the materials used in the component, including metals, composites, and other materials.
    - Critical Raw Materials: Identification of any critical or scarce raw materials within the component that may influence the decision to recycle or remanufacture.
    - SVHC: Information on any SVHC present in the component that may pose risks during processing or disposal.
    - Quantities: The amount of each material present in the component is essential for planning recycling or material recovery efforts.
4. Material Health: Focuses on evaluating the extent of degradation in the material properties over time due to factors like environmental exposure, operational stresses, or chemical reactions. This assessment is crucial for determining the remaining useful life of the component. The data attributes needed are as follows:
    - Material Degradation: Data on the extent of material degradation, such as corrosion levels, wear patterns, or other indicators of material fatigue, which directly impact the component's performance and durability.

**Performance Assessment**

The Performance Assessment is critical to evaluating the component's suitability for various circular strategies, such as repair, refurbishment, or reuse (Chen et al., 2021). This evaluation considers the present operational efficiency and future performance estimates, influencing decisions about keeping or reconditioning the component.

1. Current Performance: Measuring the component's operational efficiency, reliability, and overall effectiveness is part of the current performance parameter. This assessment offers insight into how well the component performs under current conditions. The data attributes needed are as follows:

- Current Performance: This attribute includes historical data on the component's efficiency, output, reliability, and deviations from expected performance metrics. These metrics are crucial for determining whether the component can continue to operate effectively or needs upgrades.
- Operational Records: Detailed records of the component's operation over time, including instances of failure, downtime, and repair activities. These records help understand the component's performance trends and identify patterns that may indicate underlying issues.

2. Future Performance: Evaluating how the component will likely perform over the remainder of its expected lifespan. This projection is based on current performance data, maintenance history, and any known issues that may affect the component's durability or efficiency in the future. The data attributes needed are as follows:

   - Service History: Comprehensive documentation of all components' maintenance activities, repairs, and upgrades performed. This history provides insights into how well the component has been maintained and its potential for continued use.
   - Maintenance Records: Detailed logs of routine and non-routine maintenance, including the frequency and nature of repairs. These records assess the likelihood of future failures and the need for ongoing maintenance.
   - RUL: An estimate of the RUL of the component, considering current performance, material degradation, and historical data. This attribute helps determine whether it is cost-effective to repair or refurbish the component or if it should be decommissioned.

**Compliance Assessment**
Ensuring OWT components meet required standards and regulations through Compliance Assessment is vital for resale or repurposing. This assessment verifies component adherence to industry standards and secures essential certifications to enable market acceptance, especially within circular economy strategies.

1. Meets Standards: This parameter covers all the necessary data to confirm that the component adheres to legal and regulatory standards. It includes information about compliance with safety protocols, environmental regulations, and industry standards essential for implementing a circular strategy.

2. Provision of Certification: Documentation proving the components are certified according to relevant standards. This includes records of inspections and certifications from recognized bodies.

**Economic and Environmental Assessment**
These are some of the important aspects of the circularity assessment, providing insights into the feasibility and sustainability of the selected circular strategies. These assessments are critical as they are dynamic and vary significantly based on regional aspects, policy frameworks, and organizational priorities.

1. Economic Assessment: Evaluate the financial viability of implementing various circular strategies through a cost-benefit analysis, considering market demand and ROI. This ensures the chosen strategy is financially viable, considering the regional market conditions and economic incentives available (Mendoza & Pigosso, 2023). Referring to ISO 59010 (Circular Economy: Guidance on the transition of business models and value networks) can support the economic aspect of implementing the circular strategy.

2. Environmental Assessment: Evaluate the potential environmental impacts of the circular strategies using tools like LCA. This includes evaluating waste reduction, emission control, and other carbon-emitting activities related to the implementation to ensure that the chosen circular strategy contributes positively to environmental sustainability (Ghisellini et al., 2016).

An additional layer to understand the key parameters is to map them against the circular strategies. Appendix G outlines the key parameters for assessing various circular strategies by mapping each parameter against them to indicate their relevance and application.

Table 4.6 provides a comprehensive overview of data attributes needed to evaluate the key parameters and the actor responsible for providing data. This table will also guide the development of a DPP tailored for the EoL of offshore wind turbines.

Table 4.6: Overview of DPP data attributes for key parameters for the circularity assessment of OWT components.

| Key Parameter | DPP Data Attributes | Stakeholder Responsible |
|---|---|---|
| Visual Inspection | Inspection Reports | *Operator, Maintenance Service Providers* |
| | Condition at EoL | *EoL Inspection Provider* |
| NDT | Structural Integrity | *EoL Inspection Provider* |
| Material Composition | Material List | *OEM, Supplier* |
| | Critical Raw Materials | *OEM, Supplier* |
| | Hazardous Substances | *OEM, Supplier* |
| | Quantities | *OEM, Supplier* |
| Material Health | Material Degradation | *Operator, Maintenance Service Providers* |
| Current Performance | Current Performance | *Operator* |
| | Operational Records | *Operator* |
| Future Performance | Service History | *Operator* |
| | Maintenance Records | *Operator* |
| | Residual Life & Performance | *Operator, Maintenance Service Providers* |
| Standards and Certification | Regulatory Compliance | *Repairing, Refurbishing, Remanufacturing, & Recycling Agencies* |
| | Certification | *Repairing, Refurbishing, Remanufacturing, & Recycling Agencies* |

Next to the assessment decision flow, a component may either satisfy an assessment criteria or fail. When a component fails to fulfill the condition assessment, it doesn't need to be proposed for recycling or recovery. The component can still be evaluated for other assessments to achieve maximum circularity. Figure 4.18 provides an overview of the structured approach to evaluating circular assessment decisions.

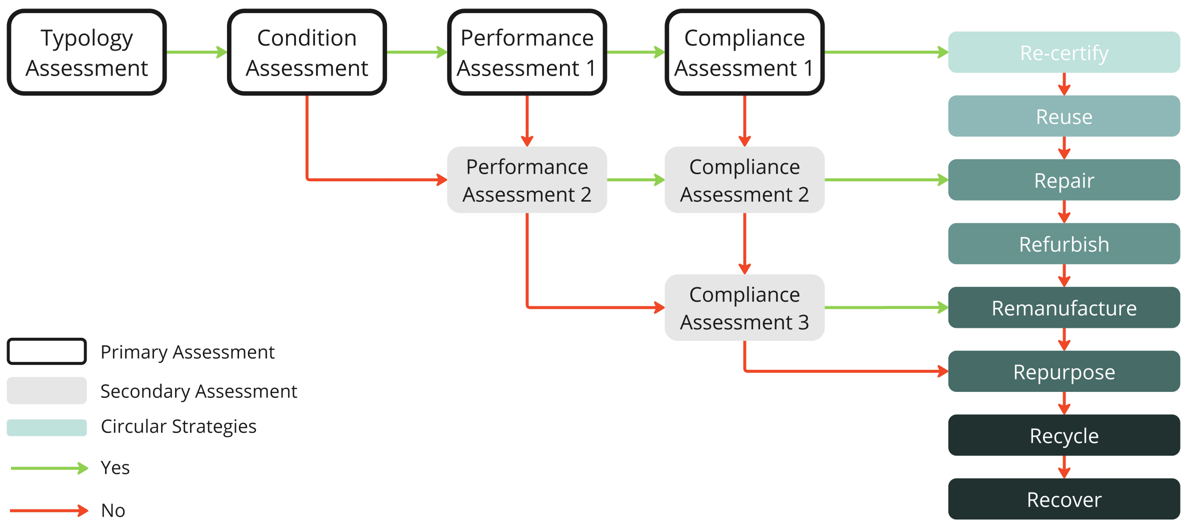



Figure 4.18: Overview of the decision flow for the circular assessments.

Suppose a specific assessment criterion fails to reach a positive threshold. In that case, the assessment is evaluated through a secondary assessment of the following assessment level. This approach makes it clear to the user of the decision-making framework that a negative threshold of an assessment will result in fewer options for circular strategies. The framework consists of primary assessments (Condition, Performance 1, and Compliance 1) and secondary assessments (Performance 2, Compliance 2 & 3) that guide the decision-making process.

### Weighing Data Attributes

Using the circular decision-making framework, it is essential to have a well-defined and consistent approach for evaluating the data attributes gathered in the DPP. The valuation of the data attributes involves classifying the values into high, medium, and low categories, which directly impact the decision results. These categories are determined based on the factual data obtained from inspection reports provided by ECHT regie in transitie, ensuring that the framework is rooted in real-world circumstances. The range of values for the DPP data attributes is categorized into high, medium, and low, as shown in Table 4.7.

Categorizing data attributes into high, medium, and low ranges is a crucial stage in the decision-making process as it dictates the impact of each attribute on the choice of circular strategies. The precision and significance of these weightings are essential for the effectiveness of the circular strategy implemented.

Table 4.7: Enhanced Ranges of Key Parameters for the Circularity Assessment of OWT Components

| DPP Data Attribute | High Range | Medium Range | Low Range |
|---|---|---|---|
| Inspection Report | | *Yes or No* | |
| Condition at EoL | No visible damage or wear | Minor visible damage or wear | Significant visible damage or wear |
| NDT | No defects detected | Minor defects detected | Significant defects detected |
| Material List | Detailed material composition | Partial material composition | Limited or unknown composition |
| REE | Critical materials present | Some critical materials present | No critical materials present |
| SVHC | High concentration of hazardous substances | Moderate concentration | Low or no hazardous substances |
| Material Degradation | <10% of the component | 10-30% of the component | >30% of the component |
| Operational Records | Comprehensive and up-to-date | Partial or outdated | Limited or missing |
| Current Performance | 100-90% efficiency | 90-70% efficiency | <70% efficiency |
| Maintenance Records | Detailed and consistent | Incomplete or irregular | Missing or unknown |
| Servicing Frequency | ≥ 2 times per year | 1 time per year | < 1 time per year |
| RUL | ≥ 10 years | 5-10 years | <5 years |
| Future Performance | >80% expected | 50-80% expected | <50% expected |
| Regulatory Compliance | Fully compliant | Partially compliant | Non-compliant |
| Certification | Multiple relevant certifications | Some relevant certifications | No certifications |

The need for effective EoL resource management in the offshore wind industry has led to a need to have a standardized data management system that would aid in circular decision-making. To tackle this need, a tool must be designed to assist stakeholders involved in EoL resource management by providing a data collection guide and circular decision-making.

*The following section will provide the process of the development of the tool.*

# Part II: Develop & Deliver

The second part of Chapter 4 focuses on developing an EoL resource management tool tailored for OWTs based on Section 4.7. Development of the tool first focuses on developing a DPP structure in Section 4.8. Next, Section 4.9 will create a circular decision-making framework. Lastly, this chapter focuses on validating the tool in Section 4.10.

# Develop (Tool for Circular Decision-Making)

The Develop section is divided into three parts: defining a DPP structure tailored for the EoL of OWT components using MS Excel, developing the decision flow for the circular decision-making framework, and incorporating the decision-making framework in MS Excel. The last step aims to capture relevant data from a DPP to evaluate the assessments through the (IF), (AND), or (OR) functions.

## 4.8. Developing the DPP Structure

The primary aspect of the development phase is to develop a DPP structure tailored for the EoL OWT components. The challenge that most of the stakeholders faced while implementing circular strategies was the need to have a standardized data management system. Data collection is a critical aspect of this system. Another challenge is the large number of actors involved in the EoL of OWF. Therefore, the data collection system must be developed in a user-friendly program to ease actor engagement and provide a systematic approach. "Microsoft Excel" was chosen for this systematic data collection. This Excel Workbook will act as a DPP by collecting, storing, and analyzing the data.

*A point to be noted here is that data collection is only possible when there is a policy for data sharing. Many stakeholders, usually the OEMs, are reluctant to share data because of IP issues. To tackle this, the data collection can be done on a blockchain network where only the relevant actors can use/view the data to evaluate the circular strategies. Several platforms support the development of a software tool for a DPP, as shown in Appendix H. Among these software developers, several provide solutions to have a blockchain network. The data input can be in Excel Datasheets for all of these platforms. Considering the scope of this research, blockchain networks will not be explored.*

As previously discussed in Table 4.4, an essential structure for a typical DPP for EoL resource management for an OWT is listed. To align the DPP for this research, a DPP that consists of data regarding the components of an OWT is necessary. The DPP will consist of various working sheets, as typically, there is more than one OWT in a single project. Table 4.8 provides an overview of the sheets for a comprehensive DPP; the explanation of the sheets will follow.
Moreover, as discussed in the next section, the decision-making framework requires the data from the DPP to be analyzed and converted into a format that the Circular Decision-Making Tool can use. This data analysis is supported by Table 4.7. The process of analyzing the raw data from the stakeholders will be automated and will be displayed alongside the raw data. This is done to engage the actors involved in data entry and give them an overview of the analysis.

Table 4.8: Overview of the Excel Workbook for DPP for EoL OWT components.

| Sheet No | Sheet Title | Sheet Objective |
|---|---|---|
| 1 | Cover_Page | This sheet will contain basic information about the project, a brief description of the DPP and the steps to the next sheet. |
| 2 | System_Overview | This sheet provides an overview of the entire OWF at the system level, with links to detailed sheets for each system type. |
| 4 | OWT_1 | This sheet lists the different components of a specific wind turbine (e.g., OWT_1) and provides links to data sheets for each component like support structure, tower, nacelle (mechanical), nacelle cover, and rotor blades. |

| Sheet No | Sheet Title | Sheet Objective |
|---|---|---|
| 4a | Support_Structure_1 | This sheet is used to enter and view detailed data for the support structure component of a specific OWT. This sheet will also present the analysis of the data entered and used for circular decision-making based on Table 4.7. The data rows will be color-coded for the type of stakeholder responsible for providing the data. |
| 4b | Tower_1 | This sheet follows the same format as Sheet 4a but focuses on the tower component of a specific OWT, capturing all relevant data attributes. |
| 4c | Nacelle_Mechanical_1 | This sheet follows the same format as Sheet 4a but focuses on the mechanical components of the nacelle, capturing all relevant data attributes. |
| 4d | Nacelle_Cover_1 | This sheet follows the same format as Sheet 4a but focuses on the nacelle cover, capturing all relevant data attributes. |
| 4e | Rotor_Blade_1 | This sheet follows the same format as Sheet 4a but focuses on the rotor blades, capturing all relevant data attributes. |

**Cover_Page:**
The cover page of the DPP as illustrated in Figure 4.19 will include the following information:

- Project-specific Information: Each offshore wind farm project is unique and thus requires specific details tailored to its particular needs. This section includes essential project information such as the project name, manager, date, and location. These details ensure the project context is clearly defined, facilitating better management and decision-making throughout the project's lifecycle.
- Collaborators: The cover page lists all the stakeholders involved in the project, their roles, and their expertise. Keeping track of collaborators is vital, as it allows for the identification of missing knowledge that could be valuable to the project. It also helps monitor changes in the stakeholder landscape, ensuring that all relevant parties are informed and involved. The stakeholders will be color-coded to clarify who is responsible for providing the data and who will be accountable for that specific data.
- Instructions: The cover page will also provide brief instructions to enter data in the DPP and steps to go to the next sheet.

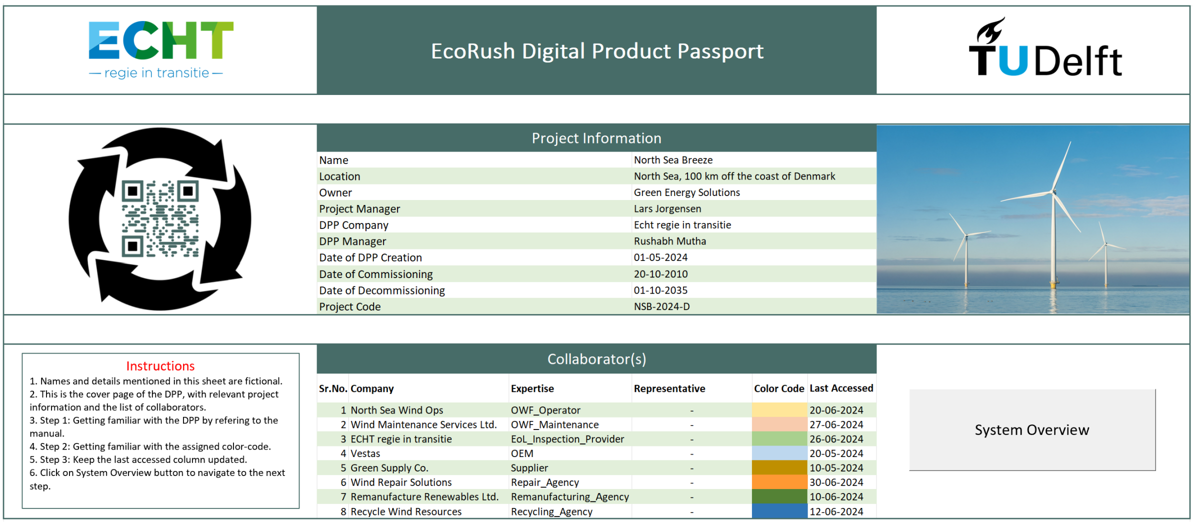


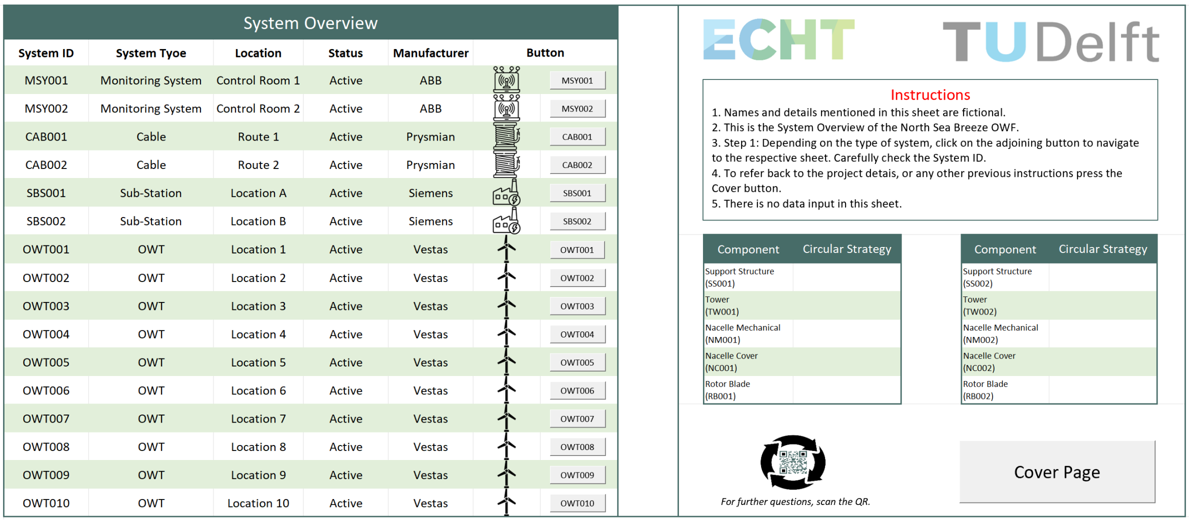

Figure 4.19: Cover Page of the DPP.

**System_Overview:**
This sheet acts as an index for the OWF at the system level with links to the systems (for example, sub-stations, cables, monitoring systems, and OWTs). The list will provide basic identifiable information for the system types, including system ID, location, status, manufacturer, and installation date. This sheet provides a comprehensive overview of the components of the entire offshore wind farm.

The DPP is structured to include the whole system, but considering the scope of the research, the DPP will break down into further details for the OWTs only. Each system entry in this sheet will link to a sheet that provides the breakdown of the system level to the component level. This is illustrated in Figure 4.20 and will include the following information.

- OWT: Detailed sheets for each OWT will include an overview of the components of the turbine.
- Sub-Stations: If expanded, detailed sheets could include transformer specifications, switchgear details, and control systems.
- Cables: Detailed sheets could provide information on cable types, lengths, burial depths, and maintenance records.
- Monitoring Systems: Detailed sheets could list sensors, data collection intervals, and performance metrics.

The primary focus will be on OWTs, where the detailed breakdown will allow for an in-depth analysis of their components and the implementation of circular strategies at the end of their life cycle. This sheet also provides an overview of the components for completing the circular decision-making, as illustrated in Figure 4.20 (right side, middle of the sheet). A similar detailed approach can be followed for other systems if required in future research or practical applications.



System Overview

| System ID | System Tyoe | Location | Status | Manufacturer | Button |
|---|---|---|---|---|---|
| MSY001 | Monitoring System | Control Room 1 | Active | ABB | MSY001 |
| MSY002 | Monitoring System | Control Room 2 | Active | ABB | MSY002 |
| CAB001 | Cable | Route 1 | Active | Prysmian | CAB001 |
| CAB002 | Cable | Route 2 | Active | Prysmian | CAB002 |
| SBS001 | Sub-Station | Location A | Active | Siemens | SBS001 |
| SBS002 | Sub-Station | Location B | Active | Siemens | SBS002 |
| OWT001 | OWT | Location 1 | Active | Vestas | OWT001 |
| OWT002 | OWT | Location 2 | Active | Vestas | OWT002 |
| OWT003 | OWT | Location 3 | Active | Vestas | OWT003 |
| OWT004 | OWT | Location 4 | Active | Vestas | OWT004 |
| OWT005 | OWT | Location 5 | Active | Vestas | OWT005 |
| OWT006 | OWT | Location 6 | Active | Vestas | OWT006 |
| OWT007 | OWT | Location 7 | Active | Vestas | OWT007 |
| OWT008 | OWT | Location 8 | Active | Vestas | OWT008 |
| OWT009 | OWT | Location 9 | Active | Vestas | OWT009 |
| OWT010 | OWT | Location 10 | Active | Vestas | OWT010 |

Instructions
1. Names and details mentioned in this sheet are fictional.
2. This is the System Overview of the North Sea Breeze OWF.
3. Step 1: Depending on the type of system, click on the adjoining button to navigate to the respective sheet. Carefully check the System ID.
4. To refer back to the project detais, or any other previous instructions press the Cover button.
5. There is no data input in this sheet.

| Component | Circular Strategy |
|---|---|
| Support Structure (SS001) | |
| Tower (TW001) | |
| Nacelle Mechanical (NM001) | |
| Nacelle Cover (NC001) | |
| Rotor Blade (RB001) | |

| Component | Circular Strategy |
|---|---|
| Support Structure (SS002) | |
| Tower (TW002) | |
| Nacelle Mechanical (NM002) | |
| Nacelle Cover (NC002) | |
| Rotor Blade (RB002) | |

For further questions, scan the QR.

Cover Page

Figure 4.20: System Overview sheet of the DPP.

**OWT_1:**
The OWT_1 sheet serves as an index and navigational hub for detailed information about the OWT_1 components. This sheet is added to streamline access to component-specific data while avoiding excessive data clutter on a single sheet. It includes links to individual component sheets and instructs users on navigating the DPP effectively. This sheet is illustrated in Figure 4.21.

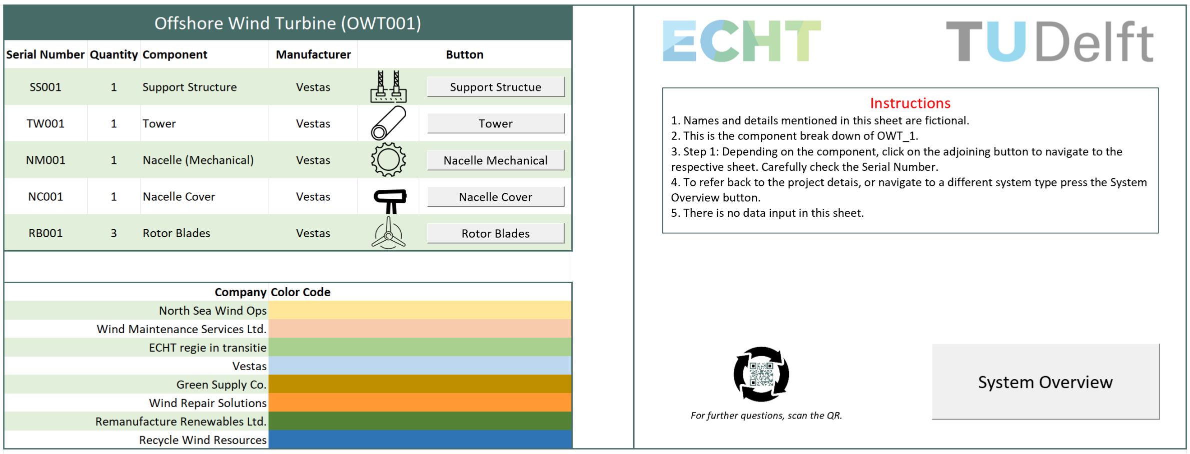



Figure 4.21: Navigation sheet for components of OWT_1.

**Component Sheets (4a-4e):**
The component sheets are designed to capture and manage detailed information about the components of an OWT. These sheets include various physical, material, environmental, and operational attributes for evaluating the component's condition, performance, and compliance.
Each component sheet includes two main categories of data attributes. The first category is mandatory for circular decision-making, and the second is optional. The required data attributes aid in the decision-making for the respective parameters. The optional data attributes include material properties, design & Production information, and EoL data. Figure 4.22 illustrates the detailed layout of a DPP for a support structure. Similar layouts for other components are available in the Excel Workbook, ensuring consistency and comprehensiveness across all OWT components.

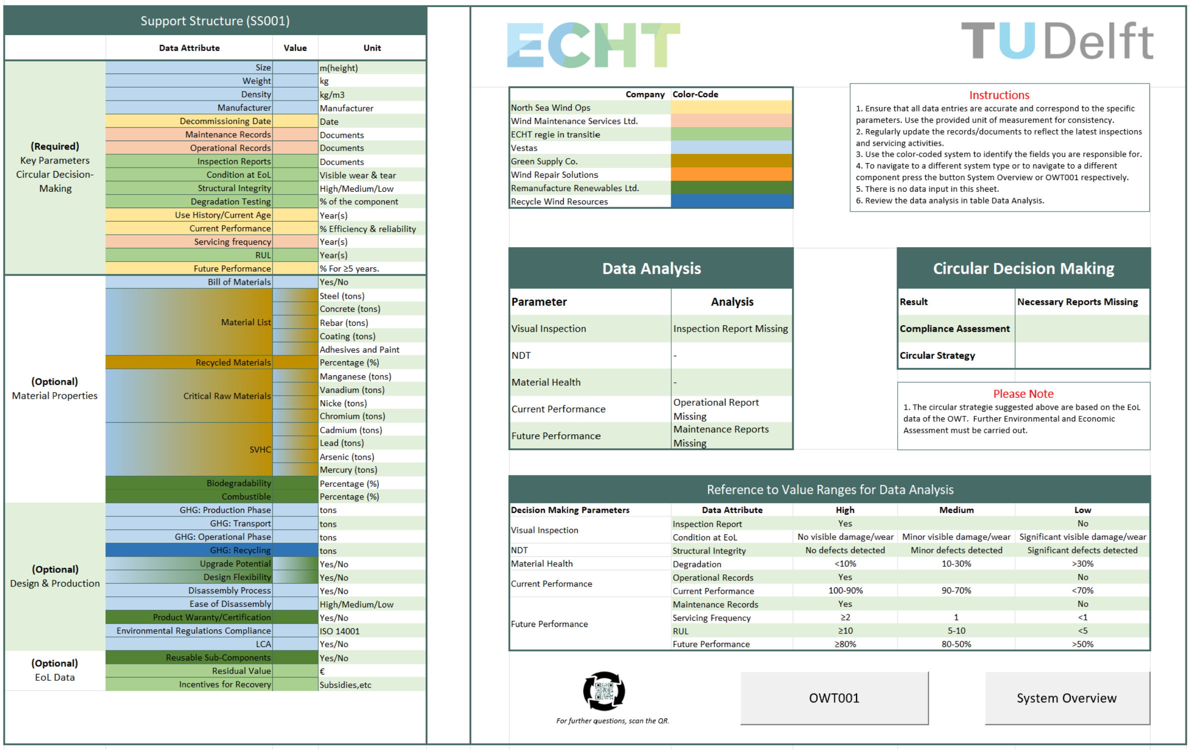



Figure 4.22: EoL DPP for the Support Structure of OWT_1.

The data entry is color-coded to make it easy for the stakeholders to identify which data attribute they need to fill in. The only change is the list of material compositions for each component. A combination of existing documentation and practical on-site assessments is necessary to collect data for the circular decision-making tool from an existing wind turbine; a more detailed approach to collect the data for the DPP is provided in Appendix J.

## 4.9. Circular Decision-Making

The second aspect of the development phase is to define the decision flow for the circular assessment, which will give depth to the decision-making process. As illustrated in Figure 4.23, each assessment consists of its respective parameters derived from Table 6.7. *(Refer to Appendix K for a better illustration of the circular decision-making framework.)* The ideal situation is when all the parameters score high, leading to the highest level of circular strategy. The assessment is directed to a lower parameter evaluation with a medium or low parameter score.

As previously discussed, economic and environmental assessments are not an integral part of the decision-making, but the decision-making will reflect where and how the two assessments play a role. Economic and environmental assessments are crucial steps after every identified circular strategy, and the false decisions made regarding these assessments must eventually lead to an immediate lower circular strategy.

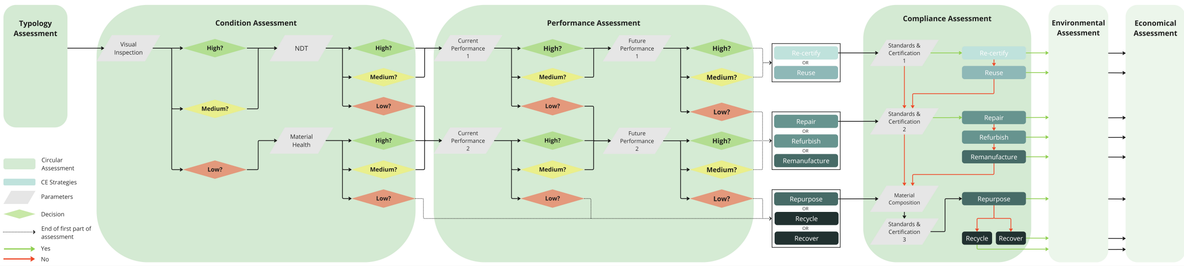



Figure 4.23: Circular decision-making framework.

Following are the decision-making flow diagrams for the circularity assessments. The decision flow is derived from the analysis of the Literature Review, the Interviews, and the Inspection Reports that were provided by ECHT regie in transitie.

### Typology Assessment

Typology Assessment consists of (1)Support Structure, (2) Tower, (3) Nacelle (Mechanical), (4) Nacelle Cover, and (5) Rotor Blades. Depending on the difficulty of the applicability of circular strategies for an OWT component, the list of possible circular strategies is further streamlined. This assessment ensures that the suggested circular strategy is technologically feasible. Figure 4.24 illustrates circular strategies that cannot be applied to the specific components as of May 2024. Since technological advancements in the wind sector are rising, the typology assessment provides flexibility for incorporating this in the future.

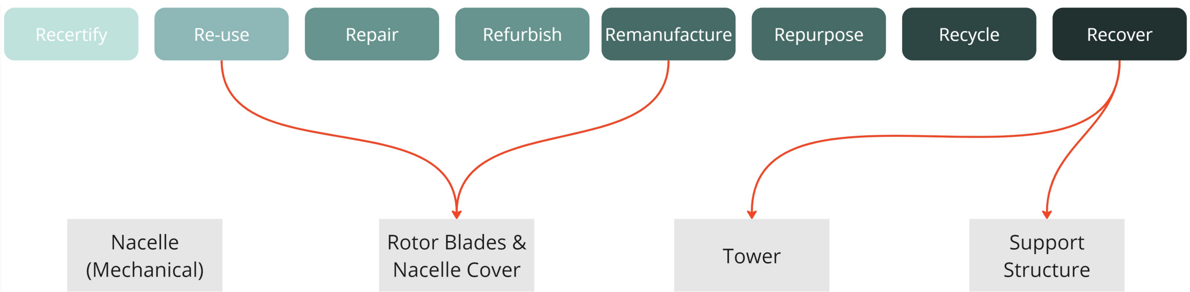



Figure 4.24: OWT components and circular strategies that cannot be applicable.

## Condition Assessment

Condition assessment consists of the following key parameters: *(1) Visual inspection, (2) NDT, (3) Material Health, and (4) Material Composition.* Depending on evaluating these parameters, the decision-making path is followed as illustrated in Figure 4.25. The figure shows that Performance Assessment 1 and Performance Assessment 2 are primary and secondary assessments, respectively. Both follow the same evaluation parameters; the only difference is the possibility of the resultant circular strategies.

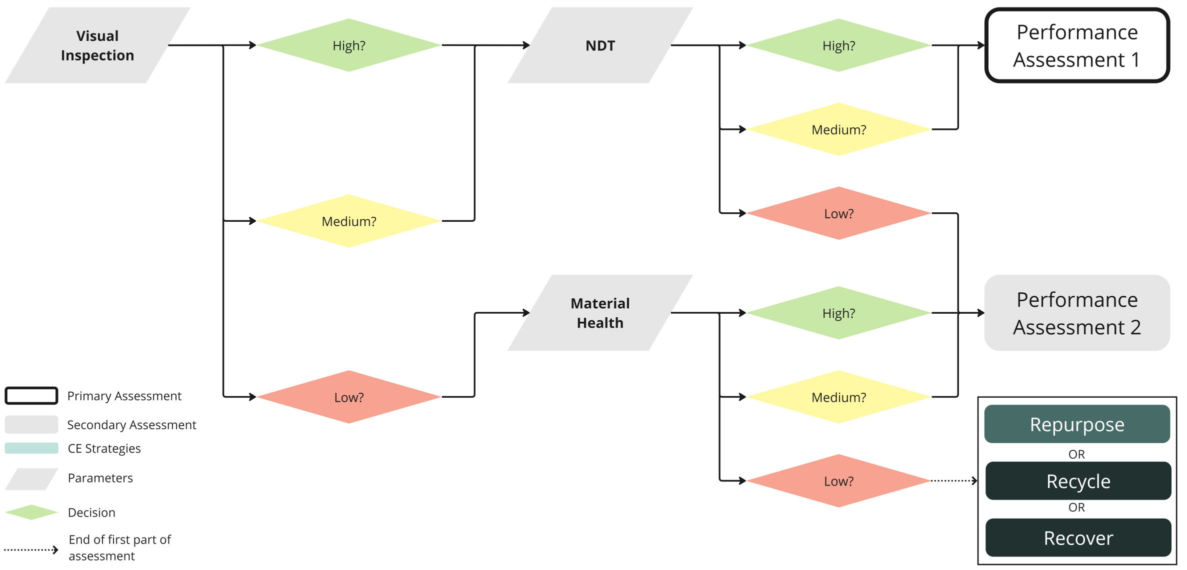



Figure 4.25: Condition assessment.

## Performance Assessment

Performance assessment consists of the following parameters: *(1) Current Performance 1, (2) Current Performance 2, (3) Future Performance 1, and (4) Future Performance 1.* Depending on the evaluation of these parameters the decision-making path is followed as illustrated in Figure 4.26. At the end of the performance assessment, the group of potential circular strategies can be seen. The groups are formed based on similarities between the circular strategy.

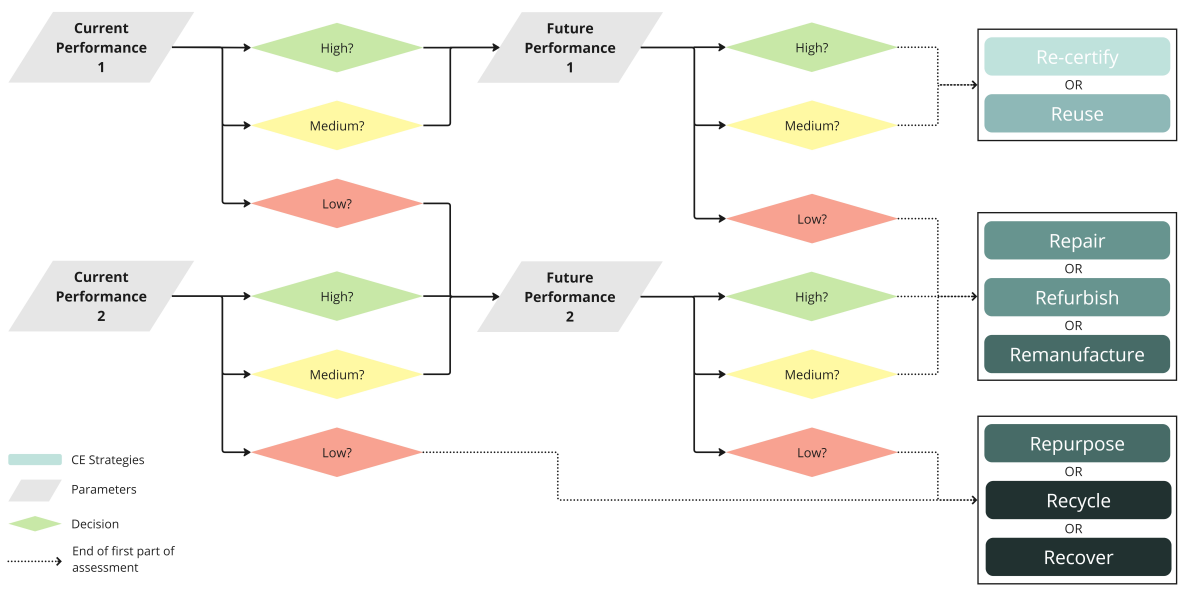



Figure 4.26: Performance assessment.

## Compliance Assessment

Compliance assessment consists of the following parameters *(1) Standards & Certification 1, (2) Standards & Certification 2, (3) Material Composition, and (4) Standards & Certification 3*. The general guides for standards regarding circularity can be referred to as the ISO 59020 (Measuring and assessing circularity performance) and ISO 590004 (Guidance on implementing circular economy). The purpose of having three different parameters is that the circular strategies preceding these parameters need different standards and certifications. Depending on evaluating these parameters, the decision-making path is followed as illustrated in Figure 4.27.

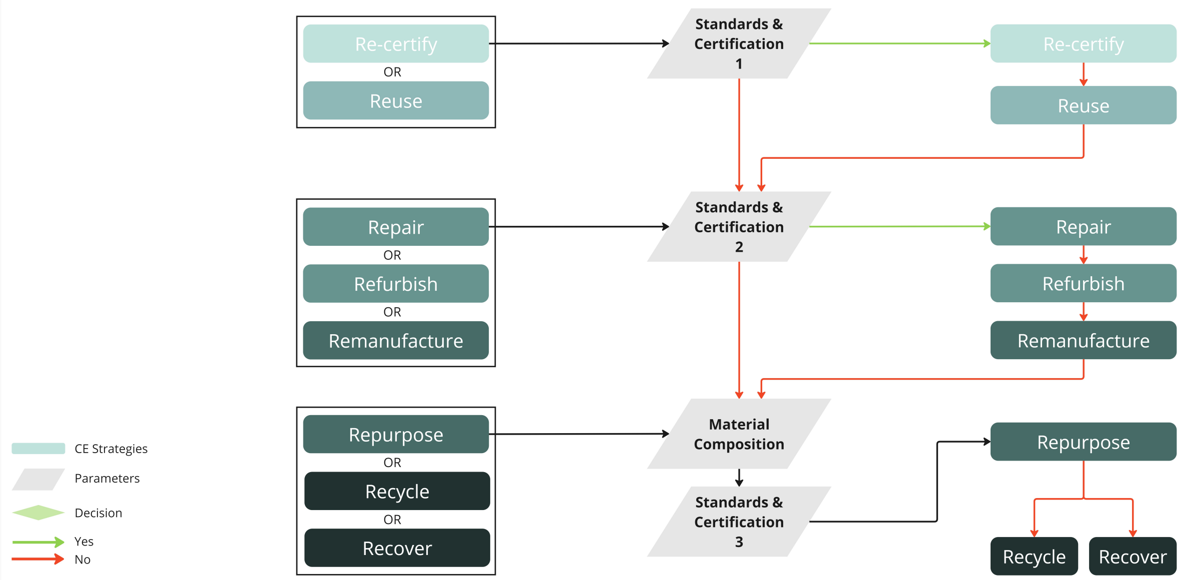



Figure 4.27: Compliance assessment.

Interesting to notice in Figure 4.27 is that the Material Composition is kept as part of the compliance assessment for components that did not qualify for any of the previous strategies; the material composition is assessed to determine suitability for re-purpose, recycle, or recover. Based on the material composition, the decision is made whether the components can be repurposed or should go for recycling or recovery.

Following is the explanation of the different parameters of the compliance assessment:

1. **Standards & Certification 1:** This parameter refers to assessing Re-certify or Reuse. Re-certify is given priority; if the component does not comply with this strategy, the component is assessed for Reuse. If the component does not comply with reuse, the component is assessed for Standards & Certification 2.

2. **Standards & Certification 2:** This parameter refers to assessing Repair, Refurbish, or Remanufacture, in the order of priority respectively. If the component does not comply with remanufacturing, the component is assessed for Material Composition.

3. **Standards & Certification 3:** This parameter refers to assessing Repurpose, Recycle, or Recover. Priority is given to repurposing, and if the component does not comply with this strategy, the component will be assessed for recycling or recovery.

Appendix I presents the checklist used to assess the standards and the details of the standards.

# 4.10. Decision-Making Tool

This section presents the integration of the DPP and the circular decision-making framework in the EcoRush Tool.
**Step 1** is to enter the data necessary for the EoL decision-making.

**Step 2** is an intermediate step that classifies the data attribute values into high, medium, and low categories by analyzing based on Table 4.7. The data for this step is stored in an intermediate table as illustrated in Figure 4.28 *(Table: Data Analysis 1)*.
The data is converted using the (IF), (AND), or (OR) functions in Excel. Following are a few examples of Excel codes used in the analysis of data attributes:

- The code here is used to analyze the Degradation level of the component: *=IF(D31=" ", "-", IF(D31<=10, "High", IF(D31<=30, "Medium", "Low")))*
- The code here is used to analyze the Current Performance of the component: *=IF(D53=" ", "-", IF(AND(D53>=90, D53<=100), "High", IF(AND(D53>=70, D53<90), "Medium", "Low")))*

**Step 3** presents the evaluation of the parameters based on the analysis conducted in Step 2.
For example, to evaluate Future Performance, the necessary data attributes are Service History, Maintenance Records, and RUL. The evaluation will only be conducted if the maintenance records are present. Once the system recognizes that necessary documents and records are available depending on the High, Medium, and Low scores of service history and RUL, Future Performance will be evaluated.

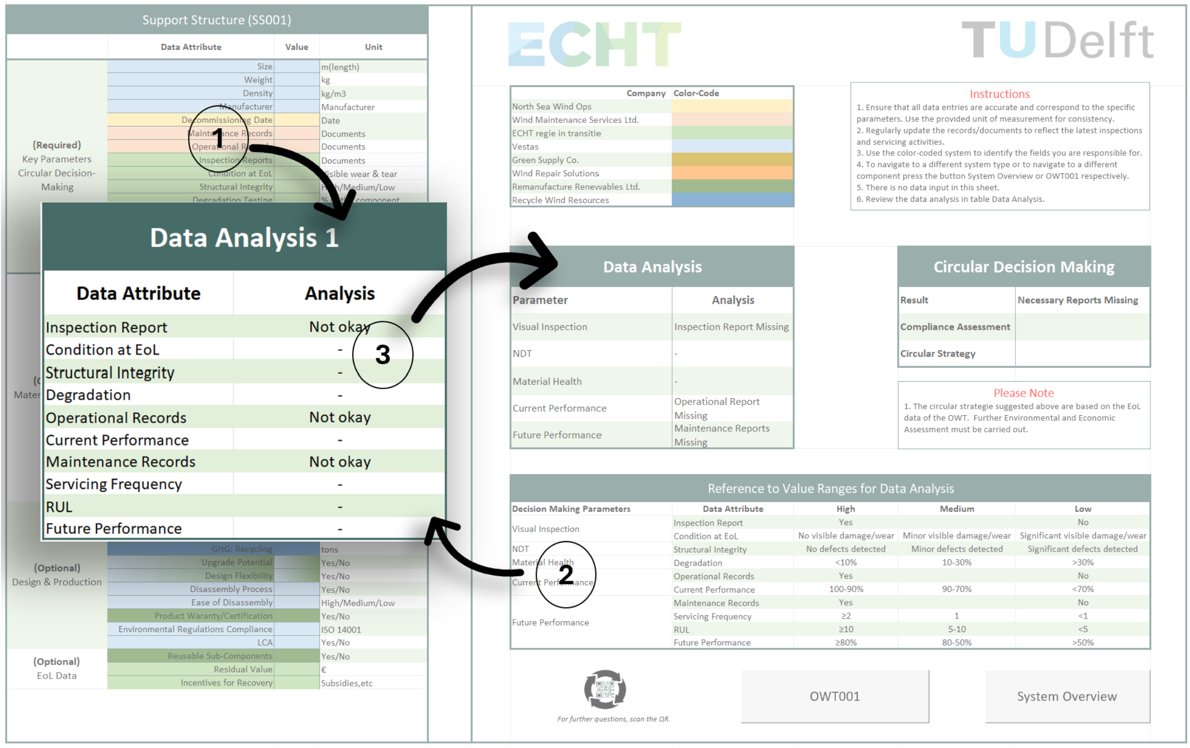



Figure 4.28: Steps 1,2 and 3 of the Decision-Making Tool.

**Step 4** follows the circular decision-making framework and assesses the Condition and the Performance assessment based on their respective parameters. The data for this step is stored in an intermediate table as illustrated in Figure 4.29 *(Table: Circular Decision-Making)*.
The results at the end of Step 4 are displayed on the tool. The only possible results are the group of circular strategies: Re-certify or Reuse, Repair or Refurbish or Remanufacture, and Re-purpose or Recycle or Recover.
*Note: The decision-making process will only begin when all the necessary reports/documents are there.*

**Step 5** of the tool suggests the Compliance Assessment depending upon the group of circular strategies presented in the previous step (For example, Standards and Certificates 1, or Standards or Certificate 2, etc.).

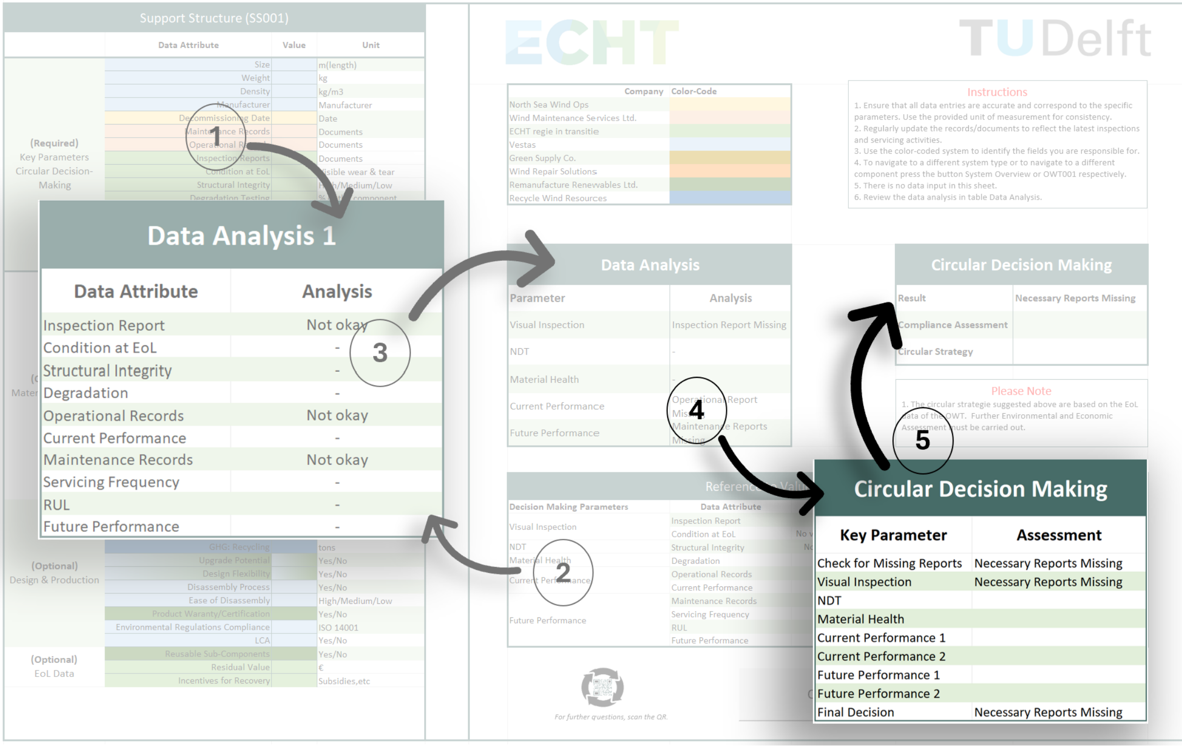



Figure 4.29: Step 4 and 5 of the Decision-Making Tool.

In **Step 6**, the user is expected to follow a checklist depending on the compliance assessment suggested in Step 5. The type of compliance assessments and their respective checklist is provided in Table 6.7.

Lastly, **Step 7**, a single circular strategy suggestion will be displayed on the EcoRush Tool provided the specific standards and certifications required for a suggested circular strategy are satisfied. Steps 6 and 7 can be seen in Figure 4.30.

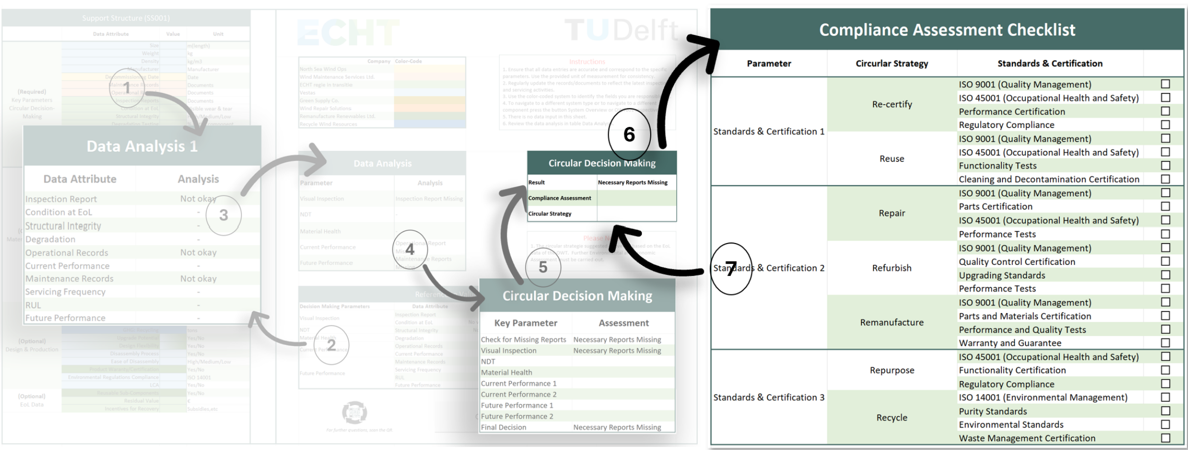



Figure 4.30: Step 6 and 7 of the Decision-Making Tool.

*The EcoRush tool will suggest (1) a **group of circular strategies**, (2) depending on the group of circular strategies, suggest the type of **Compliance Assessment to be performed**, and (3) using the compliance assessment checklist to suggest a single **circular strategy**. This provides a comprehensive answer to the SQ.4.*

# Deliver (Validation)

The final phase of the research, the Deliver Stage, is crucial for ensuring the practical applicability and effectiveness of the developed circular decision-making tool. This stage is dedicated to the comprehensive validation and refinement of the tool, engaging experts from the wind industry and utilizing real-world data to validate its functionality and relevance. The Deliver Stage is structured into three primary parts:

1. Circular Decision-Making Framework Validation: The first step involves one-on-one sessions with industry experts to obtain detailed and unbiased feedback on the circular decision-making framework. This approach allows for an in-depth understanding of the framework's usability and relevance from diverse professional perspectives.

2. Testing the tool with Real Case Data: The second step is to test the EcoRush tool. The tool is tested using actual data from previous wind turbine projects. This practical application helps in evaluating the tool's performance in real-world scenarios.

3. Validating the results: The third and final step involves a group session with experts from the first step. This collaborative approach facilitates a comprehensive review of the results obtained via the tool. The purpose of conducting this in a group session is to encourage discussion and feedback that can reveal additional insights and improvements.

*The validation process is conducted internally within ECHT regie in transitie. The experts from the field of wind industry included in the validation process are (1) a Circularity Expert, (2) a Wind Turbine Technical Expert, (3) a Project Manager (EoL Resource Management), and (4) a Sustainable Business Development Expert.*

## 4.11. Circular Decision-Making Framework Validation

The individual sessions with the experts from ECHT regie in transitie were held from the 20$^{th}$ of June until the 27$^{th}$ of June. The circular decision-making framework (Figure 4.23) has undergone several modifications as new information emerged after conducting the literature review and the interviews. The framework presented during this meeting was refined after the initial data analysis stage.
The key takeaways from the session are listed below:

- The framework looks good and is easy to understand for someone following this research closely. For others, there needs to be clear definitions to minimize the risk of misinterpretations.
- There are several attributes you collect through a DPP. There must be an additional guide to who will provide the necessary data for the circularity assessment.
- The assessments must not be a part of the flow diagram. They can be in the background to give clarity.
- The economic and environmental assessments are dynamic and cannot be generalized. It is possible to give guidelines for these assessments.
- The framework does take into account all the practical parameters that are needed to assess circularity. However, one suggestion would be to remember that the varying regional aspects of different projects may change the decision-making criteria.
- From a technical point of view, the sequencing of the assessment criteria is good, as it follows the same logic that a technician would follow but with a more structured approach.
- There are rapid technological developments in this sector, and the framework must address this challenge in a way that requires minimal changes for the framework to work efficiently.
- There needs to be more clarity on the Standards and Certification aspect of the assessment.
- The framework looks okay; the next step is exploring ways to incorporate this in a DPP system. There needs to be a systematic way in which the framework can use the varied unit data from the DPP.

The feedback received in this session led to the refinement of the decision-making framework and sparked the gap in implementing this framework in a DPP. This discussion also led to adding definitions of terms and clarity on the decision-making process in the report. Multiple variations to implement the framework were explored (MS Excel, Python, Software Development, etc) with follow-up meetings with the team. It was decided to proceed with a user-friendly, easily adaptable MS Excel platform. Lastly, this discussion led to exploring the data analysis from the DPP in a way that is usable in the decision-making process, which was researched and implemented.

## 4.12. Testing the EcoRush DPP tool with Real Case Data

This testing was conducted on the 30th of June with three different wind turbine towers that will be tested in the EcoRush. The results will be validated and discussed with the experts in the next section. While validating the Circular Decision-Making Tool, specific data attributes have been made up due to the lack of particular data in the inspection reports. This section explains why these data points are fabricated and the significance of their inclusion in the validation process.

- Completeness: Providing complete datasets, even with estimated values, ensures that all aspects of the tool can be tested comprehensively. This helps identify any gaps or areas of improvement in the tool's functionality.
- Simulating Real-World Scenarios: The made-up data simulates real-world scenarios using typical industry values and assumptions. This allows for a more realistic validation process, as the tool is tested against conditions it is likely to encounter.
- Functionality Testing: The purpose of validation is to check the accuracy of data processing and ensure that the tool functions correctly under various conditions. Made-up data helps stress-test the tool, ensuring it can handle a range of inputs effectively.
- User Interaction: Including estimated values allows stakeholders to interact with the tool as they would in a real project. This interaction is crucial for obtaining meaningful feedback on the tool's usability and effectiveness.

While some data attributes can be collected from existing records, others require dedicated efforts through inspections, testing, and advanced predictive analysis. The testing results illustrate only the data that is necessary for circular decision-making.

Following are three test projects for validating the tool with real case data.

**Test Project 1**

The test results are verified manually with the decision-making framework. The result suggested Re-certify or Reuse as illustrated in Figure 4.31. After conducting the compliance assessment, the final result suggested Re-certification.

**Tower (TW001)**

| | Data Attribute | Value | Unit |
|---|---|---|---|
| **(Required)** Key Parameters Circular Decision-Making | Size | 135 | m(height) |
| | Weight | 2,40,000 | kg |
| | Density | 7,870 | kg/m3 |
| | Manufacturer | ****** | Manufacturer |
| | Decommissioning Date | Nov. 2027 | Date |
| | Maintenance Records | Yes | Documents |
| | Operational Records | Yes | Documents |
| | Inspection Reports | Yes | Documents |
| | Condition at EoL | Minor visible damage/wear | Visible wear & tear |
| | Structural Integrity | High | High/Medium/Low |
| | Degradation Testing | 5 | % of the component |
| | Use History/Current Age | 20 | Year(s) |
| | Current Performance | 95 | % Efficiency & reliability |
| | Servicing frequency | 1 | Year(s) |
| | RUL | 10 | Year(s) |
| | Future Performance | 90 | % For ≥5 years. |

**Data Analysis**

| Parameter | Analysis |
|---|---|
| Visual Inspection | Medium |
| NDT | High |
| Material Health | High |
| Current Performance | High |
| Future Performance | High |

**Circular Decision Making**

| | |
|---|---|
| **Result** | **Re-certify or Reuse** |
| **Compliance Assessment** | **Start with Standards and Certification 1** |
| **Circular Strategy** | **Re-certify** |

Please Note

1. The circular strategie suggested above are based on the EoL data of the OWT. Further Environmental and Economic Assessment must be carried out.

Figure 4.31: Tower 1 testing results.

**Test Project 2**
The test results are verified manually with the decision-making framework. The result suggested Re-certify or Reuse as illustrated in Figure 4.32. After conducting the compliance assessment, the final result suggested Reuse.

| Tower (TW201) | | | |
|---|---|---|---|
| | Data Attribute | Value | Unit |
| **(Required)** Key Parameters Circular Decision-Making | Size | 100 | m(height) |
| | Weight | 2,00,000 | kg |
| | Density | 7,850 | kg/m3 |
| | Manufacturer | ***** | Manufacturer |
| | Decommissioning Date | Feb-30 | Date |
| | Maintenance Records | Yes | Documents |
| | Operational Records | Yes | Documents |
| | Inspection Reports | Yes | Documents |
| | Condition at EoL | Minor visible damage/wear | Visible wear & tear |
| | Structural Integrity | Medium | High/Medium/Low |
| | Degradation Testing | 15 | % of the component |
| | Use History/Current Age | 21 | Year(s) |
| | Current Performance | 85 | % Efficiency & reliability |
| | Servicing frequency | 1 | Year(s) |
| | RUL | 10 | Year(s) |
| | Future Performance | 80 | % For ≥5 years. |

| Data Analysis | |
|---|---|
| **Parameter** | **Analysis** |
| Visual Inspection | Medium |
| NDT | Medium |
| Material Health | Medium |
| Current Performance | Medium |
| Future Performance | High |

| Circular Decision Making | |
|---|---|
| **Result** | **Re-certify or Reuse** |
| **Compliance Assessment** | **Start with Standards and Certification 1** |
| **Circular Strategy** | **Reuse** |

Please Note
1. The circular strategie suggested above are based on the EoL data of the OWT. Further Environmental and Economic Assessment must be carried out.

Figure 4.32: Tower 2 testing results.

**Test Project 3**
The test results are verified manually with the decision-making framework. The result suggested Repair, Refurbish, or Remanufacture as illustrated in Figure 4.32. After conducting the compliance assessment, the final result suggested Repair.

| Tower (TW301) | | | |
|---|---|---|---|
| | Data Attribute | Value | Unit |
| **(Required)** Key Parameters Circular Decision-Making | Size | 120 | m(height) |
| | Weight | 2,20,000 | kg |
| | Density | 7,850 | kg/m3 |
| | Manufacturer | ***** | Manufacturer |
| | Decommissioning Date | Dec-36 | Date |
| | Maintenance Records | Yes | Documents |
| | Operational Records | Yes | Documents |
| | Inspection Reports | Yes | Documents |
| | Condition at EoL | nificant visible damage/wear | Visible wear & tear |
| | Structural Integrity | Medium | High/Medium/Low |
| | Degradation Testing | 10 | % of the component |
| | Use History/Current Age | 10 | Year(s) |
| | Current Performance | 97 | % Efficiency & reliability |
| | Servicing frequency | 1 | Year(s) |
| | RUL | 25 | Year(s) |
| | Future Performance | 90 | % For ≥5 years. |

| Data Analysis | |
|---|---|
| **Parameter** | **Analysis** |
| Visual Inspection | Low |
| NDT | Medium |
| Material Health | High |
| Current Performance | High |
| Future Performance | High |

| Circular Decision Making | |
|---|---|
| **Result** | **Repair, Refurbish, or Remanuf** |
| **Compliance Assessment** | **Start with Standards and Certification 2** |
| **Circular Strategy** | **Repair** |

Please Note
1. The circular strategie suggested above are based on the EoL data of the OWT. Further Environmental and Economic Assessment must be carried out.

Figure 4.33: Tower 3 testing results.

## 4.13. Validating the Results

The final step in the validation process is a group session within ECHT regie in transitie on the $4^{th}$ of July. This session involved experts from various backgrounds who will review the decision-making framework by applying it to three cases using the EcoRush DPP tool. The group validation session is planned as follows:

1. Introduction: A brief overview of the EcoRush DPP tool and the decision-making framework will be presented.

2. Case-related data: Each case will be presented with relevant data, and the decision-making framework will be applied.

3. Discussion: Experts will discuss the results, focusing on the effectiveness, feasibility, and accuracy of the framework.

4. Feedback: Experts will provide feedback on the framework, suggesting improvements or modifications based on their observations and experience.

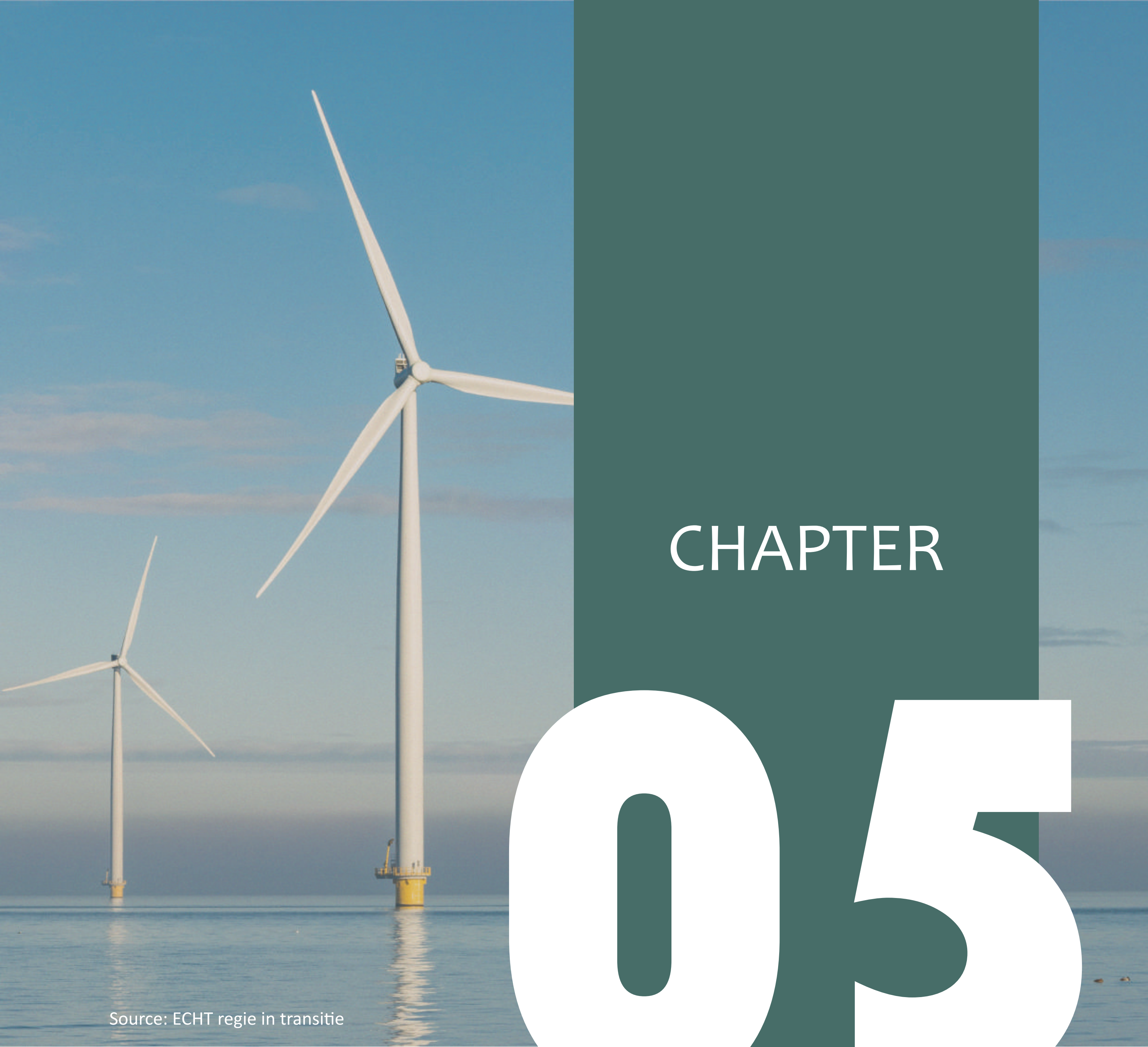
This group validation session will ensure that the decision-making framework is theoretically sound and practically applicable. The key takeaways from the session are listed below:

- The theoretical decision-making framework shown in the previous session is translated well in the tool. It is user-friendly for a person who is from a non-technical background.

- The storyline for the tool can be strengthened by an additional explanation of how the process will look like, in which step this tool comes into practice, and who will be using this tool can be provided.
- Additional to using this tool in practice, elaborate more on which data will be readily available and which data needs extra steps to be taken. The availability/unavailability of the data attributes changes according to the project landscape. ECHT regie in transitie will try to collect as much as possible from the owners and provide additional services to generate the remaining data attributes. These extra steps can create business opportunities for the company.
- It is good to have additional data attributes in the DPP as they provide a layer of guarantee (certification) for the second-hand user and significant economic benefits to the wind turbine(s) owner.
- It is clear that the tool breaks down the system into smaller components to assess their circularity. It would be interesting to know how the suggested circular strategies for individual components provide a cascading effect in deciding the circular strategy for the whole wind turbine.
- The results obtained from the tool are logical and serve as a crucial starting point to assess the circularity of a component. Still, the economic assessment, for example, transportation costs, repair vs. recycling costs, market demand, etc., will also play a crucial role in deciding the circular strategy. Of course, this is not within the scope of this research but is something that needs to be further researched.

The group validation session provided comprehensive insights into the practical applicability of the EcoRush tool and emphasized how the tool adds value to existing practices in decommissioning OWTs. Several aspects of the tool received positive recognition and led to discussions of potential future developments that can be included in the circular decision-making framework and eventually be added to the tool.

*The following Chapter 5 of the report will discuss the findings and the research limitations.*



Source: ECHT regie in transitie

CHAPTER

05

# DISCUSSIONS & LIMITATIONS

# 5

# Discussions & Limitations

The outcomes of this research have provided insight into the EoL resource management of OWT components by exploring the decision-making for circular strategies through a standardized data management system. However, the decision-making results should be interpreted with caution due to the limitations of the current research. This chapter reflects on the research process by discussing the results and limitations.

## 5.1. Discussion

This research addressed the gap in decision-making frameworks that integrate circular strategies tailored to OWT components' EoL resource management. An interesting finding of the study is the circular strategy of **"Re-certify"**, which is an extension for a combination of circular strategies such as the Refuse, Rethink, and Reduce, encouraging the extension of the operational life of an OWT, even after the expected operational life is coming to an end. Another finding revealed that circular decision-making, which includes typology, condition, performance, and compliance assessments, effectively guides the selection of suitable circular strategies. Additionally, the framework emphasizes the importance of economic and environmental assessments, although these cannot be generalized due to their dynamic nature.
The study developed a decision-making framework preceded by a standardized data management system. Both developments were combined into a single tool, EcoRush DPP. The tool enabled stakeholders to identify and apply the most appropriate circular strategies for OWT components at their EoL phase.

The validation process highlighted the framework's practical applicability and theoretical soundness. Key insights from the validation sessions included the need for clear definitions to avoid misinterpretations, the importance of specifying data collection responsibilities, and the recognition of regional variations affecting decision-making criteria. The EcoRush DPP tool was user-friendly, even for non-technical users. The results of the three test cases indicate the effectiveness in identifying appropriate circular strategies by application of the framework, thus enhancing circular practices and efficient resource management within the offshore wind industry.

### Interpretations of EcoRush DPP:

The challenges that complicate the decommissioning process identified by Topham, Gonzalez, et al. (2019) and the challenges to implement circularity identified through expert interviews resonate with each other as technical, regulatory, economic, and environmental challenges are common. This research satisfactorily addresses the technical and environmental challenges and partially addresses how the regulatory challenges in the decision-making framework.

The findings of this research align well with existing literature on CE principles and resource management in the wind industry. The identification of key parameters such as condition, performance, and compliance assessments is consistent with the approaches suggested by Stahel (2016) and Potting et al. (2017), both emphasize the importance of thorough assessments to enable effective circular strategies. The framework's structured approach to assessing the EoL phase of OWT components parallels the methodologies discussed by Velenturf (2021) and P. D. Jensen et al. (2020), highlighting the critical role of comprehensive data management systems in facilitating circularity.

Unexpectedly, the validation process revealed the need for more detailed guidelines on data collection responsibilities and additional explanations within the tool to ensure clarity for all stakeholders. This insight underscores the findings of D. R. Cooper and Gutowski (2017), who noted that clear communication and well-defined roles are essential to implement circular strategies successfully. Furthermore, the emphasis on the dynamic nature of economic and environmental assessments aligns with the perspectives of Ghisellini et al. (2016), who argues that these assessments must be tailored to specific project contexts to be effective.

## Implication of EcoRush DPP:

These results build on evidence of the importance of thorough assessments in implementing circular strategies, as discussed by Stahel (2016) and Potting et al. (2017). By providing a structured approach to condition, performance, and compliance assessments, this research contributes new information on the practical application of these principles in the offshore wind industry, specifically tailored for OWT components at their EoL phase. The development and validation of the EcoRush DPP tool demonstrate how a standardized data management system can facilitate the collection and analysis of relevant data, ultimately aiding in selecting appropriate circular strategies.

The practical implications of this study are significant for stakeholders involved in the EoL management of OWTs. The EcoRush DPP tool enhances the efficiency of data collection and analysis. It provides a systematic approach to decision-making that can be readily adopted by various stakeholders, including operators, maintenance providers, and recycling agencies. Unfortunately, the tool's ability to understand how individual component strategies can influence the overall circularity of the wind turbine is lacking.
However, the tool's flexibility in making adjustments based on technological advancements provides a more reliable framework. The additional insight to add a layer of regional variations in future research provides a clearer understanding of managing these complexities in practice.

While previous research has focused on the theoretical aspects of circular economy principles, the EcoRush demonstrates the practical applicability of a decision-making framework supported by a digital product passport.
Furthermore, the development of CPP is gaining momentum in the offshore wind farm developments in The Netherlands (RVO, 2024); the findings of the research provide a foundation for further incorporation of these data attributes in the development of CPP in the BoL to enhance circular practices in the offshore wind industry.

## Value Added & Challenges of EcoRush DPP:

**Value Added:** Most of the value added by the tool is discussed in the previous parts of this section. To summarize, the most crucial value the EcoRush DPP tool adds is its ability to centralize and standardize data management, which facilitates data-driven decision-making for the EoL phase of OWT. By consolidating all relevant data attributes into a single, accessible platform, the tool ensures that stakeholders have comprehensive and accurate information at their fingertips. This centralized approach improves communication and collaboration among stakeholders and enhances the efficiency and sustainability of the decision-making process. The tool's ability to provide clear guidelines on the necessary data attributes and their collection significantly reduces the risk of data fragmentation and loss, leading to more informed and sustainable EoL strategies for OWT components. Lastly, Platform (2024) suggests new roles will be emerging with the implementation of DPP.

**Challenges:** During the data collection and validation sessions, a few challenges were identified in the tool's implementation.

- Initial Implementation Costs: The setup and integration of the EcoRush DPP may require a significant initial investment in time and resources. This includes costs associated with software development, training stakeholders, and integrating the tool with existing systems.

- Data Collection Challenges: While the tool centralizes data management, collecting comprehensive and accurate data can be challenging. Some data attributes may require extensive manual effort or advanced technology to gather, which can be time-consuming and costly.
- Reliance on Stakeholder Cooperation: The tool's effectiveness depends heavily on the cooperation of various stakeholders, such as OEMs, maintenance teams, and inspection providers. Any reluctance or inconsistency in data sharing can compromise the quality and completeness of the data.
- Complexity in Data Analysis: The tool's ability to analyze and interpret vast amounts of data may be limited by the complexity and variability of the data collected. Inconsistencies in data formats or incomplete data sets can affect the accuracy of the decision-making process.
- Dynamic Nature of the Industry: The offshore wind industry is rapidly evolving, with new technologies and standards continuously emerging. The tool must adapt to these changes, which may require frequent updates and adjustments to maintain relevance and effectiveness.
- Security and Privacy Concerns: Centralizing data management raises concerns about data security and privacy. Ensuring that sensitive information is protected and access is controlled is crucial to maintaining stakeholder trust and compliance with regulations.

In summary, this research supports existing theories on circular economy principles while providing new insights into their practical application in the offshore wind industry. The EcoRush DPP tool represents a significant advancement in the standardization of data management and circular decision-making, offering valuable guidance for stakeholders in implementing circular practices at the EoL phase of OWT components.

## 5.2. Limitations

Despite this research's comprehensive approach, several limitations must be acknowledged to provide an accurate picture of what can and cannot be concluded from this study. These limitations, while significant, do not detract from the overall validity and relevance of the research findings but should be considered when interpreting the results.

### Literature Review

The research focused on the crossover of CE and the offshore wind industry through a systematic data management system. Throughout the research period, scientific literature on this specific topic was limited. In this case, the researcher reviewed literature on individual topics and combined these to form a coherent story.

### Circular Assessment

The dynamic nature of the offshore wind industry introduces a level of complexity that the framework must continuously adapt to. Rapid technological advancements and evolving industry standards mean the framework and tool need regular updates to remain relevant and practical. This ongoing requirement can be resource-intensive and may challenge consistent application over time.
Although acknowledged as critical, the impact of economic and environmental assessments could not be fully integrated into the decision-making framework due to their dynamic and project-specific nature. While guidelines were provided, the inability to generalize these assessments limited the comprehensiveness of the framework.

Methodological constraints also limited this study. The decision to focus on components of offshore wind turbines, such as the tower, nacelle, rotor blades, etc., means that the findings are not exhaustive of all possible sub-components, such as the generator, gearbox, etc. The exclusion of sub-components or other systems within the offshore wind farm may have overlooked additional circular strategies and data requirements pertinent to those areas.

The categorization and evaluation of data attributes within the circularity assessment framework are limited by the subjective nature and variability inherent in the process. High, medium, and low ranges for data attributes like material degradation, performance metrics, and compliance standards are defined based on inspection reports and expert judgments, which could lead to inconsistencies and biases. These ranges are not universally standardized and may differ based on stakeholder perspectives, regional practices, or specific project needs.

### Validation

One of the primary limitations of this study was the availability of the sample size, which was limited to specific case studies within the onshore wind industry. This was because of the unavailability of the data for offshore wind turbines. This limitation affects the generalizability of the results, as the findings may not fully apply to all offshore wind farms. The variability in regional regulations, project scales, and stakeholder engagement practices further limits the broad applicability of the developed decision-making framework.

Lastly, the validation process, while thorough, was conducted for a specific component of an OWT (Tower) because the research was intended within a limited timeframe. The experts involved in the validation process were a group of people within the organization. A validation process that included stakeholders from the supply chain of an OWF may have influenced the breadth of feedback and the extent to which the tool was tested across diverse scenarios.

Despite these limitations, the results of this research are valid for answering the main research question. The EcoRush DPP tool offers a significant step forward in promoting circular practices within the offshore wind industry, providing a structured approach to managing the EoL phase of offshore wind turbine components.

*The following Chapter 6 of the report will present the conclusions and the recommendations.*


CHAPTER

06

# CONCLUSIONS & RECOMMENDATIONS

# 6

# Conclusions & Recommendations

This chapter presents the core findings of this research by providing answers to the sub and main research questions employed to conduct this research. By integrating the key insights from the study, this chapter aims to provide a comprehensive summary of how they address the research objective. Following the conclusions, this chapter offers recommendations for ECHT regie in transitie and other stakeholders in the offshore wind industry, suggesting pathways for future research.

## 6.1. Conclusion

This research aimed to explore the optimal circular strategy for the EoL of an OWT component. To achieve this, a circular decision-making framework was developed for the EoL of OWTs and how a systematic data management system can be used to capture relevant data attributes necessary for circular decision-making. Firstly, sub-research questions are answered. Following this, the main research question is answered.

### Sub-Research Questions

SQ 0. *What are the existing circular strategies applied in the offshore wind industry?*

This sub-research question formed the theoretical background for the research and was explored through a systematic literature review. The literature presents that the offshore wind industry currently applies several circular strategies from the BoL to the EoL of an OWF. The strategies range from high to low levels of circularity, focusing on maximizing resource recovery and minimizing waste.
The literature reveals that while there is a significant emphasis on material recycling and recovery, there is a need for a more holistic approach that integrates higher-order circular strategies such as repair, reuse, remanufacturing, etc. This aligns with the findings from the interviews conducted for this research, as most of the stakeholders in the wind industry are considering implementing high-order circular strategies.

Figure 4.14 illustrates the various EoL scenarios for the OWTs. The EoL phase presents critical opportunities for implementing circular strategies such as (1) **Re-certify**, (2) **Reuse**, (3) **Repair**, (4) **Refurbish**, (5) **Remanufacture**, (6) **Repurpose**, (7) **Recycle**, and (8) **Recover;** in the order of high to low level of circularity which maximize resource recovery and minimize environmental impact.

Six overarching assessment themes have been identified to assess the circular strategies. These are: (1) **Typology Assessment** (2)**Condition Assessment**, (3) **"Performance Assessment"**, (4) **Compliance Assessment**, (5) **Economic Assessment**, and (6) **Environmental Assessment.** These themes support the decision-making and highlight the need for strategic partnerships and/or circular business models for a smoother transition to sustainable EoL resource management.

SQ 1. *What are the various components of an OWT and their respective EoL circular practices?*

This sub-research question was explored through a systematic literature review. The OWT's components include the Support Structure, Tower, Nacelle, and Rotor Blades. Several other sub-components exist, but the scope of the research is limited to the main components.
The technological feasibility of a component towards a circular strategy is essential to implementing a strategy. Considering the applicability of circular strategies to the components, this forms the first step of the circular decision-making framework, **Typology Assessment**.
Depending on the material composition, physical properties, available technology, and upgradability, not all components of the OWT are feasible for all circular strategies. Table 4.3 presents the EoL circular strategies for the components of an OWT.

SQ 2. *What are the key challenges faced in managing wind turbine components with regard to CE at their EoL phase by the stakeholders involved in the supply chain?*

This sub-research question was explored through a systematic analysis of nine semi-structured interviews conducted across the supply chain of the EoL of OWFs. The offshore wind industry faces numerous challenges under the umbrella of three main themes of challenges: (1) **Technical Challenges**, (2) **Economic Challenges**, and (3) **Regulatory Challenges**, which is crucial for integrating CE principles in the offshore wind energy sector. The challenges identified through the interview resonate with those identified in the literature review.

The research is focused on exploring and providing solutions for the technical challenges in the EoL resource management of wind turbine components. To overcome the technical challenges in the EoL, the industry must adopt a standardized data management system, which resonates with the findings from the literature review. Theoretical research suggests the implementation of a DPP as one of the potential solutions for a standardized data management system. Stakeholders lack a standard data management system but identify that utilizing the data available through a DPP can contribute to circular decision-making.

The answer to the sub-research question identified the need for **Compliance Assessment** and how the **Data Attributes** collected in a **DPP** can aid in evaluating the circular assessments identified in SQ.0.

SQ 3. *What are the key parameters and data attributes that are required for the circular decision-making framework for a standardized data management system tailored for the EoL of OWTs?*

This sub-research question was explored through a systematic analysis of nine semi-structured interviews conducted across the supply chain of the EoL of OWFs. The answer to this research question is twofold; firstly, the key parameters to assess the circular assessments were identified. Next, the parameters are mapped against the data attributes of a DPP for a comprehensive circular assessment.

Firstly, the parameters necessary to assess the assessments are:

1. Condition Assessment: The Condition Assessment evaluates the current state of the OWT components. The key parameters are (1) **Visual Inspection**, (2) **NDT**, (3) **Material Composition**, and (4) **Material Health**.

2. Performance Assessment: Performance Assessment evaluates the OWT components' current and future performance potential. The key parameters are (1) **Current Performance** and (2) **Future Performance**.

3. Compliance Assessment: Compliance Assessment ensures that the OWT components meet the necessary standards and regulatory requirements for their intended use. The key parameters are (1) **Standards** and (2) **Certifications**.

   *The last two assessments are out of the scope of this research and will not explore the parameters in these themes.*

4. Economic Assessment: To evaluate the financial viability of implementing various circular strategies. Methods such as cost-benefit analysis, market demand, and ROI can be used for assessment.

5. Environmental Assessment: Evaluate the potential environmental impacts of the circular strategies using tools like LCA. This includes evaluating waste reduction, emission control, and other carbon-emitting activities related to the implementation.

Next, these parameters were mapped against the data attributes that are either available in a DPP or need to be added to the structure of the DPP tailored for the EoL of OWTs.

1. Visual Inspection: A thorough examination of the component's exterior and interior (if possible) for any visible damage or wear. The data attributes needed to evaluate are (1) **Inspection Reports** and (2) **Condition at EoL**.

2. NDT: Techniques used to evaluate the properties of a component without causing damage. The data attributes needed to evaluate is (1) **Structural Integrity**.

3. Material Composition: Information on the materials used, their recyclability, and potential for reuse. This will also provide information on using hazardous materials that can cause danger while processing the components. The data attributes needed to evaluate are (1) **Material List**, (2) **Critical Raw Material**, (3) **SVHC**, and (4) **Quantities**.

4. Material Health: Assessment of any degradation in material properties that could affect the component's performance. The data attributes needed to evaluate is (1) **Material Degradation**.

5. Current Performance: Measurements of the component's operational performance metrics, such as efficiency and reliability. The data attributes needed to evaluate are (1) **Operational Reports** and (2) **Current Performance**.

6. Future Performance: Projection of the component's performance over its remaining lifespan based on current conditions and historical data. The data attributes needed to evaluate are (1) **Maintenance Reports**, (2) **Service Frequency**, (3) **RUL**, and (4) **Future Performance**.

SQ 4. *What are the implications of the identified circular strategies, key challenges, and key parameters for the EoL circular decision-making framework of an OWT?*

Next, using the data attributes of a DPP, key parameters, and circular strategies form the design requirements for the development of a **Circular Decision-Making Framework**.

The in-depth research of these parameters leads to the development of the framework that supports the stakeholders in the decision-making for the EoL of OWT components.

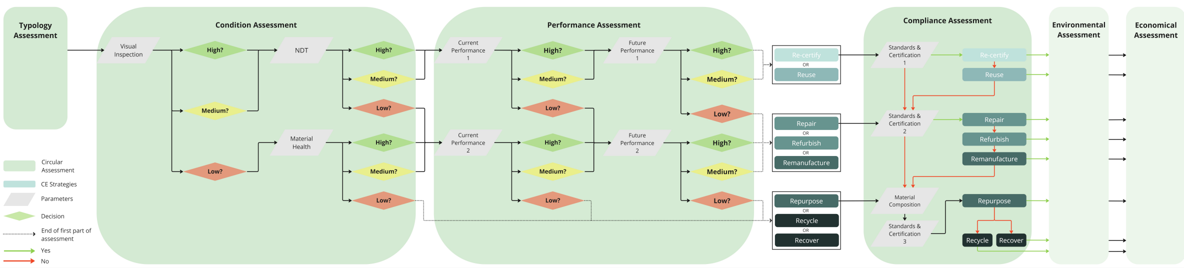



Figure 6.1: Circular decision-making framework.

## Main Research Question

The main research question addressed in this research is as follows:

*"In what ways can a decision-making framework for a standardized data management system, specifically tailored for the end-of-life phase of OWTs, contribute to enhancing circular practices by efficient resource management within the industry?"*

The research implemented the Double Diamond research methodology. This design-thinking method led to the development of a tool, **"EcoRush DPP"**, which is a step toward considering high-order circular practices during the EoL phase of an Offshore wind turbine. The development of this tool was based on research in various aspects of circular economy, properties of offshore wind turbine components, and challenges faced in implementing these strategies in the industry.

Reusing the components and materials of decommissioned wind turbines is a driving force for the future requirement of raw materials (Demuytere et al., 2024). Lately, science and industry have focused on either developing circular strategies for the BoL or recycling materials to limit future environmental impacts (Hall et al., 2022; P. D. Jensen et al., 2020). The need to address EoL resource management for the existing OWTs is emerging but still lacks a systematic approach for sustainable EoL decision-making (Delaney et al., 2021; Jadali et al., 2021; Vielen-Kallio et al., 2021; Windemer & Cowell, 2021). The wind energy sector's business units and manufacturing companies focus on developing a centralized digital service for storing and sharing circular and sustainable data (Mendoza & Pigosso, 2023).
To address the identified gap, the research developed a comprehensive circular decision-making framework that leverages a standardized data management system, specifically a Digital Product Passport. The framework includes key assessments supported by the data attributes necessary for each assessment. This structured approach ensures that all relevant data is collected, managed, and analyzed systematically, facilitating informed decision-making regarding each component's most appropriate circular strategies.

Another important aspect of further integrating circular practices is the role of collaboration and data transparency between the stakeholders involved in the decommissioning process. The development and implementation of the tool enhance collaboration, communication, and trust to some extent.

Overall, this research confirms that a well-structured decision-making framework, supported by a standardized data management system, can significantly enhance the circularity of OWT components at their EoL phase. The EcoRush DPP tool's ability to integrate and analyze diverse data attributes provides a robust foundation for making informed decisions, ultimately contributing to more sustainable and efficient resource management practices in the offshore wind industry.

## 6.2. Recommendation

Based on the discussion of the results and the acknowledged limitations, several recommendations can be made for both practical implementation and further research to build on the findings of this study.

### Practical Implementation

To enhance the practical application of the EcoRush DPP tool and the circular decision-making framework, the recommendations are specifically for ECHT regie in transitie and the stakeholders in the offshore wind industry:

- Develop Comprehensive Data Collection Protocols: Establish standardized protocols for collecting data attributes across different stages of the wind turbine lifecycle. This includes creating detailed guidelines on obtaining and recording information, such as structural integrity, material composition, degradation, etc. Ensuring consistent data collection will improve the reliability and usefulness of the DPP tool.
- Foster Collaboration Among Stakeholders: Encourage greater collaboration between OEMs, maintenance providers, inspection agencies, and other stakeholders. This can be facilitated through workshops, training sessions, and regular communication channels to ensure all parties understand their roles and the importance of accurate data collection and sharing.
- Regularly Update the Decision-Making Framework: The offshore wind industry is rapidly evolving, with new technologies and standards emerging frequently. Keeping the decision-making framework up-to-date with the latest industry developments and regulatory changes is essential. This may involve periodic reviews and revisions of the framework to incorporate new insights and best practices.
- Integrate the Data Attributes in the BoL CPP: Several initiatives have been taken to develop a CPP, including the data attributes suggested in this research to be collected from the early lifecycle of the OWFs that can support the EoL decision-making.
- Integrate Economic and Environmental Assessments: While the current framework provides guidelines for economic and environmental assessments, these should be more fully integrated into the decision-making process. Developing detailed methodologies for these assessments can enhance the comprehensiveness of the framework.
- Enhance User Training and Support: Provide extensive training and support for users of the EcoRush DPP tool. This includes creating user manuals and instructional videos and offering support services to help stakeholders effectively utilize the tool and interpret its outputs.

By following these recommendations, ECHT regie in transitie can enhance the practical implementation of the EcoRush DPP tool and contribute to more sustainable and efficient resource management practices in the offshore wind industry.

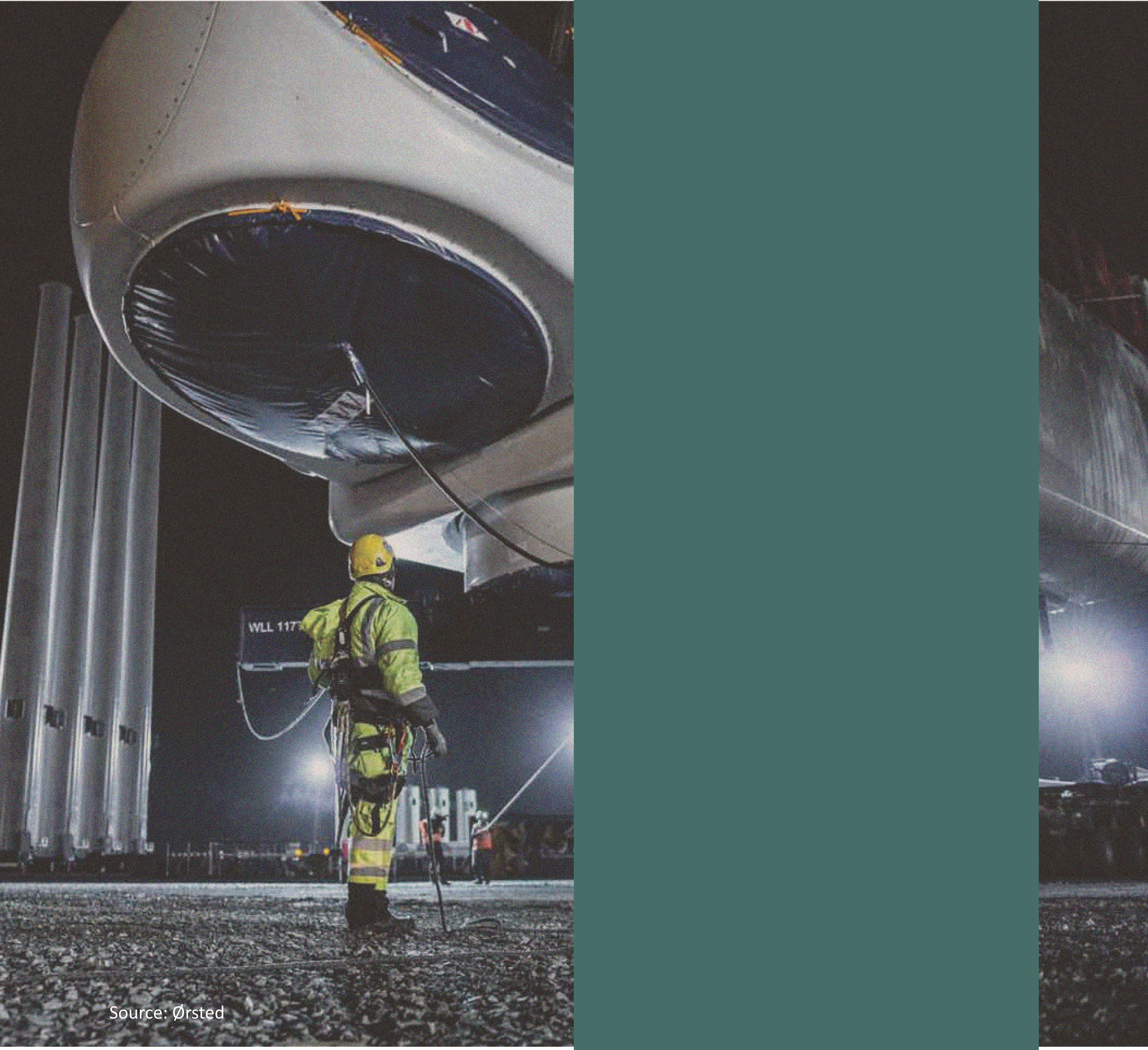
### Future Research

To address the limitations identified in this study and build on its findings, further research should focus on the following areas:

- Expand Sample Size and Diversity: Future studies should include a sample of offshore wind projects encompassing different regions, scales, and types of wind turbines. This will help generalize the findings and improve the robustness of the decision-making framework.
- Explore Real-Time Data Tracking Technologies: Investigate the potential of integrating real-time data tracking technologies, such as IoT devices, into the DPP system. This can enhance the accuracy and timeliness of data collection, providing more reliable inputs for the decision-making framework. The term used for a data management system that collects changing data is also known as a Dynamic Digital Product Passport.
- Explore Data Collection Through Blockchain: Several stakeholders face the challenge of sharing sensitive information about the components, thus exploring Blockchain systems where the data can be analyzed, keeping it safe and secure.

- Conduct Longitudinal Studies: Long-term studies or in-depth case studies are needed to evaluate the effectiveness of the decision-making framework and the EcoRush DPP tool over the entire lifecycle of offshore wind turbines. Such studies can include implementing the tool from the early design phases of an OWF.
- Incorporate Additional Sub-Components and Systems: While this research focused on specific components of offshore wind turbines, future research should explore the applicability of the decision-making framework to other critical systems within offshore wind farms, such as substations and cables.
- Assess Regional Variability: Investigate how regional differences in regulations, economic conditions, and environmental factors impact the implementation of circular strategies. This can help in tailoring the decision-making framework to different geographical contexts.
- Develop Detailed Economic and Environmental Assessment Models: Further research should aim to develop comprehensive models for economic and environmental assessments that can be seamlessly integrated into the decision-making framework. This includes exploring cost-benefit analyses, lifecycle assessments, and market dynamics.
- Crossover between Sectors: The similarities between the infrastructure of offshore wind industries with the offshore oil and gas and the onshore wind industry make a solid case to explore the cross-functional use of components to enhance the circularity of the components at the EoL.

By addressing these recommendations, future research can enhance the effectiveness of circular decision-making in the offshore wind industry. The comprehensive decision-making can be used as a starting point for complex infrastructure industries like offshore wind.



Source: Ørsted

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# Appendices

## A. Appendix - Systematic Literature Review Set-Up

The systematic review was conducted and documented using the PRISMA guidelines. Based on the sub-research questions, the keywords for the article search were chosen. Searches with these keywords were analyzed through a bibliometric network that was created using VOSviewer. Since the literature review was conducted for sub-research questions 0,1,2, and 3 an independent VOSviewewr network was created for each of the sub-questions. An expanded explanation of this procedure is given in this Appendix, beginning with the VOSviewer analysis.

### VOSviewer Analysis

The keywords were carefully chosen based on the sub-research questions. Following is the individual VOSviewer analysis for sub-research questions.

SQ.0 *What are the existing **Ciruclar strategies** that are applied in the **offshore wind industry**?*

The most important topics of this research question are (1) Circular Economy Strategies and/or (2) Offshore Wind Industry. Moreover, the use of CE in the offshore wind industry is the main focus of this thesis. During the search, this should also be taken into account.

The above topics were used to identify potential relevant keywords, which are displayed in Table 6.1. Based on these keywords several article searches were conducted and the searches were analysed with bibliometric network mas created using VOSviewer.

| | |
|---|---|
| Circular Economy Strategies | Circular economy<br>Sustainability<br>Zero waste strategies<br>Circular business models<br>Closed loop systems<br>Circular economy policies<br>Re-manufacturing strategies<br>Recycle, reuse, & re-power<br>Life cycle assessment |
| Offshore Wind Industry | Offshore wind energy<br>Offshore wind farms<br>Offshore wind resource management<br>End-of-life<br>Wind Turbine<br>Decommissioning strategies |

Table 6.1: Keywords for SQ0 systematic literature search.

Through the Vosviewer analysis, it was evident that ”Circular Economy”, ”Life cycle Assessment”, and ”Recycle, reuse, & re-power” together with ”offshore wind farms” ”End-of-life”, and ”Wind turbine” were the most important keywords. Since CE is not just about recycling, related terms such as reuse & re-power were identified as important. On the other hand, it was clear that EoL and terms related to the infrastructure of offshore wind industry were important. The final combination for the systematic literature search can be found in Table6.2.

The search was conducted on 01st of April 2024 using the Scopus search input of *”Circular Economy” OR ”Recycle” OR ”Reuse” AND ”Offshore wind” AND ”Wind Turbine” OR ”End-of-life”* and recorded 21 articles that cover the themes of Circular Economy and offshore wind industry as one. Thus for this,

| | |
|---|---|
| Circular Economy Strategies | Circular economy<br>Recycle, reuse, & re-power<br>Life cycle assessment |
| Offshore Wind Industry | Offshore wind farms<br>End-of-life<br>Wind Turbine |

Table 6.2: Scopus search for SQ0 conducted on 01st April 2024

no filtration criteria were applied and all the literature was reviewed.

SQ.1 *What are the various **components/materials** of an **offshore wind turbine** and their respective EoL **Circular** practices?*

The most important topics of this research question are (1) Offshore Wind Turbine Components and (2) Circular Economy. Here circular economy is considered in the context of wind turbines.

The above topics were used to identify potential relevant keywords, which are displayed in Table 6.3. Based on these keywords several article searches were conducted and the searches were analysed with bibliometric network mas created using VOSviewer.

| | |
|---|---|
| Offshore wind turbine | Components<br>Turbine Materials<br>Wind turbine<br>Wind Energy<br>Wind turbine blade<br>Composite material<br>Rare earth elements |
| Circular Economy | Waste management<br>Material flow analysis<br>End-of-life<br>Life cycle assessment<br>Recycling<br>Renewable energy |

Table 6.3: Keywords for SQ1 systematic literature search.

Through the Vosviewer analysis, it was evident that ”Waste Management”, ”Life cycle assessment” and ”Recycle” along with ”Turbine Materials” and ”Wind turbine” were the most important keywords. The final combination for the systematic literature search can be found in Table6.4.

| | |
|---|---|
| Offshore Wind Turbine | Wind turbine<br>Turbine Materials |
| Circular Economy | Waste Management<br>Recycle<br>Life cycle assessment |

Table 6.4: Scopus search for SQ1 conducted on 01st April 2024

The search was conducted on 01st of April 2024 using the Scopus search input of *”Offshore Wind Turbine” OR ”Turbine Materials” AND ”Waste Management” OR ”Recycle” OR ”Life cycle Assessment”* and recorded 45 articles that cover the combination of the keywords presented in Table6.4. After manually filtering the articles by their keywords, title, abstract, and removing duplicates a selection of 19 articles was done on the basis of relevance for this research.

SQ.2 *What are the key **challenges** faced in managing wind turbine components with regard to CE at their EoL phase by the **stakeholders** involved in the supply chain?*

The most important topics of this research question are (1) Challenges and (2) Stakeholders. These topics are in reference to the offshore wind industry at the EoL phase.

The above topics were used to identify potential relevant keywords, which are displayed in Table 6.5. Based on these keywords several article searches were conducted and the searches were analysed with bibliometric network mas created using VOSviewer.

| | |
|---|---|
| Challenges | Technical<br>Economic<br>Regulatory<br>Decommissioning<br>Logistics |
| Stakeholders | Supply chain<br>Contractors<br>Second-hand users<br>Government |

Table 6.5: Keywords for SQ3 systematic literature search.

The Vosviewer analysis showed that the keywords identified in Table6.5 were all important. Thus the combination of these was used for the systematic literature search of SQ2.

The search was conducted on the 01st of April 2024 using the Scopus search and recorded 11 relevant articles that contribute to exploring SQ2.

SQ.3 *What are the key **parameters and data attributes** that are required for the circular decision-making framework for a **DPP** system tailored for the EoL of offshore wind turbines?*

The most important topics of this research question are (1) Parameters and Data Attributes and (2) DPP. These topics are in reference to the offshore wind industry at the EoL phase.

The above topics were used to identify potential relevant keywords, which are displayed in Table 6.5. Based on these keywords several article searches were conducted and the searches were analysed with bibliometric network mas created using VOSviewer.

| | |
|---|---|
| Parameters | Data Points<br>Data attributes<br>Data collection |
| DPP | Product passport<br>Circular Economy<br>Second-hand users<br>Digital Twin |

Table 6.6: Keywords for SQ2 systematic literature search.

Through the Vosviewer analysis, it was evident that the keywords identified in Table6.6 were all important. Thus the combination of these was used for the systematic literature search of SQ3.

The search was conducted on the 01st of April 2024 using Scopus search and recorded 19 articles. After manually filtering these articles based on the article keywords, title, abstract, and removing duplicates a selection of 5 articles that are relevant to SQ3 was done. This was supported by additional articles that explain the DPP system in general.

# B. Appendix - Semi-Structured Interview Set-Up

*Note: Interview questions/set of questions may vary depending on the person being interviewed. This document contains all question sets. Themes 1, 2, and 3 will be presented to all interviewees.*

The interview consists of three parts:

1. **Introduction**
2. **Topics, Questions, and follow-up questions**
   - Theme 1: Role/expertise of the interviewee within the organization in relation to the research topic, followed up with the challenges they face in the EoL resource management of wind turbine components.
   - Theme 2: Understanding the key parameters that will guide the decision-making.
   - Theme 3: Second-hand market for wind turbine components, followed by understanding the existing knowledge about DPPs.
3. **Future Perspective & Additional comments from the interviewees**

## Introduction

(±5 mins)

For my Master Thesis Research from TU Delft, Construction Management and Engineering (CME), I am investigating the challenges in EoL resource management of offshore wind turbine components. This research is conducted in collaboration with ECHT regie in transitie.

The proposal outlines the urgent need for sustainable practices in the wind industry, considering the increasing demand for materials and limited recycling capabilities. It emphasizes the development of a framework for CE decision-making for a DPP system tailored to offshore wind turbines.

For my research, I focus on the current CE strategies applied in the offshore wind industry and the possibility of implementing a DPP system as a standardized system for EoL resource management in OWF. The end goal of my research is to set up a framework that can be used to capture data from the decommissioning process of an offshore wind farm in the most possible circular way. This data collected would aid the DPP system to be more efficient and easily adaptable in the industry.

Conducting these semi-structured interviews with various experts who are involved in the supply chain of the decommissioning of a wind farm, including you. I want to collect information to (a) understand the current state of affairs and challenges faced in the supply chain to be more circular and sustainable. (b) Have a practical insight into the framework, to ease actor adaptation. (c) And lastly, to understand the existing awareness about CE, especially a DPP system.

Interesting to note: The idea behind semi-structured interviews is that I have prepared some questions in advance, but the answers you give will also guide the conversation. Good to mention that there are no wrong or bad answers, and your opinion and experience will only be used for scientific purposes.

### Privacy and Data

Based on privacy rules, I would like to draw your attention to the following: If you agree, this interview will be recorded. After our conversation, I will transcribe this interview. After this, you will also receive this if you have requested it in the informed consent form. Only after your approval will I use the information from the interview for my research. Furthermore, all video material will be deleted after the transcription has been approved. The interview will also be anonymized. The information is only analyzed from the perspective of the position/role within the supply chain of the EoL decommissioning.

«start recording»

Could you please provide the following information:

- Your name, position/role within the company/institution that you represent today.
- Please also indicate if you agree to record this interview.

Topics, Questions, & Follow-up Questions
(30-35 mins)

Before this interview, I mainly delved into scientific literature. Based on the theoretical knowledge acquired, I came up with 3 main themes. For each of these themes, I have formulated some questions in advance, I will explain each theme as we proceed. There are 18 questions in total, but certainly flexibility to deviate from these questions during the interview.

«Optional explanation of themes»

- Theme 1: Role/expertise of the interviewee within the organization in relation to the research topic, followed up with the challenges they face in the EoL resource management of wind turbine components.
- Theme 2: Understanding the key parameters that will guide the decision-making.
- Theme 3: Second-hand market for wind turbine components, followed by understanding the existing knowledge about DPP.

Shall we start the interview?
«start the interview now»

## Theme 1

(±12 mins)

Role/expertise of interviewee within the organization in relation to the research topic. Followed up with the challenges and motivations they face in the EoL resource management of wind turbine components. (This should be led with a personal experience in an ongoing project or a previous project)

1. Could you describe a typical project you've worked on in the area of wind farm decommissioning? What role did you play? And how did you acquire this project?

   This question aims to get a narrative of their daily tasks and responsibilities, providing context for their experiences.

2. Can you share a particularly memorable experience from your work in the decommissioning of a wind farm?

   This encourages storytelling, which can reveal deeper insights into practical challenges and how theoretical solutions apply in real scenarios.

3. How many stakeholders (contractors & sub-contractors) are usually involved in this process?
   - Adding on to this who is responsible for the regulatory obligation for dismantling wind turbines and what is the most important legislation they have to deal with?
   - Which legislation has the most impact on your business operations?
   - Do you expect this to change?

4. Can you briefly explain the most significant challenges you have faced in the decommissioning of wind farms?

   Focuses on problem-solving and challenges, highlighting their experience and innovative approaches.

5. What are your thoughts on Circularity? Are there any circularity ambitions during this process? If yes how have you addressed them?

   This question will start to connect the dots between circularity and the decommissioning process.

6. Do you find the topic of circularity adding to the challenges that you previously described?

   This will give actual insights into the challenges that are faced in the implementation of circular practices.

That was insightful as we discussed the current trends of circularity and the decommissioning process, this leads us to the 2nd theme of the interview.

## Theme 2
(±10 mins)

Exploring what are the key parameters and data attributes that need to be accessible by the decision maker of the EoL of components of a wind turbine. This will form the basis of the framework that will guide the CE decision-making.
This relates to the parameters that actually can be collected and shared. For example: Structural integrity, maintenance schedule, current age, future lifespan, etc.

1. From your perspective, if a specific component of a wind turbine were to be reused, what parameters would be needed to assess the reusability?

   This encourages the interviewee to think about reusability and will provide practical insights about reusing a component.

2. From the parameters that you mentioned which ones do you think are the most difficult to collect?

   - Following up on what factors make it difficult to collect this data?

   Discussing the level of data availability and the problems faces in data collection. To gain insights on the company's private data policies and improper documentation.

3. If this data were to be easily available, is there any technology yet that collects this data in a standardized manner?

   This will help in understanding the different types of existing technologies that are available out there to collect the EoL data and process it. Maybe a possibility to get a validation for a DPP.

Until now we discussed the decommissioning phase. In this last set of questions, I would like to discuss more about the post-decommissioning phase.

## Theme 3
(±10 mins)

As the focus of this research is to maximize the reuse of second-hand components, it is necessary to understand the perspective of the second-hand market for wind turbines. This will be followed up with the understanding of a digital product passport and discussing how this can help the supply chain in the second-hand market to be more efficient.

1. What role do transparency and traceability play in your business operations? / in the wind energy sector?

   - What has to be transparent and why? Supply chain transparency requires companies to know what is happening upstream in the supply chain and to communicate this information to the downstream stakeholders.
   - What has to be traceable and why? Supply chain traceability is the process of tracing the provenance of products and their inputs, from the very beginning of the supply chain through manufacturing to end-use.
   - Do you expect this to change? For example the changes through CSRD.

2. Is the market ready to use the second-hand components that will be decommissioned in the future?

   This will start the discussion about the current market trends.

3. Apart from the technological challenges what do you think is holding back the market from becoming 100% circular?

   This will make the interviewee reflect back on the current technology that is available to process second-hand components.

4. If there was supposed to be a standardized data collection technology tailored for wind turbines, where all of this information is collected and analyzed would the market be open to this idea?

   To understand if the concept of DPP is accepted in practice.

5. And lastly, if there was a system that could aid in providing the optimal CE strategy for a specific component does that change anything in your previous answer?

### Future Perspective & Additional comments from the interviewees

(±5 mins)

As we approach the end of this interview, I would like to have some general comments from you.

The general idea of this research is to explore the CE challenges faced in the process of decommissioning a wind farm and explore if there can be a standardized system that could aid in the implementation of CE in the process.

Firstly, what is your view on this research topic, and any suggestions for me?

Finally, any topics/interview content you would like to add more?

Thank you for your time and effort to participate in my research. As I indicated at the beginning, I will transcribe the interview and if you wish to review it I will send it to you.

# C. Appendix - Offshore Wind Farm Stakeholder Mapping

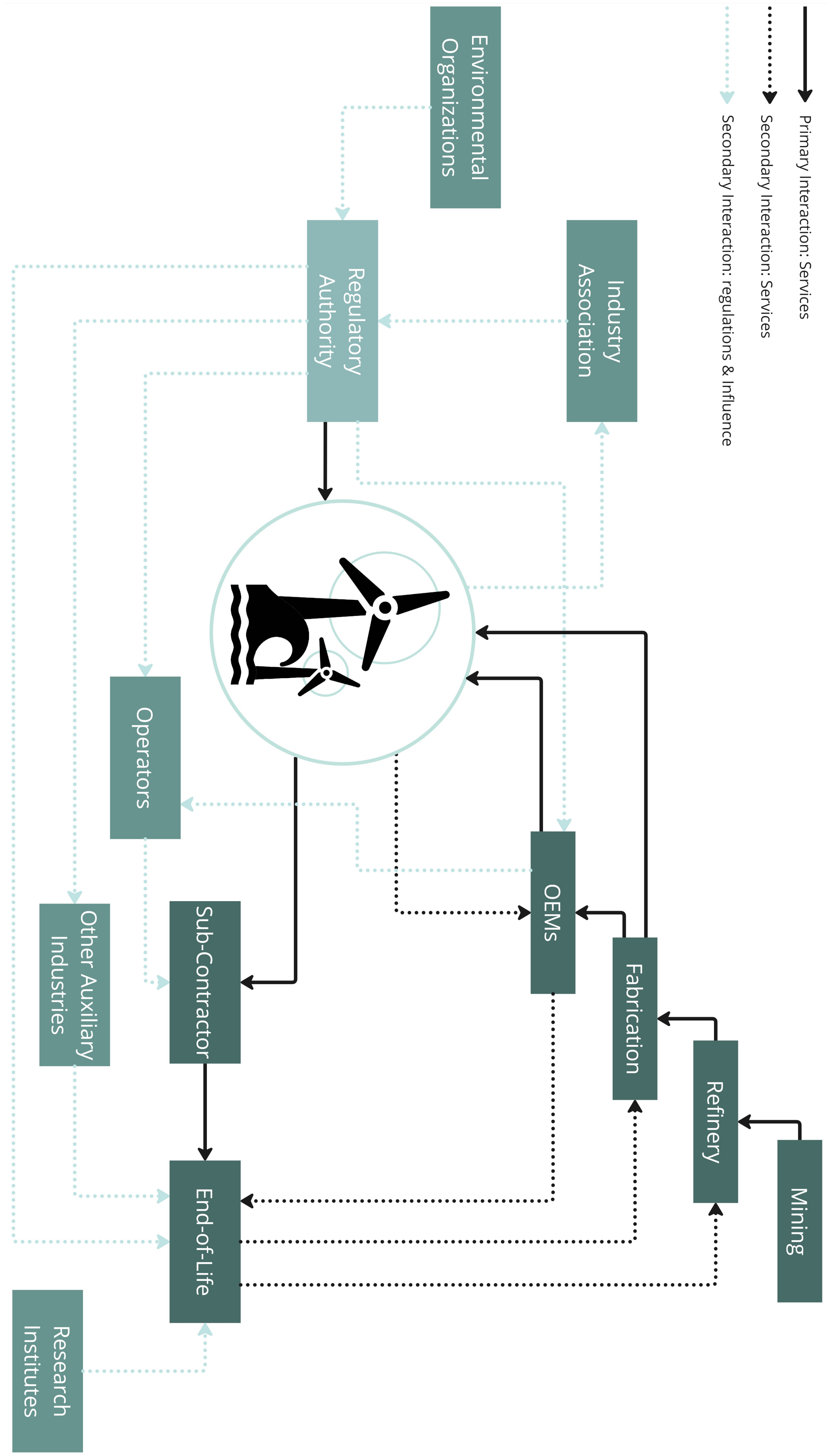


Figure 6.2: Mapping OWF stakeholders.

# D. Appendix - Circular Strategies

**R0 Refuse:** This strategy involves making a product redundant by either stopping its use or offering a different product that serves the same purpose. .
Directly prevents waste creation; reduces environmental footprint by avoiding production and consumption of natural resources. May limit functionality or convenience for consumers and potential economic impacts on industries reliant on high consumption (Stahel, 2016). The parameters for assessing the effectiveness of this strategy include the extent to which the product's function can be abandoned or substituted and the potential reduction in resource consumption and waste production. Parameters include:

- Functional need: Assess if the product's function can be completely abandoned or substituted by a radically different product (Stahel, 2016).
- Resource Saving: Measure the reduction in raw material and energy use.
- Consumer Acceptance: Evaluate how well consumers can adapt to the absence or substitution of the product.
- Economic Feasibility: Analyze the economic implications for industries that rely on high consumption (Potting et al., 2017).

**R1 Rethink:** Rethinking focuses on designing products in a multi-functional way or sharing among different users to increase efficiency. The parameters for assessing the effectiveness of this strategy include:

- Functional need: Assess if the product's function can be increased by sharing or multi-functionality (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016).
- Technological Feasibility: Assess the development of multi-functional use.
- Market demand: Analyzing shift in customer behavior towards product sharing and access-based consumption.
- Economic Feasibility: Analyze the economic implications for a business model to support shared and multi-functional products.

Promotes efficiency and sustainability by encouraging the design of multi-functional products; fosters innovation in product use rather than ownership. It may require a significant shift in consumer behavior and business models and potential initial resistance from traditional markets (Bocken et al., 2016).

**R2 Reduce:** Increase efficiency in the product manufacture or use by consuming fewer natural resources and materials.
Conserves resources and minimizes waste; improves efficiency in production and consumption. Efficiency improvements may be offset by increased consumption elsewhere, a phenomenon known as the rebound effect (Allwood et al., 2011).The parameters for assessing the effectiveness of this strategy include:

- Material Intensity: Quantify the reduction in material usage per unit of product (Allwood et al., 2011).
- Energy Efficiency: Measure the reduction in energy consumption during production and use.
- Waste Generation: Assess the decrease in waste produced.
- Rebound Effect: Evaluate the potential increase in consumption elsewhere due to efficiency gains (Allwood et al., 2011).

**R3 Re-use:** Re-use by another consumer of a discarded product that is still in good condition and fulfills its original function.
Extends the life of products; reduces demand for new products and the resources needed for their production. Reused items may be perceived as less desirable; logistical challenges in collecting and redistributing items (Geissdoerfer et al., 2017). The parameters for assessing the effectiveness of this strategy include:

- Product Condition: Assess the condition of the product for re-use (Geissdoerfer et al., 2017).
- Demand for Second-hand Products: Measure consumer demand and market acceptance for reused items.
- Logistics: Evaluate the efficiency of collection, sorting, and redistribution systems.
- Reduction in Resource Use: Quantify the decrease in demand for new products and associated resource savings.

**R4 Repair:** Repair and Maintenance of defective product so it can be used with its original function.
Maintains product value and functionality; promotes local economies and skill development. May be economically or technically infeasible for some products and consumer preference for new over repaired items (Stahel, 2016). The parameters for assessing the effectiveness of this strategy include:

- Repairability: Assess the ease and feasibility of repairing the product (Stahel, 2016).
- Technological Feasibility: Measure the availability of necessary skills and knowledge for repair.
- Economic Feasibility: Evaluate the cost-effectiveness of repairs compared to buying new.
- Consumer Preference: Analyze consumer willingness to choose repaired items over new ones.

**R5 Refurbish:** Restore the old product and bring it up to date.
Products are updated and improved, potentially with better features or efficiency; reduces waste and extends product lifespan. It can require significant energy and resource input and may not always be cost-effective compared to new products (Ijomah, 2002). The parameters for assessing the effectiveness of this strategy include:

- Product Upgrading: Measure the extent and quality of updates and improvements (Ijomah, 2002).
- Energy and Resource Input: Quantify the energy and materials required for refurbishment.
- Economic Feasibility: Evaluate the economic viability of refurbishing versus producing new products.
- Market Acceptance: Assess consumer demand for refurbished products.

**R6 Re-manufacture:** Use parts of discarded products in a new product with the same function.
Saves energy and materials compared to new manufacturing; can improve product performance and lifespan. Requires collection and sorting systems; consumer acceptance of re-manufactured products may vary (Ijomah, 2002). The parameters for assessing the effectiveness of this strategy include:

- Component Recovery: Assess the ability to recover and reuse parts from discarded products (Ijomah, 2002).
- Quality and Performance: Measure the performance and lifespan of re-manufactured products.
- Collection and Sorting: Evaluate the efficiency of systems for collecting and sorting discarded products.
- Market Acceptance: Analyze market acceptance and trust in re-manufactured products.

**R7 Re-purpose:** Use discarded product or its parts in a new product with a different function.
Innovative use of materials and products; can give waste a new value in different applications. The functional and aesthetic match may not always be optimal; limited by the creativity and technical feasibility (T. Cooper, 2005). The parameters for assessing the effectiveness of this strategy include:

- Material Reuse: Measure the ability to reuse materials in new products with different functions (T. Cooper, 2005).
- Innovation and Creativity: Assess the innovative potential for finding new uses for discarded materials.

- Technical Feasibility: Evaluate the technical challenges in repurposing components.
- Functional Feasibility: Analyze the suitability of repurposed materials for new applications.

**R8 Recycle:** Process materials to obtain the same (high grade) or lower quality primary materials.
Reduces demand for virgin resources; can significantly lower environmental impact compared to raw material extraction. The quality of recycled materials can degrade; recycling processes can be energy-intensive (Ghisellini et al., 2016). The parameters for assessing the effectiveness of this strategy include:

- Material Recovery Rates: Measure the efficiency and yield of material recovery processes (Ghisellini et al., 2016).
- Energy Consumption: Quantify the energy required for recycling processes.
- Material Quality: Assess the quality of recycled materials compared to virgin materials.
- Environmental Impact: Evaluate the overall environmental benefits, including reductions in raw material extraction and waste.

**R9 Recover:** The incineration of materials with energy recovery.
Recovery can offset fossil fuels and reduce landfill volume. May discourage higher-order R-strategies; incineration can produce pollutants (Velenturf & Purnell, 2017). The parameters for assessing the effectiveness of this strategy include:

- Energy Yield: Measure the amount of energy recovered from incineration processes (Velenturf & Purnell, 2017).
- Reduction in Landfill: Quantify the decrease in waste sent to landfill.
- Emission Control: Assess the effectiveness of technologies to control pollutants produced during incineration.
- Impact on Higher-order Strategies: Evaluate whether energy recovery discourages more sustainable circular strategies.

# E. Appendix - Circular Strategies for OWF by Velenturf.

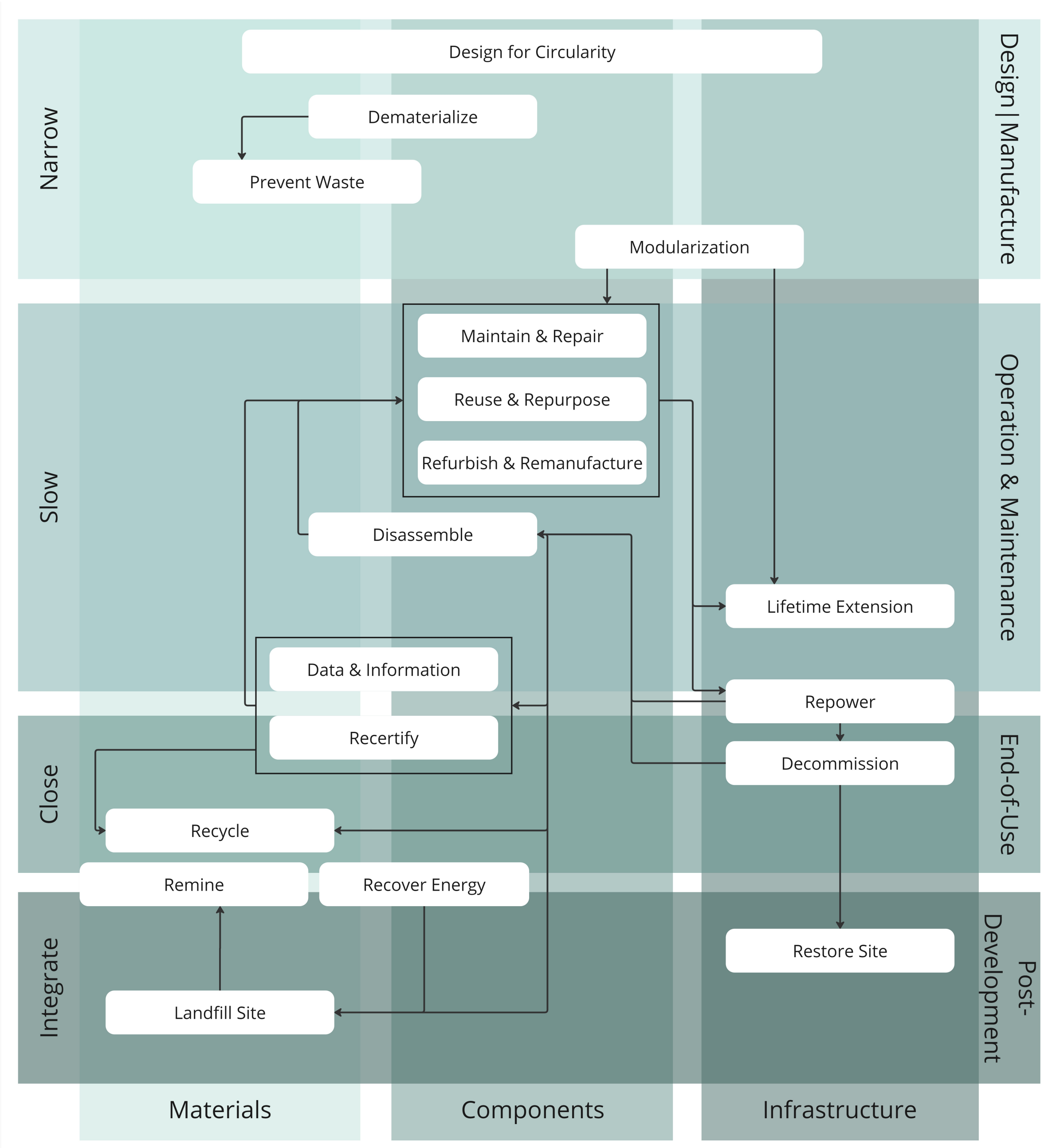


Figure 6.3: Circular strategies for offshore wind organized by their application to materials, components, and whole infrastructure (columns). The narrowing, slowing, and closing of resource flows and their integration into the environment (rows, left side), throughout the offshore wind infrastructure lifecycle, from design to the end-use and beyond (rows, right side). Arrows indicate that one strategy enables another. Source: Velenturf (2021).

# F. Appendix - Circular Strategies necessary for the EoL of OWT

## Step One

The importance of the CE strategies concerning the lifecycle of the wind turbines. Here the research is focused on the existing wind turbines and the CE strategies that can applied during the operational and the EoL phases. Thus the following Figure 6.4 illustrates the relevance of the CE strategies for this research. Here darker the background more relevant are these strategies in terms of the EoL.

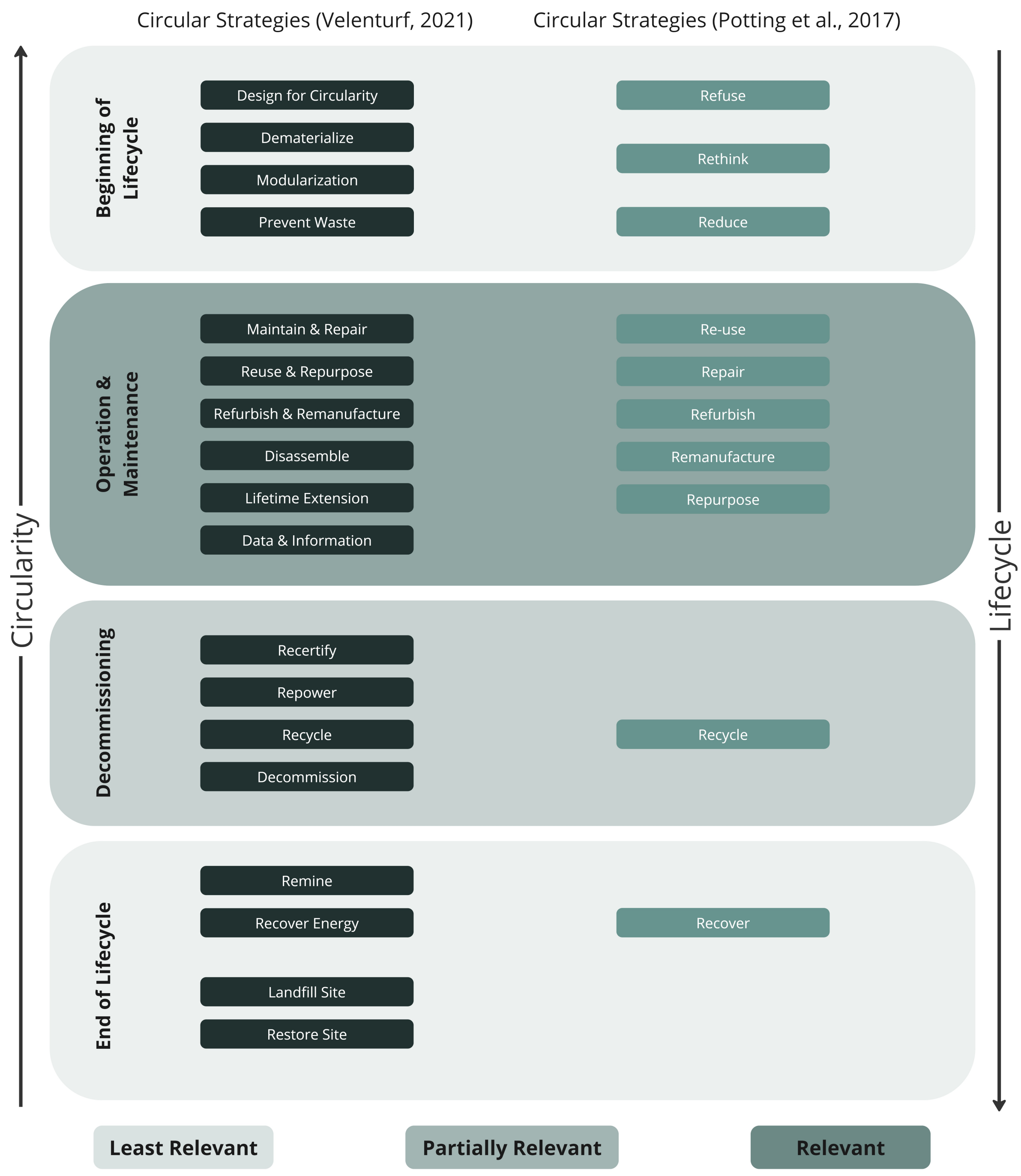


Figure 6.4: Relevance of the CE strategies concerning the EoL phase of existing wind turbines. Adapted from: Potting et al. (2017); Velenturf (2021)

## Step two

Next, the CE strategies were analyzed, considering the relevance of these strategies to the different information levels and scale of a wind turbine. These are divided into 3 parts: Infrastructure level (lightest background), Component Level (darkest background), and Material Level (medium background). The darker the background more relevant CE strategy, this is based on the the scope of this research as CE is explored on the component level. This can be seen in the illustration in Figure 6.5.

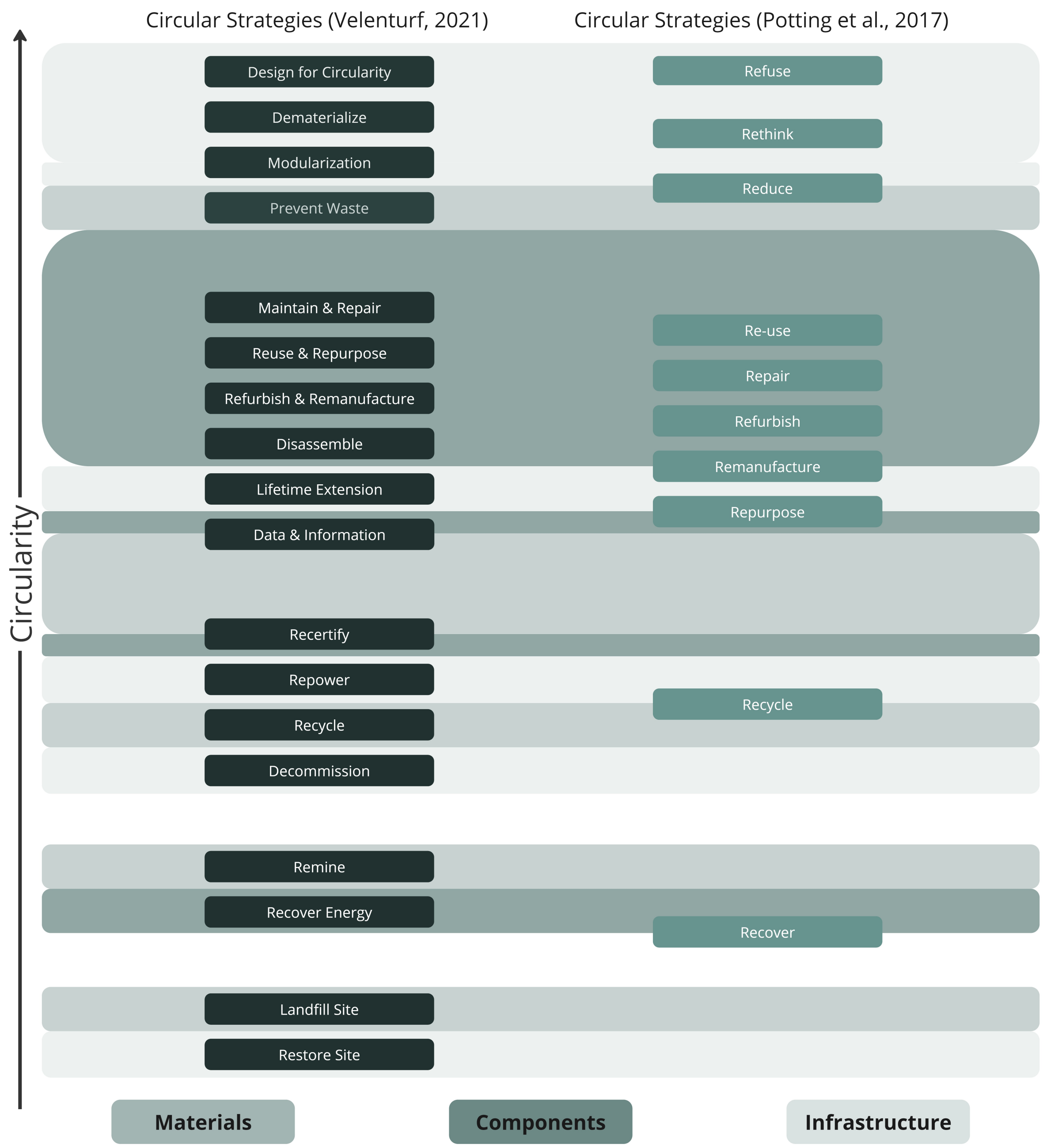


Figure 6.5: Relevance of the CE strategies concerning the level of scales. Adapted from: Potting et al. (2017); Velenturf (2021)

## Step Three

Finally, the following circular strategies illustrated in Figure 6.6 are the most relevant for the EoL resource management of a wind turbine.

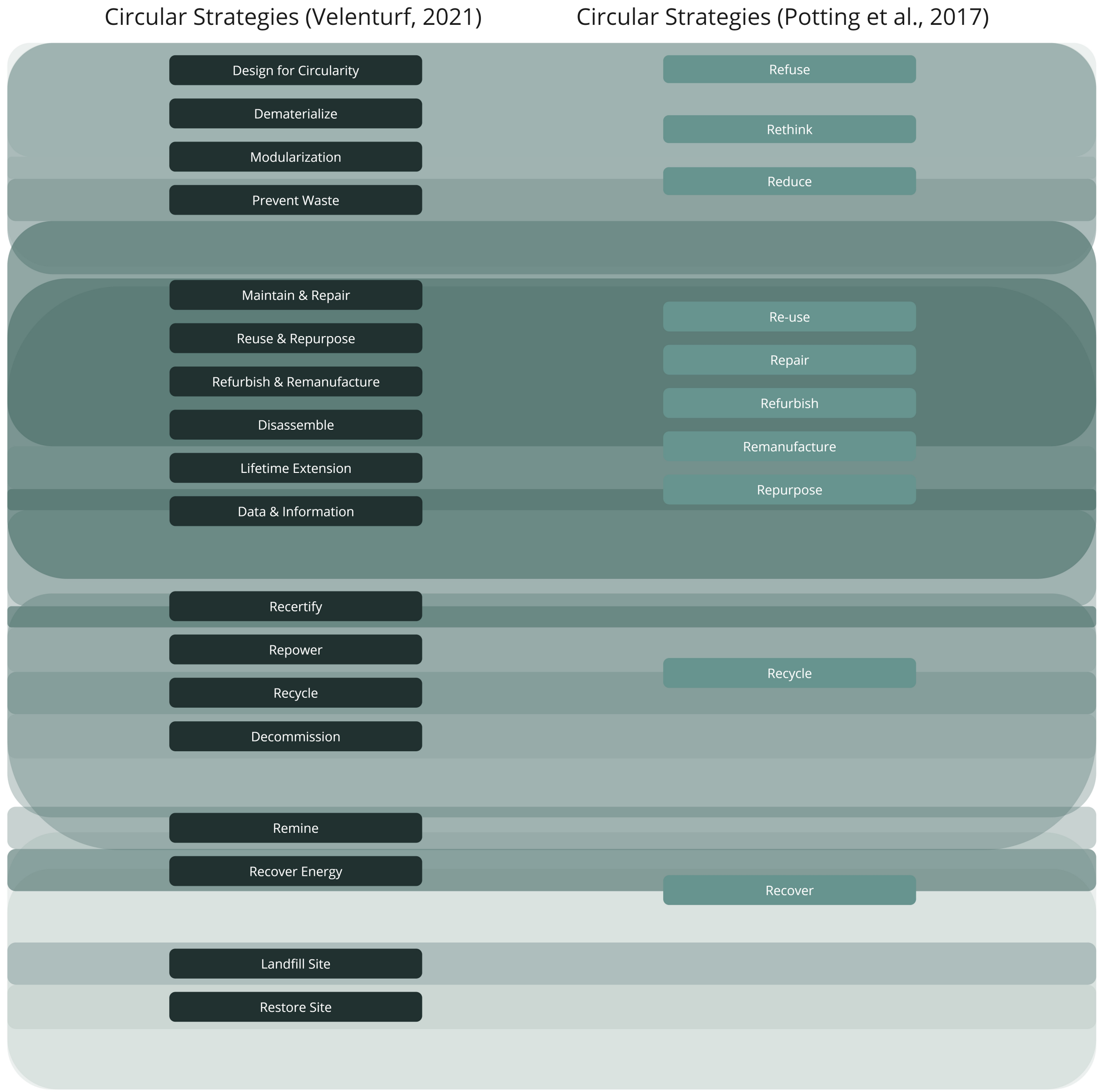


Figure 6.6: Circular strategies relevant for this research. Adapted from: Potting et al. (2017); Velenturf (2021).

The exercise to determine relevant circular strategies for the EoL resource management of OWTs presented the following circular strategies:

1. **Re-certify:** Re-certification involves verifying that components or systems of the OWT meet current operational standards and regulations, ensuring they can continue to function safely and efficiently. This strategy is relevant for all the components which can be tested and certified for extended use. Re-certification helps maximize the utilization of existing resources, reducing the need for new materials (Velenturf, 2021). This strategy's successful implementation depends on re-certifying high-value components such as the nacelle and wind blades.

2. **Reuse:** This strategy implies using OWT components in their original form without significant changes. For example, during the decommissioning of an OWT, there are changes that a specific component has been replaced in recent years for maintenance purposes and has an extended life compared to the other components that reach their end of the operational phase.

3. **Repair:** Repair involves fixing defects or damages in the OWT components to restore them to operational condition. This strategy applies to various parts, including nacelles, blades, and electrical systems, allowing them to continue their service life. Repair at the EoL implies that the components are decommissioned and repaired at an onshore location for use in another OWT/WT.

4. **Refurbish:** Refurbishment refers to restoring and updating OWT components with new sub-components to improve performance and operational life. Refurbishment is usually implemented for outdated components that can be used in another OWT/WT with the latest updates.

5. **Remanufacture:** Remanufacturing involves dismantling the OWT components and using them to manufacture new components. Remanufacturing is possible only if the sub-components meet the current standards.

6. **Repurpose:** This strategy aims to find new uses for the OWT components that can no longer serve their original function even after repairs/remanufacturing. For example, decommissioned blades can be used in bridges, architectural elements, etc. It is necessary to document the condition of the component to enable the repurposing.

7. **Recycle:** Recycling involves processing materials from decommissioned OWT components to recover raw materials that can be used to produce new products. Steel from towers, copper from electrical systems, and rare earth metals from generators are examples of materials that can be efficiently recycled.

8. **Recover:** The non-recyclable materials from an OWT can be incinerated to generate energy. While this strategy is considered a last resort, it ensures that some value is extracted from the waste, reducing the volume of materials sent to landfills. However, the environmental benefits must be carefully weighed against the potential emissions from incineration Velenturf and Purnell (2017).

# G. Appendix - Mapping key parameters against circular strategies.

*(To be noted: circular strategies repair and refurbish have similar application and functionality thus the data attributes for these are the same)*

Table 6.7: Mapping key parameters against circular strategies.

| Key Parameter | Re-Certify | Reuse | Repair & Refurbish | Re-Manufacture | Re-Purpose | Recycle | Recover |
|---|---|---|---|---|---|---|---|
| Condition Assessment | | | | | | | |
| Visual Inspection | X | X | X | X | - | - | - |
| NDT | X | X | X | X | - | - | - |
| Material Composition | - | - | - | - | X | X | X |
| Material Health | X | X | X | X | X | X | X |
| Performance Assessment | | | | | | | |
| Current Performance | X | X | X | X | - | - | - |
| Future Performance | X | X | X | X | - | - | - |
| Compliance Assessment | | | | | | | |
| Industry Standard | X | X | X | X | X | X | X |
| Certification | X | X | X | X | X | X | X |

# H. Appendix - Existing Products similar to EcoRush

Table 6.8: Potential Software Developers for an OWF EoL DPP.

| Company Name | Description | Website |
|---|---|---|
| Cirdax | Material Passport | `https://www.cirdax.com/materiaal-paspoort/` |
| TNO | UWiSE tool for efficient decommissioning of offshore wind farms. | `https://www.tno.nl/nl/newsroom/2023/11/uwise-ontmanteling-windparken/` |
| Circularise | Digital Product Passports | `https://www.circularise.com/dpp` |
| Properli | Asset Management Tools | `https://proprli.com/` |
| BAMB (Buildings as Material Banks) | Material Passport | `https://www.bamb2020.eu/topics/materials-passports/` |
| Loopfront | Material Passport | `https://www.loopfront.com/product/how-it-works` |
| DecomBlades | Blade Material Passport | `https://decomblades.dk/` |
| DNV- REWind | Digital Product Passport | `https://www.dnv.com/services/digital-product-passport-231993` |
| EPEA | Product Circularity Passport | `https://epea.com/nl/onze-diensten` |
| Madaster | Material Passports | `https://madaster.com/platform/` |

# I. Appendix - Standards and Certification Checklist

| Compliance Assessment Checklist | | | |
|---|---|---|---|
| **Parameter** | **Circurlar Strategy** | **Standards & Certification** | |
| Standards & Certification 1 | Re-certify | ISO 9001 (Quality Management) | ☐ |
| | | ISO 45001 (Occupational Health and Safety) | ☐ |
| | | Performance Certification | ☐ |
| | | Regulatory Compliance | ☐ |
| | Reuse | ISO 9001 (Quality Management) | ☐ |
| | | ISO 45001 (Occupational Health and Safety) | ☐ |
| | | Functionality Tests | ☐ |
| | | Cleaning and Decontamination Certification | ☐ |
| Standards & Certification 2 | Repair | ISO 9001 (Quality Management) | ☐ |
| | | Parts Certification | ☐ |
| | | ISO 45001 (Occupational Health and Safety) | ☐ |
| | | Performance Tests | ☐ |
| | Refurbish | ISO 9001 (Quality Management) | ☐ |
| | | Quality Control Certification | ☐ |
| | | Upgrading Standards | ☐ |
| | | Performance Tests | ☐ |
| | Remanufacture | ISO 9001 (Quality Management) | ☐ |
| | | Parts and Materials Certification | ☐ |
| | | Performance and Quality Tests | ☐ |
| | | Warranty and Guarantee | ☐ |
| Standards & Certification 3 | Repurpose | ISO 45001 (Occupational Health and Safety) | ☐ |
| | | Functionality Certification | ☐ |
| | | Regulatory Compliance | ☐ |
| | Recycle | ISO 14001 (Environmental Management) | ☐ |
| | | Purity Standards | ☐ |
| | | Environmental Standards | ☐ |
| | | Waste Management Certification | ☐ |

Figure 6.7: Compliance assessment checklist.

The standards and certifications that are assessed for Re-certify are:

- ISO 45001 (Occupational Health and Safety): Ensure the component is safe.
- Performance Certification: Assure that the component will perform as intended.
- Regulatory Compliance: Ensure all relevant regulations and industry standards are met.

The standards and certifications that are assessed for Reuse are:

- ISO 45001 (Occupational Health and Safety): Ensure that the reused component poses no safety risks.
- Functionality Tests: Verify that the component is still functional.
- Cleaning and Decontamination Certification: Ensure the component is free from harmful substances.

The standards and certifications that are assessed for Repair are:

- Parts Certification: Certification for parts used in the repair to ensure they meet quality standards.
- ISO 45001 (Occupational Health and Safety): Ensure that the repaired component is safe for use.
- Performance Tests: Verify the component performs as expected after repair.

The standards and certifications that are assessed for Refurbish are:

- Quality Control Certification: Certification of the quality control process.
- Upgrading Standards: Specify any upgrades made during refurbishment.
- Performance Tests: Verify the component performs as expected after refurbishment.

The standards and certifications that are assessed for Remanufacture are:

- ISO 9001 (Quality Management): Comprehensive guidelines for the remanufacturing process.
- Parts and Materials Certification: Certification for parts and materials used in remanufacturing.
- Performance and Quality Tests: Ensure the remanufactured component meets original performance and quality standards.
- Warranty and Guarantee: Provide a warranty for the remanufactured component.

The standards and certifications that are assessed for Repurpose are:

- ISO 45001 (Occupational Health and Safety): Ensure the repurposed component does not pose any safety risks in its new application.
- Functionality Certification: Verify that the component can perform effectively in its new function.
- Regulatory Compliance: Meets all relevant regulations for its new application.

The standards and certifications that are assessed for Recycle are:

- ISO 14001 (Environmental Management): Guidelines for efficiently recovering materials.
- Purity Standards: Ensure the recycled materials meet purity requirements for reuse.
- Environmental Standards: Ensure the recycling process is environmentally friendly.
- Waste Management Certification: Ensure proper management of any waste produced during recycling.

The standards and certifications that are assessed for Recover are:

- Energy Recovery Standards: Guidelines for the safe and efficient energy recovery from materials.
- Emission Standards: Ensure emissions from the recovery process meet environmental regulations.
- ISO 45001 (Occupational Health and Safety): Ensure the recovery process does not pose any safety risks.
- Waste Management Certification: Ensures proper waste management during recovery.

# J. Appendix - Data collection process for a DPP

1. Fundamental data attributes such as size, weight, manufacturer, etc., can be typically obtained directly from the OEM. OEMs keep comprehensive records of their turbines, including all physical specifications. Therefore, a simple request to the OEM can provide details such as the turbine components' height, weight, and density, eliminating the need for on-site measurements.

2. Maintenance records and operational logs are maintained by the OWF operator and the maintenance service providers. Regular maintenance logs and operational performance records are usually stored in digital asset management systems, adhering to standards like ISO 55000 for asset management. Access to these systems can be requested to retrieve the necessary documents.

3. For more specific data attributes such as degradation testing, structural integrity, and future performance, on-site inspections, and tests are required. Degradation testing, for instance, involves assessing the wear and tear of materials over time. This can be performed using techniques such as NDT, including ultrasonic or radiographic testing, to identify internal flaws or degradation that aren't visible to the naked eye. These tests are conducted by specialized maintenance service providers who follow standardized procedures outlined in ISO 9712. Structural integrity assessments involve both visual inspections and advanced testing methods. Visual inspections can identify apparent signs of damage or wear, while NDT methods provide a deeper understanding of the component's condition compared to visual inspection; this comprehensive approach ensures that structural weaknesses are identified early, essential for accurate lifecycle management.

4. Estimating the RUL and future performance of the turbine components requires predictive analysis. This involves collecting and analyzing historical performance data, maintenance records, and degradation rates. Advanced software tools often use algorithms and machine learning to project the components' future performance and remaining lifespan.

5. For data attributes like the condition at EOL, it involves final inspections carried out by EoL inspection providers. These thorough inspections ensure that all relevant data is captured before decommissioning. The findings are documented in detailed reports, which form the basis for making decisions about the next steps in the component's lifecycle.

# K. Appendix - Circular Decision-Making Framework

Typology Assessment
Condition Assessment
Performance Assessment
Compliance Assessment
Environmental Assessment
Economical Assessment
Visual Inspection
High?
Medium?
Low?
NDT
Material Health
Current Performance 1
Current Performance 2
Future Performance 1
Future Performance 2
Re-certify
OR
Reuse
Repair
Refurbish
Remanufacture
Repurpose
Recycle
Recover
Standards & Certification 1
Standards & Certification 2
Material Composition
Standards & Certification 3
Circular Assessment
CE Strategies
Parameters
Decision
End of first part of assessment
Yes
No

Following is the breakdown of the decision-making framework:
(Selection of the typology would decide which of the end results are valid or not)

### 1. Condition Assessment

**Visual Inspection** **High:** Proceed to NDT.

**Medium:** Proceed to NDT.

**Low:** Skip to Material Composition.

**NDT (Non-Destructive Testing)** **High:** Proceed to Performance Assessment 1.

**Medium:** Proceed Performance Assessment.

**Low:** Skip to Material Composition.

**Material Health** **High:** Proceed to Performance Assessment 2.

**Medium:** Proceed to Material Composition.

**Low:** Proceed to Material Composition.

**Material Composition** **High:** End process with circular strategy options Repurpose, Recycle, or Recover.

**Medium:** End process with circular strategy options Repurpose, Recycle, or Recover.

**Low:** End process with circular strategy options Repurpose, Recycle, or Recover.

### 2. Performance Assessment

**Current Performance 1** **High:** Proceed to Future Performance 1.

**Medium:** End process with circular strategy options Repair, Refurbish, or Remanufacture.

**Low:** End process with circular strategy options Repurpose, Recycle, or Recover.

**Future Performance 1** **High:** End process with circular strategy options Re-certify or Reuse.

**Medium:** End process with circular strategy options Repair, Refurbish, or Remanufacture.

**Low:** End process with circular strategy options Repurpose, Recycle, or Recover.

**Current Performance 2** **High:** Proceed to Future Performance 2.

**Medium:** End process with circular strategy options Repair, Refurbish, or Remanufacture.

**Low:** End process with circular strategy options Repurpose, Recycle, or Recover.

**Future Performance 2** **High:** End process with circular strategy options Repair, Refurbish, or Remanufacture.

**Medium:** End process with circular strategy options Repair, Refurbish, or Remanufacture.

**Low:** End process with circular strategy options Repurpose, Recycle, or Recover.

### 3. Compliance Assessment

**Standards & Certification 1** **Pass:** End process with circular strategy options Re-certify or Reuse.

**Fail:** Proceed to Standards & Certification 2.

**Standards & Certification 2** **Pass:** End process with circular strategy options Repair, Refurbish, or Remanufacture.

**Fail:** Proceed to Material Composition.

**Material Composition** **Pass:** End process with circular strategy options Repurpose, Recycle, or Recover.

**Fail:** End process with circular strategy options Repurpose, Recycle, or Recover.

# L. Appendix - The Use of AI During the Research

During the course of this research, AI tools were utilized to improve various aspects of the study, mainly enhancing work efficiency and quality.
ChatGPT proved especially valuable in identifying scientific literature for specific topics when traditional methods were inadequate. Its ability to provide concise, relevant information made it a valuable alternative to conventional search engines, streamlining our learning process for new topics. A few instances in the study needed specific comparisons between topics, and ChatGPT saved significant time and allowed us to take a more targeted approach to our research. Additionally, ChatGPT assisted in generating Overleaf code for tables, ensuring efficient handling of the technical aspects of the report. All information provided by ChatGPT was thoroughly cross-verified with relevant sources and links to maintain accuracy.

Grammarly, another AI tool, played a vital role in ensuring grammatical accuracy and improving sentence structure throughout the report. At times, Grammarly was also used to summarize lengthy paragraphs, saving time while maintaining clarity and coherence. Both tools were used as aids to complement human analysis and critical thinking, allowing us to focus more time and effort on the conceptual and strategic aspects of the study.

These tools contributed to refining the clarity and coherence of written content, ensuring that complex ideas were communicated effectively. The use of AI in this research was not a replacement for human analysis and critical thinking but rather a complement that enhanced the depth and breadth of the work. It allowed for more time to be dedicated to the conceptual and strategic aspects of the study.

# M. Appendix - Self Reflection

Embarking on this research journey has been an eye-opening and demanding experience that has significantly contributed to my academic advancement and personal growth. Initially, I undertook the study of circular strategies for offshore wind turbine components with a sense of curiosity and ambition. The intricate nature of the topic, along with the abundance of new knowledge, seemed overwhelming. However, as I delved further into the research, I discovered that these challenges also provided opportunities to acquire new skills and enhance my comprehension.

One of the most crucial elements of this journey was mastering the balance between the research's analytical requirements and the necessity for creativity and critical thinking. This became particularly apparent during the creation of the decision-making framework, as I had to constantly assess and reassess my approach based on expert feedback and the evolving nature of the data. The iterative process of refining the framework taught me the significance of adaptability and flexibility in research. Throughout this process, I realized the importance of time management as I juggled multiple deadlines and worked with various stakeholders. Learning to prioritize tasks and effectively maintain a consistent workflow was crucial. I encountered challenges, especially when dealing with complex technical issues or unexpected obstacles, but these experiences taught me the significance of perseverance and the value of incremental progress. There were times when my expected deliverable seemed challenging for the expected time frame, but pushing a bit harder for a couple of weeks got me there. Also, my committee understood my challenges and tried their best to help me achieve my goals.

My research process took on a new dimension as I used AI tools. At first, I had doubts about relying on technology for tasks traditionally handled by humans, such as looking up new topics to read, writing codes, etc. However, integrating AI into my research made these tasks more efficient and allowed me to concentrate more on the interpretive and strategic aspects of the study. This experience has made me more receptive to adopting technological advancements in future research.

Throughout this research process, I have realized the importance of a strong support system. My family and my fiancée have consistently encouraged and understood me, especially during the more difficult stages of the project. Their support has underscored the significance of maintaining a healthy work-life balance, crucial for productivity and overall well-being.
In summary, this research journey has been an incredibly enriching experience. It has not only furnished me with valuable skills and a deeper understanding of circular economy principles but has also reinforced my determination to make a meaningful contribution to this field. As I progress in my academic and professional endeavors, I will carry the insights gained from this process, recognizing that every challenge presents an opportunity for personal growth.