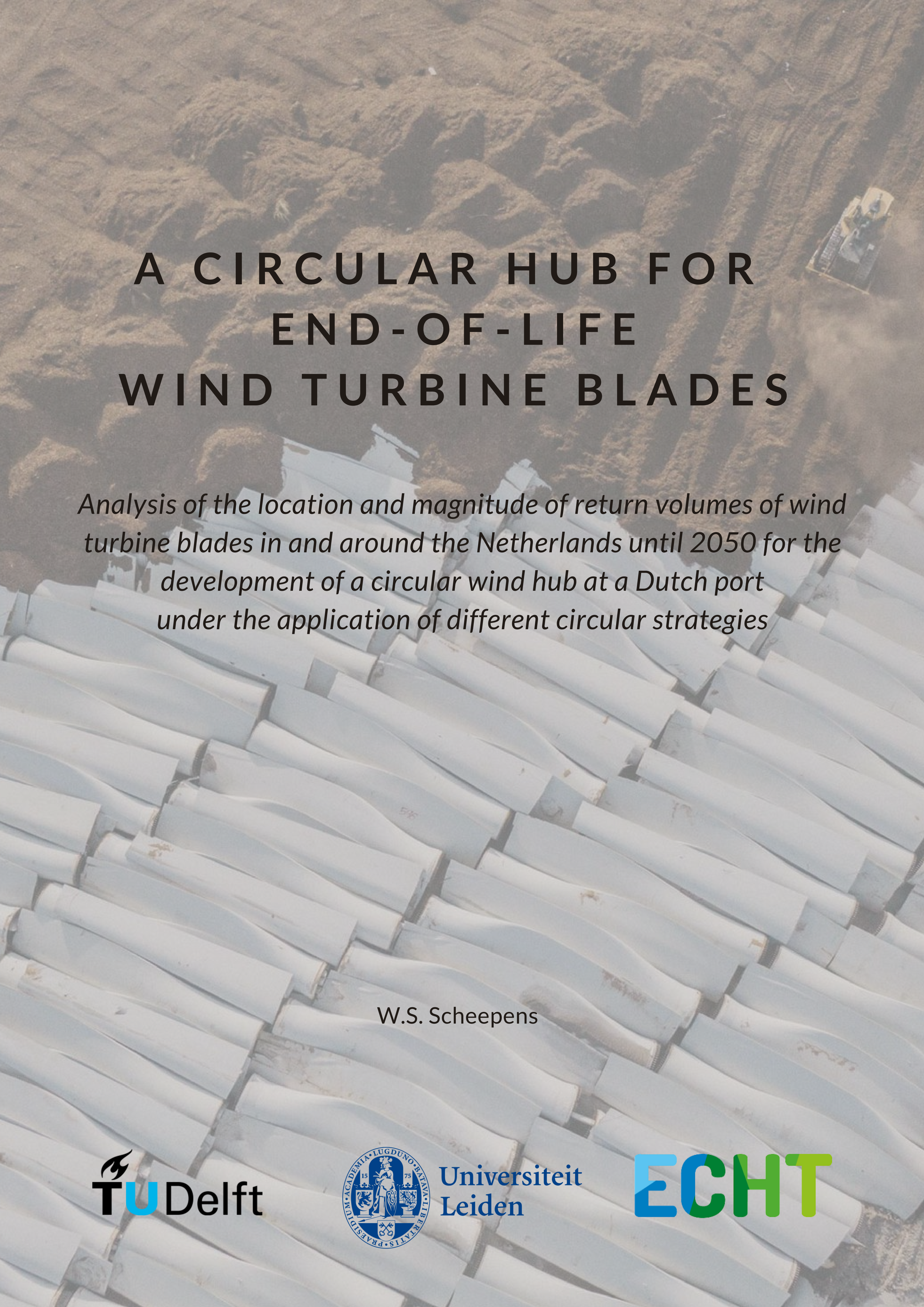

A CIRCULAR HUB FOR END-OF-LIFE WIND TURBINE BLADES

Analysis of the location and magnitude of return volumes of wind turbine blades in and around the Netherlands until 2050 for the development of a circular wind hub at a Dutch port under the application of different circular strategies

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ECHT

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Master thesis submitted to Delft University of Technology and Leiden University
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by

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ABSTRACT

Wind turbine blades are composed of complex composite material structures that are difficult to recycle at the end of their operational lifetime. As such, they are oftentimes landfilled or incinerated. Following the Circular Economy principles, there are a multitude of strategies that may be applied to these structures; these range from more to less desirable, where landfill and incineration are categorised as least desirable. In the ambition to reduce greenhouse gas emissions and reach agreed upon climate goals, the implementation of wind power plays a central role in the Netherlands, and hence the number of end-of-life wind turbine blades will significantly increase in the coming decades. In an attempt to better manage this issue, the creation of a central circular hub as treatment facility for these end-of-life blades has been suggested. Hence, a framework is developed to compare ports with regard to their suitability for the development of a circular wind hub. The framework is based on six categories: port willingness, available space, existing companies and infrastructure, accessibility, focus on circular strategies, and centrality with respect to return volumes. Subsequently, different ports in the Netherlands are compared for the establishment of a circular wind hub. The Port of Den Helder and Port of Amsterdam come forward as most suitable locations, with a strong willingness and being most centrally located. However, it is also highlighted that the hub need not be limited to one single location - in fact, it could be valuable to collaborate and create synergies across ports. Additionally, interregional collaboration with neighbouring countries of the Netherlands – Germany, Denmark, the United Kingdom, France, and Belgium – will help to improve the economic viability of such a hub. This research therefore performs a geographical explicit quantification of the availability of end-of-life wind turbine blades in this region between 2020-2050, and places the results in the context of three circular strategies based on reusing, repurposing and recycling the blades, respectively. This is done through the use of a dynamic Material Flow Analysis and the use of a Geographic Information System. The results indicate a clear increase in end-of-life wind turbine blades in the defined region until 2050, reaching a cumulative amount of 690 kilotonnes by 2050. Application of the circular strategies strongly influences the amount of material for which it is economically viable to be treated in the hub. In all cases, this is significantly lower than the total amount of material in the region. Among the three strategies, reusing the blades results in the highest amount of material treated, energy saved and economic benefits realised. However, the potential market size seems largest for recycling the blades and smallest for reusing them; hence regulation for this disparity is called for. Furthermore, a push is needed for the viable volumes under application of the circular strategies to better approach the total volume in the region. To accomplish this, it is imperative that the economic value of the secondary material be increased, as well as the documentation of wind turbine blades and transparency in the value chain be improved. All in all, this research expresses the urgency, feasibility and potential value of the development of a circular wind hub for end-of-life wind turbine blades in the Netherlands.

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ABBREVIATIONS

CE	Circular Economy
CF	carbon fibre
CFRP	carbon fibre reinforced polymer
dMFA	dynamic Material Flow Analysis
(d)MFA	(dynamic) Material Flow Analysis
DSM	dynamic stock model
EoL	end-of-life
EPR	Extended Producer Responsibility
EU	European Union
FRP	fibre reinforced polymer
GF	glass fibre
GFRP	glass fibre reinforced polymer
GIS	Geographical Information System
GHG	greenhouse gas
GSP	Groningen Seaports
GWP	Global Warming Potential
IE	Industrial Ecology
LCA	Life Cycle Assessment
MFA	Material Flow Analysis
NSP	North Sea Port
O&G	oil & gas
O&M	operations & maintenance
PoA	Port of Amsterdam
PoDH	Port of Den Helder
PoR	Port of Rotterdam
recycle	circular strategies based on recycling
RL	reverse logistics
repurpose	circular strategies based on repurposing
reuse	circular strategies based on reusing
SGRE	Siemens Gamesa Renewable Energy
SDG	Sustainable Development Goals
TBL	Triple Bottom Line

TRL	Technology Readiness Level
UK	United Kingdom
UN	United Nations
WTB	wind turbine blades

Units of measurement:

a	annum
g	gram, with prefix k (kilo)
J	joule, with prefixes G (giga), P (peta)
t	tonne, with prefix k (kilo)
W	watt, with prefixes M (mega), G (giga)
Wh	watt-hour, with prefix k (kilo)

1 INTRODUCTION

1.1 BACKGROUND

Sustainable development is generally defined according to the concept of three main pillars that it rests on. Each of the three pillars – social, economic and environment – is a crucial component and these must develop in harmony (Purvis et al., 2019). At present, this is oftentimes not the case, as economic prosperity tends to go paired with increasing environmental pressures (United Nations, nd). In fact, mankind's current annual use of natural resources and its generation of waste and emissions actually requires 1.7 Earths (Global Footprint Network, 2021). A key reason for this is our fossil-based energy system, which rests on the use of a finite material supply and is a large source of greenhouse gas (GHG) emissions - and thus the advancement of climate change. This has called for a large-scale transition to a renewable and clean energy system.

Simultaneously, sustainable development means that more careful use and management of natural resources is imperative. This realisation has brought about the Circular Economy (CE): an economy whereby economic growth is decoupled from environmental degradation and material cycles are closed. The CE principles dictate that there is a multitude of circular strategies that may be applied to close material cycles. Summarised, these are prevention, reusing, repurposing, recycling, recovery and disposal.

The strategies are divided in a hierarchical manner ('the circular ladder'), indicative of how circular – and therefore how desirable – the strategies are (Potting et al., 2017). The goal of CE is to keep materials at an as-high-as-possible level for as long as possible (Jensen and Skelton, 2018). Globally, the urgency of a CE as a means to achieve sustainable development is increasingly recognised: it is adopted in the United Nations (UN) Sustainable Development Goals (SDG), the European Union (EU)'s Green Deal, and the Netherlands has set the goal to have a complete CE by 2050 - yet is currently at 24.5% (de Wit et al., 2020).

Hence, the transition of our energy system towards a renewable-based one and the implementation of a circular economy are crucial components of sustainable development - and they are moreover interrelated.

Wind turbines are an incredibly important asset to the global energy transition. The Netherlands aims to achieve a decrease in CO_2 emissions of 49% by 2030 and of 95% by 2050 compared to 1990 levels (Rijksoverheid, nd), and wind is to become the main electricity producer by 2050 (PBL, 2017). Yet while the focus is mainly on building and expanding such a renewable energy system, little thought is given to the end-of-life (EoL) phase of its components (Topham and McMillan, 2017). For instance, in Life Cycle Assessment (LCA) of wind turbines, the decommissioning phase and reverse logistics (RL) has often been neglected to date (Andersen et al., 2014; Rentizelas et al., 2021). To arrive at a complete CE, knowledge of decommissioning and proper EoL treatment of these components is crucial.

Even though wind turbines can already reach impressive theoretical recyclability rates of up to 90% (ETIPWind, 2019), this is not the case for the wind turbine blades (WTB). The blades must be strong in order to withstand high wind speeds, though at the same time be as light as possible in order to reach higher efficiencies. Complex composite material structures allow for such a design, yet are difficult to recycle

(Yang et al., 2012). High-quality recycling methods that do exist are not yet suitable for large-scale use, nor are they economically competitive (ETIPWind, 2019). A further implication for this is the fact that blades are becoming ever-larger, now reaching dimensions similar to Boeing 747 airplanes (Martin, 2020). This lack of viable recycling options, combined with numerous limitations to apply strategies higher on the circular ladder, has meant that a large number of EoL WTB are being landfilled or incinerated (Schmid et al., 2020; van der Meulen et al., 2020b). These are the least preferred strategies in terms of CE.

At the same time, the wind energy industry is growing significantly, and hence the number of EoL blades grows also. This means that in the coming years, an ever-growing amount of EoL blades will be ready for decommissioning, for which there is currently little use-case; estimations are set at 15.000 WTB over the next five years in Europe (ETIPWind, 2019).

In an attempt to better manage this issue, the creation of a central circular hub as treatment facility for these EoL WTB has been suggested (Devic et al., 2018; Lobregt et al., 2021). This would reduce costs of RL and storage (WindEurope, 2017). A port lends itself well to set up such a hub: they are strategically located at sea, already have infrastructure in place, and are already used for the installation and maintenance of offshore wind projects (Lobregt et al., 2021).

Research by Roelofs (2020) concluded that the volume of composite waste from EoL blades from solely the Netherlands is at present insufficient for the minimum required throughput for a viable recycling plant. Hence, interregional collaboration with neighbouring countries of the Netherlands – Germany, Denmark, the United Kingdom (UK), France and Belgium – will help to improve the economic viability of such a hub. Indeed, combined, these six countries will make up a significant share of Europe's on- and offshore wind capacity in 2030: 50% and 84%, respectively (Komusanac et al., 2020b).

Finally, following the CE principles, a central circular hub for the treatment of EoL WTB should ideally practice strategies that are higher up the circularity ladder. Different strategies have a different economic potential and environmental impact. The choice of circular strategy therefore impacts the potential environmental benefits and profitability of such a circular wind hub, as well as the maximum distance to which it makes economic sense to transport the material to the hub.

1.2 PROBLEM STATEMENT

To achieve sustainable development, a transition towards a clean energy system and a CE are imperative. With a strong growth in the number of installed wind turbines, the number of EoL WTB will rapidly increase in the coming decades. Yet the decommissioning phase and RL of wind turbines is uncertain and challenging, and has received little attention so far. Meanwhile, the Netherlands aims towards a fully CE by 2050. Therefore, it is important to develop EoL treatment facilities for this material, which are centrally-located for current and future installed wind power (Andersen et al., 2016).

While quantifications have been made for the total amount of EoL WTB from different regions and/or specific countries, for instance Cao et al. (2019); Lichtenegger et al. (2020); van der Meulen et al. (2020b); Roelofs (2020), these analyses do not include location-specific data of the origin of the WTB. Furthermore, this has not been done for the region specified for this research. In order to develop proper and useful waste treatment solutions, and to shed light on RL, this geographical explicit quantification of the blade material is a necessity (Andersen et al., 2016). Further elaboration on these aspects can be found in Chapter 2.

1.3 RESEARCH OBJECTIVES

The main objective of this research is to aid the development of a circular wind hub in the Netherlands. To do so, the aims of this research are threefold.

First of all, the research aims to distinguish specific characteristics that deem a location feasible for the development of a circular wind hub, to arrive at a general framework that may be used to score port locations. Subsequently, the five main ports in the Netherlands are compared with regard to their suitability for the placement of a circular wind hub to treat the EoL WTB.

The second research objective is to analyse the development of the location and magnitude of return volumes of WTB material over time from 2020 until 2050. This gives an indication of the total volume that would qualify for treatment in the circular hub. This analysis is based on the Netherlands, Germany, Denmark, the UK, France and Belgium. For the Netherlands, it includes both on- and offshore turbines; for the other countries, only offshore turbines are considered. This is due to the fact that transport over land is much more challenging and as such, will be much more limited by distance than transport over sea. It may therefore be expected that for onshore WTB outside of the Netherlands, solutions will be looked for more locally. Furthermore, onshore wind includes many smaller-sized wind farms or individual turbines, while offshore wind farms are generally large and therefore provide a notable amount of material at once upon decommissioning. Hence the return volumes of offshore wind will be more significant than onshore wind. New wind installations will only be considered up to 2030; developments after this time are highly uncertain and wind turbines generally have a design lifetime of some 20 years (Cooperman et al., 2021).

Third, the research aims to determine the effect of different circular strategies on the final volume of EoL WTB to be treated at the hub. This component compares three different circular strategies with respect to their economic potential and environmental impact, namely reusing, repurposing and recycling the blades. Subsequently, supposing a central wind hub is placed in the Netherlands for the processing of EoL WTB, the research will give an indication as to which on- and offshore wind farms in the region could be processed in this hub under the application of the different circular strategies. In this way, the research makes the challenge of EoL WTB more concrete and maps out the magnitude of this challenge in light of different circular strategies. It additionally gives an idea of what economic and environmental benefits can be achieved by developing a hub under the application of each circular strategy.

The analysis additionally provides insight and data for RL of EoL WTB, which is a step towards making the LCA of the wind industry more complete.

All in all, the research aids the development of an optimal waste management infrastructure for EoL WTB. As such, it provides an advancement towards making a sustainable energy system truly sustainable – in all its phases.

Based on the steps needed to develop a more circular wind industry, Lobregt et al. (2021) have defined a circular strategies framework. This framework highlights the different domains and timelines that the industry should focus on. The framework can be seen in Figure 1.1, with the focus areas of this research enclosed in orange.

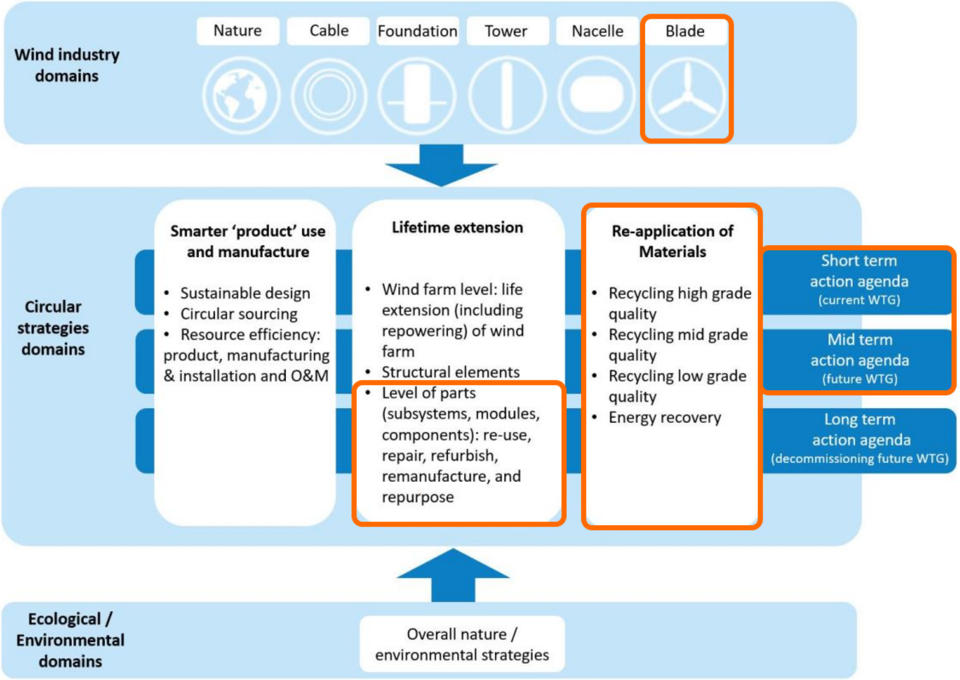


Figure 1.1: Circular strategies framework for the wind industry (Lobregt et al., 2021, p. 16)

1.4 RESEARCH QUESTIONS

The focus of this thesis is on the development of a circular wind hub in the Netherlands to better fit the expected return volumes of end-of-life wind turbine blades inside a circular economy. As such, the main research question of this thesis reads:

How do Dutch ports compare in terms of suitability for the development of a circular wind hub, and what return volumes of end-of-life wind turbine blades in and around the Netherlands may be treated there until 2050 under application of different circular strategies?

This research question can be split into four sub-questions, which can subsequently be further narrowed down as follows:

1. What characteristics are important for a location to possess for the development of a circular wind hub to treat the return volumes of end-of-life wind turbine blades?

2. How do Dutch ports compare in terms of suitability for the development of a circular wind hub?

3. What return volumes of end-of-life wind turbine blades can be expected in and around the Netherlands between 2020 – 2050?
   a) What is the current on- and offshore wind capacity in this region and where are the wind farms located?
   b) What is the planned installed on- and offshore wind capacity in this region until 2030 and at which locations will these wind farms be developed?

4. How does the choice of circular strategy influence the final volume of end-of-life wind turbine blades to be treated at a circular wind hub and what economic and environmental implications does this have?
   a) How do the circular strategies compare in terms of their economic potential?

b) How do the circular strategies compare in terms of their environmental impact?
c) For which wind farms is it economically viable to transport the end-of-life wind turbine blades to the hub?
    i. What are the transport costs of on- and offshore end-of-life wind turbine blades?
    ii. For which wind farms does the value of the secondary material outweigh the transport costs of the wind turbine blades to the port?
d) What economic and environmental benefits can be achieved under application of each circular strategy?

1.5 REPORT STRUCTURE

This report first provides background information with regards to key concepts of this research and provides the context and backdrop of the research in Chapter 2. Next, Chapter 3 covers the applied research methods and data requirements. Subsequently, Chapter 4 presents the results from the research methods and offers answers to the research questions. Finally, Chapter 5 presents final conclusions and a discussion of the research.

2 CONTEXT AND BACKGROUND

This chapter offers the context of the research and dives into the background and backdrop of this research. Understanding the concepts and the backdrop of the research is important prior to interpreting the research findings. Since this is a thesis in the research field of Industrial Ecology (IE), the general field of IE is first introduced. Second, sustainable development and the role of a CE is described. Next, the general design and material composition of WTB is described. Subsequently, the circular strategies model is introduced and the EoL treatment of WTB under each of the circular strategies is described. Finally, the EoL management of WTB is outlined.

2.1 THE FIELD OF INDUSTRIAL ECOLOGY

The scientific field of IE, emergent since the 1990s, is concerned with the flows of materials and energy through society. It is an interdisciplinary research field which combines an engineering, environmental and social science perspective. It is precisely this interdisciplinary approach that is required to achieve sustainable development.

While the term IE may sound like an internal antithesis, the idea behind it is that industrial processes become inspired by natural processes. In nature, we observe closed-loop cycles whereby the waste of one ecosystem is a valuable product for another ecosystem. This can be translated to industrial processes, where the by-products and/or waste streams of one process become the useful feedstock for another process, thereby achieving industrial symbiosis. As such, material and energy streams are optimised and used as efficiently as possible. In this way, the use of virgin resources and the output of potentially harmful wastes to the environment is reduced. This idea has been dubbed the *biological analogy* of IE. (Lifset and Graedel, 2002). While there are limits to this concept due to the fact that our economic system does not function the same as a natural ecosystem (Ayres, 2004), it is nevertheless valuable to allow our technosphere to be inspired by the biosphere as much as possible.

A central element of the field of IE is the application of a system-wide perspective. This avoids the chance of disregarding important elements that may lead to unintentional effects (Lifset and Graedel, 2002). An example of this is a problem shift: solving one aspect of a sustainability issue may lead to inadvertent consequences elsewhere, and if a too narrow perspective is taken, such unwanted effects may manifest undetected. Furthermore, a system-wide perspective implies the consideration of the full supply chain of a product or process: the sourcing of the materials, the manufacture of the product, use of the product, and final treatment of the product and its constituent materials when it reaches EoL. This allows for full consideration of the environmental impacts.

2.2 CIRCULAR ECONOMY IN THE WIDER SUSTAINABILITY CONTEXT

Sustainable development was defined in 1987 by the Brundlandt Commission as the ability to "meet the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 1987, p. 15). To do so, the three pillars of sustainability - social, economic and environment - must develop in harmony (Purvis et al., 2019), visualised in Figure 2.1. This concept has been translated to business purposes as the Triple Bottom Line (TBL) of people, profit and planet, as introduced by John Elkington in 1994 (Purvis et al., 2019). Unfortunately, the general trend thus far has been such that economic or social development has gone hand in hand with growing environmental pressures (United Nations, nd). To encourage sustainable development, the UN adopted the SDG in 2015. This set of 17 goals to be achieved by 2030 span the elements of the TBL.

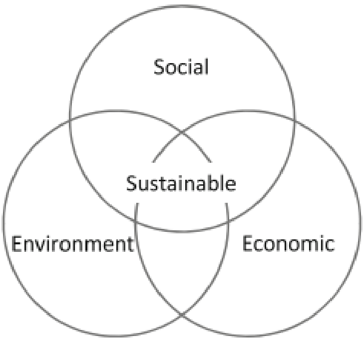


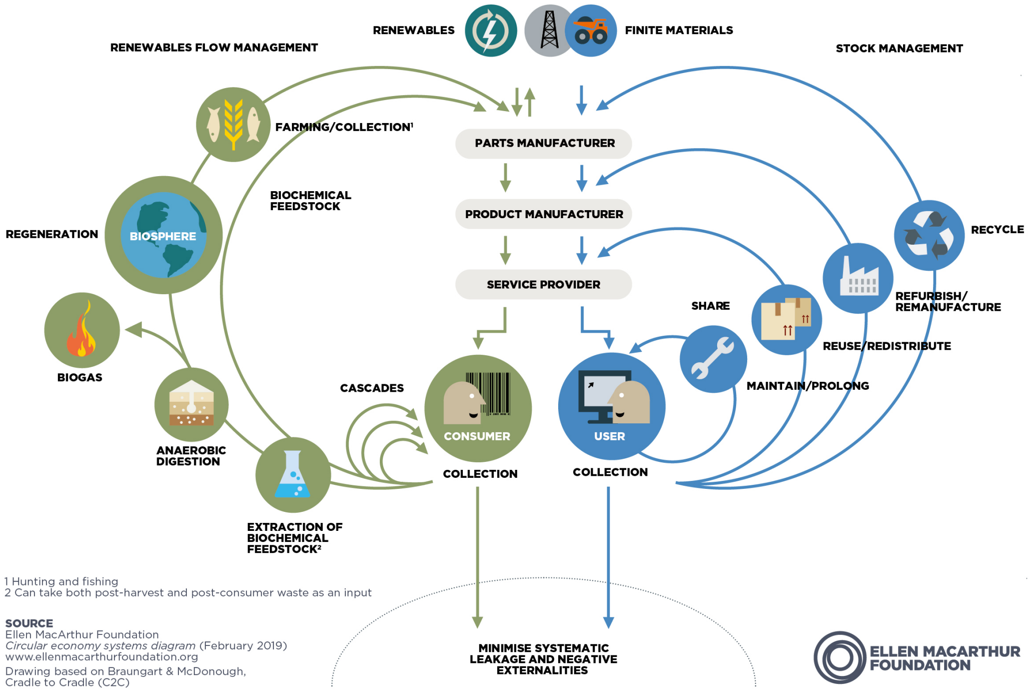
Figure 2.1: Three pillars of sustainability (Purvis et al., 2019, p. 682)

Economic development must thus exist in balance with social and environmental development. At present, mankind's annual use of natural resources and generation of waste actually requires 1.7 Earths (Global Footprint Network, 2021). The day where humanity has used a single Earth's resources for a year has been named *Earth Overshoot Day*, and since 1970 this day has become earlier and earlier. Today it is around the end of July (Global Footprint Network, 2021). This is clearly in contrast with the Brundlandt definition of sustainable development - and clearly does not offer a viable long-term perspective.

Enter the circular economy. CE aims to efficiently use Earth's natural resources and to decouple economic growth from environmental degradation. It aims to achieve clean production processes, which is done by adopting renewable materials and technologies (Ghisellini et al., 2016). This is connected to goal 12 of the UN SDG: *responsible consumption and production*. The Ellen MacArthur Foundation (Ellen MacArthur Foundation, nd) defines three principles that the CE is based on:

1. The eradication of waste and pollution;
2. Long-lasting use of products and materials;
3. The reproduction of natural systems (related to the biological analogy of IE).

In a CE, material cycles are closed. That is to say that 'waste' in the traditional sense of the word no longer exists - or at least to a minimal amount. This is illustrated in Figure 2.2. By closing material cycles and making efficient use of natural resources, a number of desired effects can be accomplished. Firstly, a reduction in raw material use and therefore a reduction in emissions and other environmental impacts related to mining of materials. Secondly, a reduction in waste generation and therefore a reduction in emissions related to waste treatment. And thirdly, a reduction in emissions from the production of raw materials since secondary materials are reused. Through the adoption of a CE, sustainable development as defined above may be achieved.



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

SOURCE
Ellen MacArthur Foundation
Circular economy systems diagram (February 2019)
www.ellenmacarthurfoundation.org
Drawing based on Braungart & McDonough,
Cradle to Cradle (C2C)

Figure 2.2: Circular Economy systems diagram (Ellen MacArthur Foundation, 2019)

Apart from closing material cycles, a CE is built on the application of renewable energy sources. Such energy sources are based on natural resources that are continually restocked after being used (IEA, 2002), as opposed to fossil-based ones for which the feedstock (on a human timescale) is finite and GHG emissions are significant. One such source is wind energy. Wind power emits significantly less carbon dioxide during its lifetime per kWh of generated electricity than traditional systems; between 9-38 g CO_2/kWh, versus 786-990 g CO_2/kWh for coal and 488 g CO_2/kWh for natural gas (Ortegon et al., 2013). It should be noted that these figures are based on analysis that disregards the EoL phase of a wind turbine and its components. Precisely this EoL analysis has often been neglected for wind turbines, even though closing material cycles and using materials responsibly is a critical element in sustainable development - as this Section has illustrated. Hence it is crucial that more focus be directed towards this field.

The crucial role of the CE in achieving a sustainable society and reducing GHG emissions has become a widespread realisation. This is reflected in the UN SDG, but also in the EU's Green Deal where one of three pillars is achieving economic growth without the depletion of Earth's resources (European Commission, nd). Furthermore, countries have set their individual circularity targets: for instance, the Netherlands aims to have a fully CE by 2050.

The interface between the CE and the research field of IE is indisputable. As mentioned, IE is concerned with the flows of materials and energy through society, with the aim to better understand these flows and as such, be able to reduce their environmental impact. Such reduction can be achieved by aiming for closed-loop systems that mimic natural, cyclic processes. Hence, IE generates the knowledge required for the implementation of a CE.

2.3 WIND TURBINE BLADE DESIGN AND MATERIALS

A wind turbine consists of several components, as can be seen in Figure 2.3.

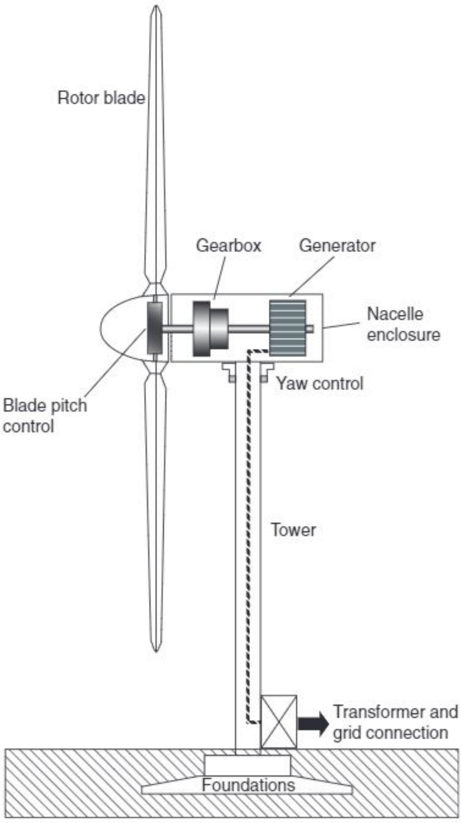


Figure 2.3: Wind turbine components (Papadakis et al., 2010, p. 445)

The rotor blades of a wind turbine deserve special attention as they are the most challenging component in terms of EoL treatment and the most costly (Mishnaevsky et al., 2017). The blades are constructed using fibres - most often glass - and thermosets, which together form a fibre-reinforced composite material (Mishnaevsky et al., 2017). Thermosets are polymers that, once heated, become impossible to dissolve and melt, and this reaction is irreversible (Ratna, 2009). This extreme hardening makes it so appealing to use as adhesive. In total, around two-thirds of the blade is made up of the fibre-reinforced polymers (Papadakis et al., 2010). The glass fibre (GF) are very attractive as they have high strength and high stiffness (Beauson and Brøndsted, 2016), which makes them very suitable to withstand strong wind speeds.

In general, the blade is made up of several different elements as shown in Figure 2.4. The spar cap has as function to introduce stiffness in the spanwise direction, i.e. over the length of the blade, to avoid collision with the tower. The spar cap is mostly made up of glass fibre reinforced polymer (GFRP). With a growth in blade size, the spar cap may be reinforced with carbon fibre reinforced polymer (CFRP) as carbon fibre (CF) has an even higher stiffness and lower weight than GF (Beauson and Brøndsted, 2016). The shear webs link the two sides of the blade and also add stiffness (Mishnaevsky et al., 2017). The shell of the blade and the shear webs are made up of a sandwich structure with balsa or foam at the core and GFRP surrounding it (Beauson and Brøndsted, 2016). The two sides of the blade and the individual elements are connected using adhesives.

While this general material composition holds, blades of different sizes, turbine types and manufacturers do vary in their exact material composition, hence it is important to know what materials are inside each blade and how to manage this

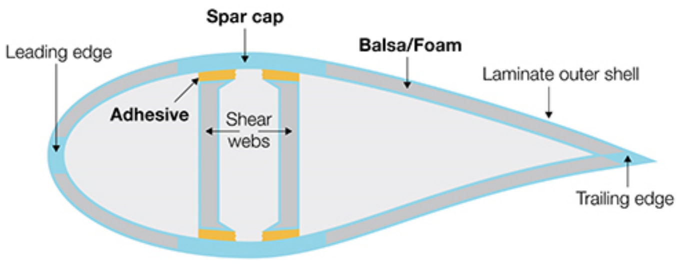


Figure 2.4: Cross-section of a wind turbine blade (Olympus, nd)

diversity of materials (Lefeuvre et al., 2019). With the growth of the wind power sector, the use of composites grows also. In fact, the wind power sector is one the quickest growing consumers of these fibre-reinforced composites (Psomopoulos et al., 2019).

Adding to the challenge of complex blade structure is the fact the WTB are growing in size in order to generate more electricity (Enevoldsen and Xydis, 2019). In the last decades, a strong growth in rotor diameter, i.e. blade size, has been observed, and this is still increasing (Enevoldsen and Xydis, 2019). This can be seen in Figure 2.5. As mentioned, the growth in blade size means a growth in the use of CF. This therefore means that analysis of the current design of blades is required, as well as consideration of developments in design until 2030. This is covered in more detail in Section 4.2.1.4.

Further information on turbine manufacturers, material composition, size and mass of the blades is offered in Sections 4.2.1.3, 4.2.1.4, 4.2.1.5 and 4.2.1.6, respectively.

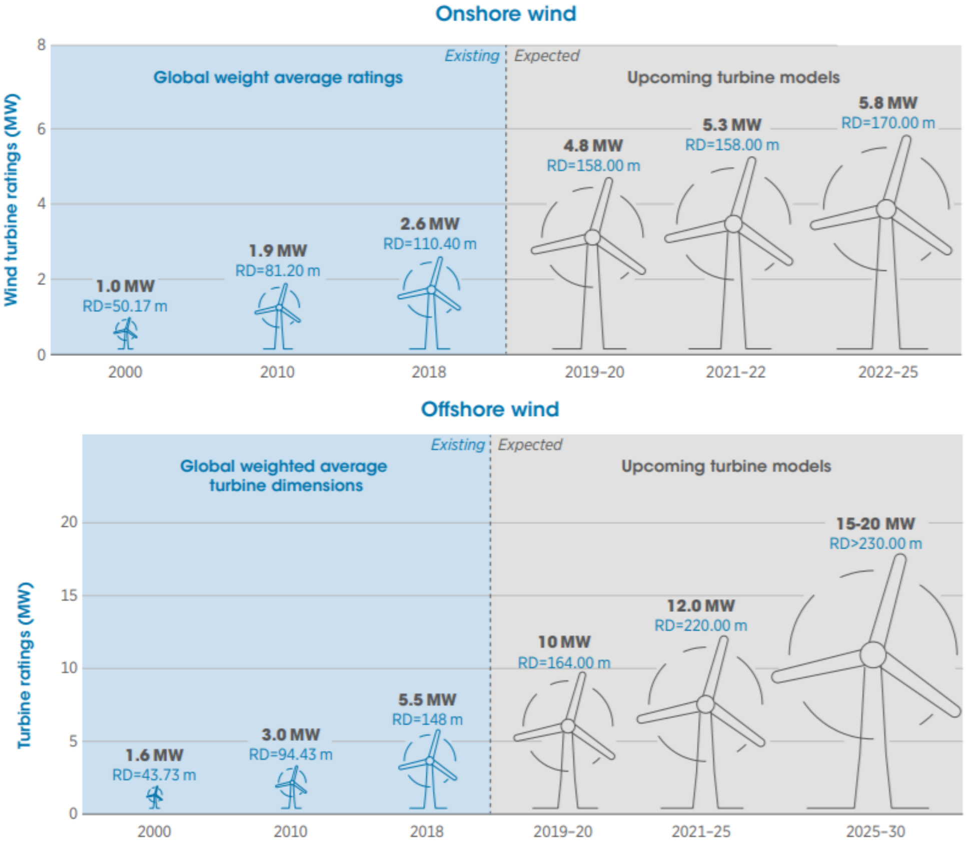


Figure 2.5: Rated power and rotor diameter (RD) of wind turbines over time (IRENA, 2019, p. 40, 56)

2.3.1 Environmental impact of wind turbine blades

Environmental impact can be measured in a multitude of ways. Common impact categories include Global Warming Potential (GWP) and the carbon footprint. Other impact categories may include water use, land use change, acidification and eutrophication, to name a few examples. With a lack of complete data, this research focuses on the energy intensity of the blade materials in MJ per kg to approach the environmental impact of the blade. Energy intensity is used as a proxy for carbon footprint[1]; namely, the higher the energy intensity, the more CO_2 is emitted. As the energy mix transitions to a higher share of renewable sources, this assumption should be reconsidered.

As has been illustrated, WTB mainly consist of GF and resin (the thermoset polymers). A common resin used is epoxy. Neither glass - made from sand, soda ash, and limestone - nor epoxy are critical materials. Therefore, material recovery is not integral from a perspective of material criticality or scarcity; however, producing the individual materials and the blade as a whole goes paired with significant energy costs which are important to consider.

Even though the use of CF is required to limit the weight of the blade for larger blade sizes, and therefore yields lighter blades than fully GF ones, the environmental impact of blades with CF is more significant due to a much higher energy intensity and carbon footprint of CF (Liu and Barlow, 2016). For common blade materials, the energy intensity of production for polyester is 63-78 MJ/kg; for epoxy 76-80 MJ/kg; for GF 13-32 MJ/kg; and for CF 183-286 MJ/kg (Olivieux et al., 2015). Producing new CF is also 18 times as energy intensive as producing recycled CF (Cherrington et al., 2012).

Comparison of two blades, of which one is made entirely from GF and the other is reinforced with CF, shows that the blade made from only GF has a lower energy consumption and lower carbon emissions. In fact, the hybrid blade has 50% higher energy consumption and 60% higher carbon emissions (Liu and Barlow, 2016), even though their blades are almost the same size. This is illustrated by Table 2.1. Almost all (96%) of the energy consumption can be attributed to the manufacturing stage; the remainder is split equally between transport and operations & maintenance (O&M) (Liu and Barlow, 2016).[2]

	GF blade	Hybrid GF-CF blade
Turbine capacity [MW]	1.5	2.0
Blade length [m]	45.2	45.3
Energy consumption [GJ]	795.0	1194.0
CO_2 emissions [ton]	42.1	67.7

Table 2.1: Environmental impact of blade manufacturing for two types of blade (Liu and Barlow, 2016; Liu et al., 2019)

2.4 CIRCULAR STRATEGIES APPLIED TO END-OF-LIFE WIND TURBINE BLADES

When a WTB reaches the end of its operational lifetime, it needs to be treated accordingly. In the CE, a number of circular strategy possibilities are offered. These are in part shown in Figure 2.2, but a more elaborate overview is illustrated by Figure 2.6, where the circular ladder is related to the waste hierarchy framework. This ladder demonstrates the most to least preferred options for waste handling in a CE, from top to bottom. It generally holds that the higher up the ladder, the more

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[1] This can be defined as the amount of CO_2 emissions resultant from a certain activity

[2] This comparison disregards the environmental impact resultant from EoL treatment

circular a strategy is; and the lower down the ladder, the more energy is required for the process, the more costly it is, and - in the case of WTB - the less valuable the secondary material is.

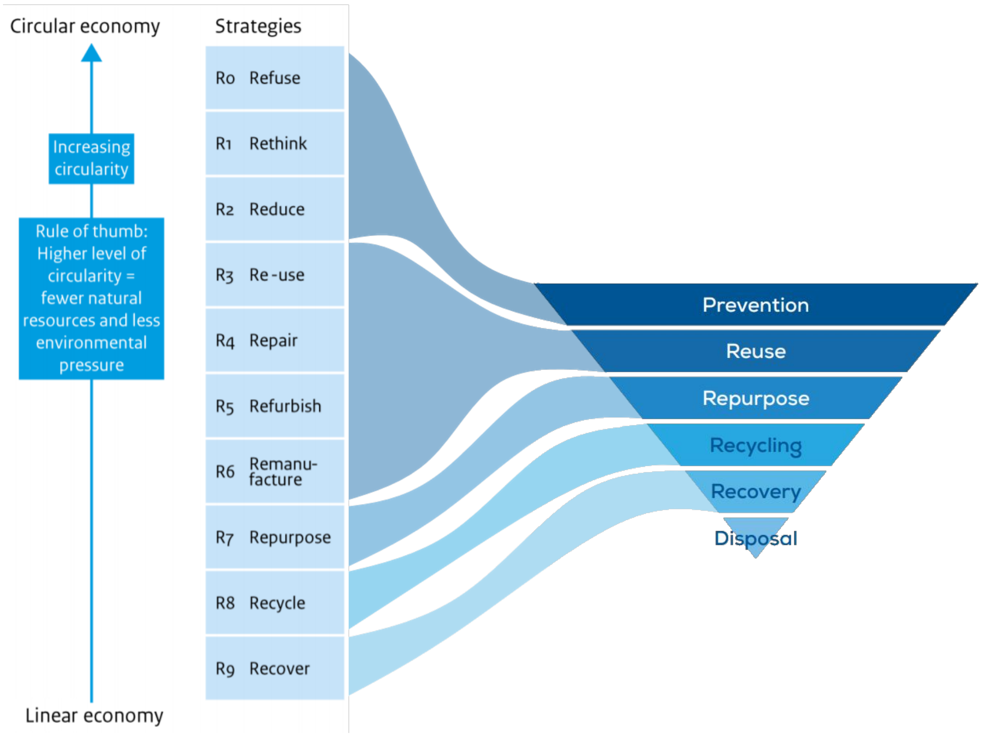

Figure 2.6: Circular strategies model (Potting et al., 2017, p. 19; Schmid et al., 2020, p. 20, edited by the author)

The top three categories - refuse, rethink and reduce - are grouped under *prevention* and are concerned with decreasing the volume of waste and/or the (harmful) substances in it (Gharfalkar et al., 2015). Reuse, repair, refurbish and remanufacture are concerned with returning the product to its original specifications and using it again for the same purpose. Repurpose, on the other hand, lends the product to a new destination. Recycling and recovery refer to the recovery of individual materials and energy. Finally, disposal and incineration are not included in the model as these are not considered *circular* strategies. In reality, though, these are still commonly practiced.

What makes application of the circular strategies challenging has to do with the properties of the WTB waste flow: the design and exact construction of the blade is different per manufacturer; each EoL blade is found in a different condition regarding quality; and the amount of material varies each time, as sometimes it is a single turbine that must be decommissioned, and other times an entire wind farm – which are also all different in size (Beauson and Brøndsted, 2016; Mishnaevsky et al., 2017). This makes for a heterogeneous waste flow. Another difficulty is that the information on material composition and build of the blades is not readily available at the required level of detail to the receiving party (Zotz et al., 2019).

Naturally, the application of the circular strategies strategies also require resources in the form of materials and energy. It is only viable to adopt these strategies if their application results in a lower environmental impact than the baseline, i.e. raw materials production and waste treatment through incineration and landfill. To determine this, the energy intensity and associated environmental impacts (including but not limited to GHG emissions) of the circular strategies and the baseline must be quantified and compared. The sections below elaborate on each of the outlined circular strategies.

2.4.1 Prevention

Prevention means decreasing the volume of waste and/or the (harmful) substances in it (Gharfalkar et al., 2015). There are a number of developments in this category, particularly regarding the replacement of the complex thermoset composites. There are advancements in the development of degradable thermosets (Post et al., 2020), as well as in the development of recyclable epoxy (Wu et al., 2019). Another option is the use of natural fibre composites (Chen et al., 2019). All of these developments are still at laboratory-scale and have yet to overcome various limitations before exploitation at industrial scale is possible.

A more developed option is replacing the thermosets with thermoplastics. In contrast to thermosets, thermoplastics can be molten and reshaped (PlasticsEurope, 2020), which would facilitate EoL treatment. First results have shown that the thermoplastic composites score higher than the thermosets regarding strength, environmental impact, and lifetime of the blades (Forsythe et al., 2014). However, this research assumes that thermoplastic blades will only be produced on a significant scale from 2030 onwards, and as such, will not be taken into account in the analysis. Background information and argumentation for this are offered in Appendix A.1.

Reducing the amount of waste can additionally be accomplished by extending the lifetime of the wind turbine. For this, new procedures and data management systems would need to be developed in order to properly keep track of aspects such as site conditions, operational history, as well as design data of the wind turbines (Ziegler et al., 2018). Furthermore, the appeal of lifetime extension is highly dependent on the (un)availability of subsidies or other incentives to develop a new wind farm (Ziegler et al., 2018).

2.4.2 Reuse

Reusing the waste item concerns handling it in such a way that it can be used again for the same purpose (Gharfalkar et al., 2015). This can be difficult for WTB as the industry is growing at such a fast pace (van der Meulen et al., 2020a; Ortegon et al., 2013). Figure 2.5 illustrates the development of the rotor diameter of wind turbines over time, which indicates the difficulty of reusing a WTB after some 20 years at the same location.

Nevertheless, reusing the blades can be an appealing option for less mature markets. Apparently 'spent' wind turbines with capacities that are no longer interesting for a mature market may be exported to a country where wind energy is just beginning (Cooperman et al., 2021; Marsh, 2017). This is for instance happening at Dutch wind farm Oosterscheldekering, where a number of well-functioning turbines will be replaced with larger models, hence they will be exported to Tuscany, Italy, where they can operate for another fifteen years (Balkenende, 2021). There are a number of companies active in selling used wind turbines or their components, such as Business in Wind, Reusable Parts and Spares in Motion. Naturally, the quality of the blades must first be ascertained in order to determine whether they are fit to serve a second lifetime. Inevitably, the turbines must at some point be dismantled and treated at EoL. If they have been reinstalled in a secondary market where much less stringent environmental regulations are in place, this may result in a problem shift (Wehrmann, 2021). This aspect must be considered and properly handled.

Another challenge for reusing the blades is the fact that, although there is a general consensus on design and material composition of the blades, these do differ per manufacturer and per location (van der Meulen et al., 2020b). This hinders the possibility to exchange components between manufacturers (van der Meulen et al., 2020b). For this reason, reusing individual blades is not likely to happen on a large scale; rather, reusing the turbine in its entirety.

2.4.3 Repurpose

Repurposing the waste item means using it in its existing form for a new purpose or application (Jensen and Skelton, 2018; ETIPWind, 2019). This has been achieved in numerous ways. EoL blades have for instance been used in playgrounds, as outside benches (Beauson and Brøndsted, 2016), as a bike shed or bridge (Schmid et al., 2020), or as a bus stop (Belton, 2020). It should be noted that these are generally small-scale demonstration projects which do not offer a complete solution for the vast volume of expected WTB waste in the future.

In that regard, Joustra et al. (2021b) investigated the potential to cut the WTB into structural elements such as beams and panels that can be used in a wide range of applications. Their research shows that these elements perform very well in terms of stiffness and strength compared to traditional materials such as steel, aluminium and wood (Joustra et al., 2021b). The advantage of this is that, compared to recycling the blades, much more of the material quality is preserved with much less required effort (Joustra et al., 2021b). One blade may offer many metres and tonnes of material that can be used for repurposing; it is imperative to find markets that can absorb this such that scalability can take place. A balance must be found between the supply, processing capacity and market demand (personal communications with Jelle Joustra).

2.4.4 Recycling and recovery

Recycling means using the waste material in a new application (Jensen and Skelton, 2018), thereby (partially) replacing virgin materials. Recycling and recovery are combined in this section; for a critical reflection of these concepts and their definition, the reader is referred to Appendix A.2. There are currently three main recycling techniques (Beauson et al., 2014; Chen et al., 2019):

1. Mechanical: shredding, grinding
2. Thermal: pyrolysis, fluidised bed
3. Chemical: solvolysis

The different recycling techniques can be divided based on the level of material reclaim, as shown in Figure 2.7. The grey-coloured techniques (microwave assisted pyrolysis, fluidised bed, solvolysis) currently do not have a high enough Technology Readiness Level (TRL)[3] to be viable on an industrial scale. Mechanical recycling and co-processing in cement kiln are applicable to GFRP, while the other techniques are applicable to CFRP. Although pyrolysis may be applied to both, it is most advanced and cost-effective for CFRP. Mechanical grinding and cement co-processing have the lowest process costs of all available techniques. (ETIPWind, 2019). Still, due to the variability in material composition and build of the blades, the recycling costs will vary (van der Meulen et al., 2020b).

An inspiring recent development from September 2021 is Siemens Gamesa Renewable Energy (SGRE)'s launch of a fully recyclable blade, which will already be installed in 2022 at a German offshore wind farm as first pilot installation (SGRE, 2021). The news of this development arrived too late for inclusion in this research, but it is a development that deserves appreciation and also illustrates how quickly certain changes may arise in this environment.

This research only focuses on mechanical grinding as recycling technique. At present, mechanical recycling is the most commercially feasible recycling method

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[3] To determine how advanced and practicable the strategies are, the TRL indicator offers insight. The levels are divided into nine stages, in a hierarchical order. Stages 1-3 are concerned mainly with development of the initial idea; stages 4-5 with development of a prototype; stages 6-7 with validating the prototype; and stages 8-9 with actual production. Stage 9 is the most advanced and means the technology is ready for full commercial application. (European Commission, 2014)

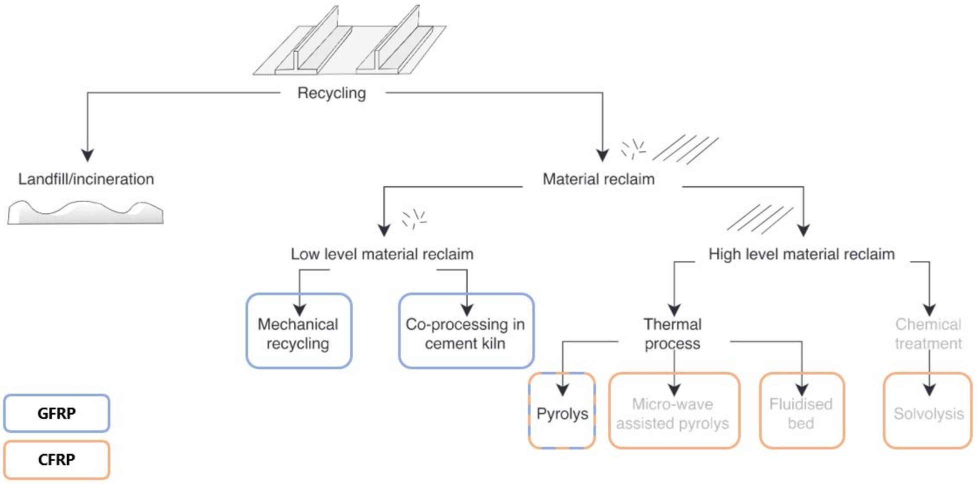

Figure 2.7: Recycling strategies for fibre-reinforced composite materials (Hagnell and Åkermo, 2019, p. 960, edited by the author). The techniques in grey text currently do not have a high enough TRL

for GF (Bax & Company, 2019; Rybicka et al., 2016). For CF, this is pyrolysis (Bax & Company, 2019). Research by Rybicka et al. (2016) indicates that thermal and chemical recycling often go paired with a form of mechanical recycling as a first step in order to reduce the size of the material. This is the case for GF as well as CF. Thus, even though mechanical recycling is not the optimal recycling technique for CF, it is still applied. Furthermore, CF is only used in larger blades and even then, only to a limited extent (further details on this can be found in Section 4.2.1.4), hence GF still plays the largest role. Additionally, in terms of environmental impact, Liu et al. (2019) state that mechanical recycling is currently the most recommended technique for both GF and hybrid GF-CF blades. In the future this may shift to chemical recycling as this technique undergoes further development.

2.4.5 Disposal

The final option for waste treatment is disposal, which means landfilling or incinerating the EoL blades with no energy or material recovery (ETIPWind, 2019). Whilst landfilling of composites is officially forbidden in the Netherlands, an exception is made if the cost of waste treatment exceeds €200/tonne, which is the case for mechanical recycling (Schmid et al., 2020). Thus, landfilling does still happen in practice (Schmid et al., 2020). In the UK, 98% of the composite waste is being landfilled at EoL (Sultan et al., 2018).

Incineration is far from ideal since it means a complete loss of material quality and additionally, 60% of the material remains as ash (Bax & Company, 2019). However, under current costs of more circular treatment options, landfill and incineration will remain appealing choices from an economic perspective without proper regulation (Dong et al., 2018). Compared to incineration, landfilling does not go paired with harmful emissions or ash generation, and there is no material destruction. Therefore, between these two options, landfill may be argued to be the preferred choice, as then the blades are stored for a time until better treatment options become available.

2.4.6 Selection for this research

From the five clusters of circular strategies, prevention is more concerned with to-be built blades and the developments in this category are not expected to play a significant role in blade manufacturing before 2030. Therefore, this strategy will not be further analysed in this research. Disposal, i.e. landfill and incineration, is not actually considered part of the CE, hence these treatment options will not be further analysed in this research. The remaining strategies - reusing, repurposing and recycling (only mechanical) the blades - will each be described in Section 4.3.1 in terms of their opportunities, limitations, requirements for market development, potential market size, and monetary value of the secondary material. In Section 4.3.2, their environmental impact is discussed and compared.

2.5 REVERSE LOGISTICS OF WIND TURBINE BLADES

RL is the process of moving a good from its location of use backwards through the supply chain for EoL treatment. This therefore includes decommissioning and the application of the circular strategies mentioned above in Section 2.4.

The decommissioning phase of wind turbines is a relatively new area of focus. In LCA of wind turbines, the decommissioning phase has often been neglected (Andersen et al., 2014; Ortegon et al., 2013; Sakellariou, 2018). Similarly, hardly any studies of waste WTB have analysed the RL aspect of the waste stream (Rentizelas et al., 2021).

Decommissioning faces a number of challenges. Firstly, there is at present little commercial use-case for the EoL blades. Secondly, RL of such large structures, in increasing volumes, is a challenge (Ortegon et al., 2013; Sakellariou, 2018). Part of the solution could be incorporating recycling/recovery and other circular economy principles into the design of the blade (Sakellariou, 2018; Invernizzi et al., 2020). This, however, requires a mentality shift away from purely economic goals (van der Meulen et al., 2020a), which is not swiftly done. Another solution might be moving towards continued blade ownership of the manufacturer (Sakellariou, 2018), which could help lower costs of the decommissioning phase (van der Meulen et al., 2020a).

An additional difficulty for the decommissioning phase is that it is still relatively new territory, especially for offshore wind farms. There is a lack of experience and know-how of how best to approach the EoL phase, and the experience that has been acquired was on small-scale projects (van der Meulen et al., 2020b). At present, there are no EU-wide regulations to aid this (van der Meulen et al., 2020a; Zotz et al., 2019). WindEurope has recently published an industry guiding document to aid the development of a European standard for the decommissioning of wind turbines, however this is a first step and is not very specific yet (O'Sullivan, 2020).

The underestimation of total decommissioning costs is a recurring challenge. This is partly due to the fact that initially, the decommissioning costs are divided by the 20+ year operational lifetime of the turbine, thereby appearing much smaller than they ultimately are (Topham and McMillan, 2017). Moreover, the decommissioning phase demands long-term planning and it inherently goes paired with cost uncertainties, which means that developers do not know how much money they should set aside (van der Meulen et al., 2020a). In the Netherlands, specifically, a bank guarantee of 120,000 €/MW must be submitted by the wind park operator for decommissioning, however the total costs for decommissioning are expected to be much higher than this (van der Meulen et al., 2020b). Furthermore, the cost of decommissioning is still higher than the possible financial gains that can be made from it (Bulder and van Roerund, 2016; Sakellariou, 2018), rendering it unattractive for the responsible party. More extensive and detailed planning of the decommissioning phase could help overcome this (Topham and McMillan, 2017), as well as matching the decommissioning phase to when the scrap metal prices are highest (Topham et al., 2019).

After decommissioning, the WTB must undergo treatment. The possibilities for this have been described in Section 2.4. What is important for any of the EoL strategies is gaining a better idea of how much material will become available over the years.

A number of studies have been completed to predict future waste flows of WTB. Many of these take a global view where a few main regions are studied, such as China, Europe, the US and the rest of the world (Liu and Barlow, 2015, 2017; Albers et al., 2009; Lefeuvre et al., 2019). This gives a good global overview, yet misses country-specific information. Lichtenegger et al. (2020) address this by performing the first Europe-wide study where European countries are studied separately. While it is interesting to draw comparisons between countries, it is still quite a large scope and thus misses specific information per country regarding where exactly the waste is coming from.

A number of country-specific studies have been performed. For instance on Germany (Albers et al., 2009; Zimmermann et al., 2013), Sweden (Andersen et al., 2016), the USA (Cooperman et al., 2021), the UK (Sultan et al., 2018; Tota-Maharaj and McMahon, 2020), Denmark (Cao et al., 2019), and the Netherlands (Roelofs, 2020). A recent study by van der Meulen et al. (2020b) predicted the material flows from EoL wind turbines from 2020 to 2050 in the North Sea, but only for offshore wind. They estimate a steadily increasing annual material flow of composites that reaches between 40 to 50 kilotonnes in 2050 for this area (van der Meulen et al., 2020b).

Roelofs (2020) found that the volume of composite waste from EoL blades from solely the Netherlands is currently not sufficient for the minimum required throughput for a viable recycling plant; thus interregional collaboration will be necessary. Furthermore, interregional collaboration in the EU will aid the development of a harmonised regulatory framework, which is currently missing (Sommer and Walther, 2021). Another option to reach minimum required volumes may be cross-sectoral collaboration, for instance with the automotive or aviation sector, but a drawback thereof is that it would create an even less homogeneous waste flow which would further encumber recycling (Roelofs, 2020).

Thus, interregional collaboration helps to reach higher throughput volumes and improve the economic viability of treatment facilities. In this regard, the creation of a central circular hub has been identified as an important development (Lobregt et al., 2021). The question remains which location would be most suitable for such a hub. This aspect is further elaborated in Section 4.1. This also means that apart from the quantification of future material flows, another key aspect is their localisation, as this information is required in order to determine where treatment facilities should be placed, or which ones should be expanded (Andersen et al., 2016). With the exception of the study by Sultan et al. (2018) of the UK, all of the country-specific studies omit the geographical data of the wind farms. Therefore, a regional synthesis of the volume of waste flows in the defined area of this research for the coming decades and their localisation must be completed. More information on this is offered in Section 4.2.

3 METHODS AND DATA

This research is a combination of a quantitative and a qualitative research approach. The quantitative approach makes use of a dynamic Material Flow Analysis (dMFA) combined with a Geographical Information System (GIS) analysis, and further evaluation of the results is done in Microsoft Excel. An overview of the system demarcation and modelling assumptions can be found in Appendix B. The qualitative research covers desk research, semi-structured interviews and expert communication which yield additional and more in-depth information. These are required for the port consideration, model parameter definitions and evaluation of the circular strategies.

The research questions from Section 1.4 indicate that the research consists of three main components. The first component concerns the potential development of a circular wind hub, consisting of the conducting of interviews, desk research and GIS analysis; the second component is the quantification and localisation of EoL WTB, consisting of the dMFA, desk research and expert communication; the third component is analysis of the EoL WTB under different circular strategies, which is also done by GIS analysis, desk research and personal communication with experts. In the following sections, the research methods will be described in more detail and their data requirements are outlined, as well as how missing data or data issues are dealt with.

3.1 MATERIAL FLOW ANALYSIS

A Material Flow Analysis (MFA) is a method whereby a system-wide view is taken to track a material throughout its lifecycle (Allesch and Brunner, 2017). The fundamental principle of an MFA is the mass balance, i.e. all mass that enters the system must also leave it or remain inside it as stocks. It therefore offers a complete overview of the processes the material experiences, where it goes and where it stays, and additionally allows for analysis of the interaction between such processes and the environment (Allesch and Brunner, 2017). A generic overview of an MFA is illustrated by Figure 3.1.

A dMFA provides yet a deeper dimension by allowing for past, present and future analysis of the material flows (Müller et al., 2014). This offers insight in the material stocks as the material is in use or hibernating (that is to say, taken out of use but not yet having entered the waste stream; the outflow) (Graedel, 2019). Furthermore, scenarios can be implemented in the model in order to examine the impact of different policy approaches on the entire system (Allesch and Brunner, 2017). This makes dMFA a powerful tool to design effective policy measures or improve existing ones. While this is outside the scope of this research, it offers interesting opportunities for further research.

Limitations of a (dynamic) Material Flow Analysis ((d)MFA) include the lack of social and economic factors in the model (Allesch and Brunner, 2017), which are important ones to consider for ultimate policy recommendations. This study approaches this limitation by including economic considerations in the further analysis of the results, where these are placed in the context of different circular strategies. Other limitations of a (d)MFA are uncertainties in the data used or missing data (Allesch and Brunner, 2015). Nevertheless, despite data uncertainties and varying

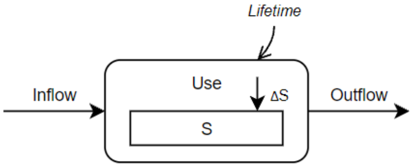

Figure 3.1: System overview of a generic dMFA, after Müller et al. (2014)

data quality, a (d)MFA remains a strong tool for assisting in policy discussions due to its potential to effectively communicate general material trends (Graedel, 2019). Therefore, it is still a valuable tool as input for policy makers (Graedel, 2019).

In addition, it is imperative that the boundaries of the (d)MFA system are clearly defined, since these will strongly determine the results of the study (Allesch and Brunner, 2015). In the case of a good or product being analysed rather than a specific substance, Allesch and Brunner (2015) advise to also track the key substances in the good, for instance hazardous materials. For EoL WTB it is therefore important to consider the various materials that make up the blade.

In general terms, a dMFA model can be described according to equations 3.1 and 3.2. The in-use stock at a time t is dependent on the difference between the inflow and outflow of material at that time, as well as the level of stock at initial time 0 (equation 3.1).

$$S_t = \sum_{T_0}^{T}(F_{in}(t) - F_{out}(t)) + S_0 \tag{3.1}$$

This dMFA is a delay model, that is to say that outflows are dependent on prior inflows and a certain lifetime, *L(t)* (equation 3.2).

$$F_{out}(t) = F_{in}(t - L(t)) \tag{3.2}$$

There are different ways to model the lifetime distribution. This research adopts a Normal distribution (equation 3.3). More information on this choice of distribution and the definition of the parameters can be found in Section 4.2.1.7.

$$f(x;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(\frac{1}{2}(\frac{x-\mu}{\sigma})^2)} \tag{3.3}$$

Summarised, the parameters in the above equations are:

S_t	stock at time t
S_0	stock at time 0
$F_{in}(t)$	inflow at time t
$F_{out}(t)$	outflow at time t
L(t)	lifetime
μ	mean of Normal distribution
σ	standard deviation of Normal distribution
e	Euler's number

The dMFA can be inflow-driven or stock-driven. In an inflow-driven dMFA, the stocks and outflows are determined based on given inflows and a lifetime distribution; in a stock-driven dMFA, the inflows and outflows are determined based on given stocks and a lifetime distribution (Müller et al., 2014). This research is primarily an inflow-driven dMFA. However, the future scenarios for onshore wind development are given as stocks. Therefore, the historic inflows are first converted to stocks, and subsequently the total stocks are converted back into inflows. More information on this can be found in Appendix C.

The dMFA is executed in Python, using the dynamic stock model (DSM) as developed by Pauliuk (nd). The advantage of using Python as opposed to other software is its suitability to process large datasets, as well as the fact that it is open-source. The system boundaries of this dMFA are illustrated in Figure 3.2, where the dotted line indicates the boundaries of the dMFA model. While the output of the dMFA, namely the material outflows, are input for the subsequent analysis of EoL strategies (part three of this research), this is not part of the dMFA model itself. It is assumed that there is no material leaching or hibernating stock in the model.

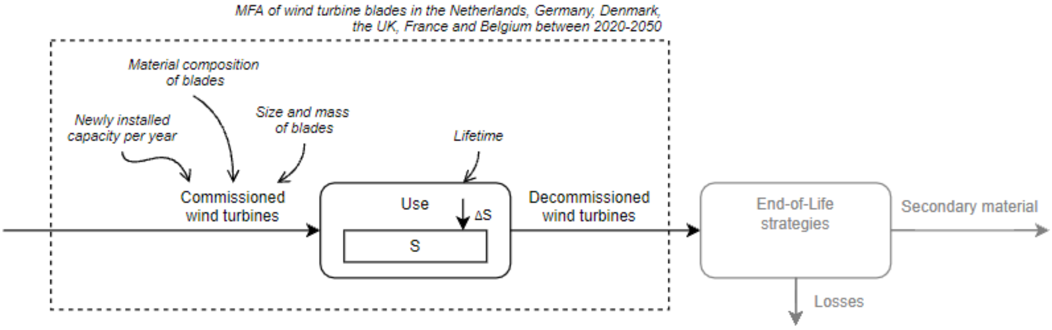

Figure 3.2: System boundaries of the dMFA in this research

3.2 GEOGRAPHIC INFORMATION SYSTEM

A GIS is an effective way to handle spatial data (Huisman and de By, 2009). Through GIS mapping, it is possible to visualise and analyse which locations the EoL material will come from. In order to ascertain which Dutch port is most centrally located, the GIS will be used for network analysis. The ports under consideration are Port of Amsterdam (PoA), Port of Rotterdam (PoR), Port of Den Helder (PoDH), Groningen Seaports (GSP) and North Sea Port (NSP), illustrated in Figure 3.3. These are five large seaports spread along the Dutch coastline.

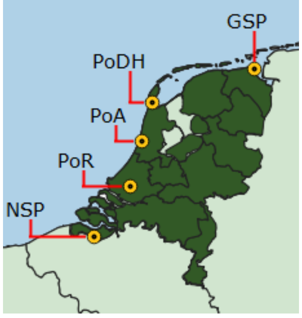

Figure 3.3: Locations of ports in the analysis

Network analysis is commonly applied to questions of logistics and lends itself well to incorporate characteristics such as transport distance and costs (Huisman and de By, 2009). One metric of network analysis is closeness centrality: by calculating each port's closeness centrality, the Dutch ports included in the research can be compared based on how they central they are to the to-be decommissioned wind farms. This facilitates decision-making on where to develop potential recycling plants. The analysis is done using QGIS, an open-source geo-processing software. Further analysis of the effects of the circular strategies is completed in Microsoft Excel.

Closeness centrality is measured as the inverse of the sum of the distances between the ports and the wind farms. With $d(x, y)$ as the distance between the ports, x, and the wind farms, y, the closeness of each port is calculated as:

$$C(x) = \frac{1}{\sum_y d(x,y)} \tag{3.4}$$

This calculation is enhanced by introducing a weight to each wind farm according to its size, i.e. the amount of material that it would bring to the port. While it is desired to minimise the distance, it is simultaneously of interest to maximise the material retrieval. Therefore, the distance between the port and the wind farm is divided by the amount of blade material of the wind farm, denoted as w_y. The equation then becomes:

$$C(x) = \frac{1}{\sum_y \frac{d(x,y)}{w_y}} \tag{3.5}$$

3.3 QUALITATIVE RESEARCH METHODS

The qualitative research methods consist of desk research, interviews, and the consultation with experts from the wind sector.

Most of the concepts required for completing the research methods (the port analysis, (d)MFA and GIS analysis, as well as subsequent evaluation of the circular strategies) are defined and approached based on desk research. In Section 3.4 and Figure 3.4, an overview of required data can be found. The desk research involves a literature review of previously-performed studies on the same topic, as well as the consultation of reports published by governmental organisations and sector-specific associations. The results of these papers and reports are as much as possible cross-validated by each other, or validated by expert opinion.

The interviews have taken place with representatives from the different ports in the Netherlands in order to determine which aspects are important for the development of a circular wind hub, and how well each port would lend itself for the development thereof. The interviews are of semi-structured nature. A semi-structured interview means that a certain number of open-ended questions have been formulated in advance, and that during the interview, there is room for new questions to arise from the ongoing dialogue (DiCicco-Bloom and Crabtree, 2006). In this way, the interviewee is an active participant in shaping the interview (DiCicco-Bloom and Crabtree, 2006).

The interview questions were tested prior to the interview in order to ascertain that they are not guiding or suggestive. This was done through a trial-interview with fellow graduate intern Lobke Jurrius on May 7th, 2021, as well as through having the supervisors of this thesis proof-read the questions.

From the interviews and desk research, a framework is designed to compare ports' suitability to develop a circular wind hub. For each category, the ports are given a score, which are subsequently normalised in order to arrive at a final score that allows for comparison. Further detail on the scoring metrics and normalisation of these can be found in Section 4.1.1.

The overview of the interviewees and the date that the interviews have taken place are listed in Table 3.1 below.

Port	Interviewee	Function	Date of interview
Groningen Seaports	Erik Bertholet	Business Manager Offshore Wind	May 20th, 2021
Port of Amsterdam	Dorothy Winters	Programme Manager Offshore Wind	May 21st, 2021
	James Hallworth	Commercial Manager Circular & Renewable Industry	
Port of Den Helder	Katja Naber	Commercial Manager	June 3rd, 2021
	Kees Turnhout	Acting Director, Head of Infrastructure and Space	
Port of Rotterdam	Joost Eenhuizen	Business Manager Maritime & Offshore Industry	June 14th, 2021
North Sea Port	Peter Geertse	Commercial Manager	June 28th, 2021

Table 3.1: Overview of interviewees

Alongside the semi-structured interviews, a significant number of personal communications in the form of video calls and e-mail contact with experts from the field were conducted to better understand certain concepts, especially where the desk research did not yield complete information, or to validate the retrieved information. This was for instance done to get a better idea of realistic developments in blade design, recycling technologies and the monetary value of the secondary blade material from different circular strategies. The different organisations contacted include:

- Blade manufacturers: Martijn Koelers (LM Wind Power), Jonas P. Jensen (SGRE)
- Logistics: Twan Kolkert (Heerema)
- Circular strategies: Markku Vilkki (Conenor Ltd), Jos de Krieger (Superuse Studios), Cora Burger (Demacq)
- Research: Marylise Schmid and Ivan Komusanac (WindEurope), Anne Velenturf (University of Leeds), Julie Teuwen and Jelle Joustra (Delft University of Technology), Albert ten Busschen (Windesheim University of Applied Sciences)

3.4 DATA REQUIREMENTS

The research requires a range of input data, summarised as follows:

- Port selection:
  - Characteristics relevant to the development of a circular wind hub (Section 4.1.1)
- The dMFA model:
  - Installed capacity of wind energy (Section 4.2.1.1)
  - Design of the blades in terms of material composition, size and mass (Sections 4.2.1.4, 4.2.1.5, 4.2.1.6)
  - Lifetime of the wind turbines (Section 4.2.1.7)
- The GIS analysis:
  - Locations (coordinates) of wind farms (Section 4.2.1.2)
- The circular strategies:
  - Economic potential and monetary value of secondary material from different circular strategies (Section 4.3.1)
  - Environmental impact of the different circular strategies (Section 4.3.2)
  - Onshore and offshore transport of EoL blades (Sections 4.3.3 and 4.3.4)

These concepts must be explored and defined for their current and future values. Each of these aspects is discussed in further detail in Section 4. The installed capacity, design and lifetime are concerned with built and to-be built turbines. For these items, developments will only be considered until 2030. Developments after 2030 will not be considered for two reasons: first of all, developments after this time are highly uncertain; and second of all, wind turbines generally have a design lifetime of some 20-30 years (Kruse, 2019), meaning that wind turbines built after 2030 will likely be decommissioned after 2050, i.e. outside of the scope of this research.

Figure 3.4 illustrates the data requirements for the research and how these are interrelated.

The research is based on the current and future installed wind capacity in the specified region[1]. The current installed capacity was retrieved from *The Wind Power* database on March 16th, 2021. This database includes information on installed wind power for all six countries under analysis, including the coordinates of the wind farm in WGS84 form, the manufacturer, turbine type, number of turbines, total power, and the commissioning and decommissioning dates, when applicable. This database is subsequently compared to country-specific data found from the sources summarised in Table 3.2 below. More detailed analysis of the currently installed capacity in each country can be found in Appendix D.

	Sources
All	4C-Offshore, WindEurope
the Netherlands	RVO, CBS, WindStats
Germany	Deutsche Windguard
Denmark	Danish Energy Agency
The UK	RenewableUK, Crown Estate
France	ENCP, France Energie Eolienne
Belgium	Flemish Wind Energy Association, Belgian Offshore Platform, Apere

Table 3.2: Summary of sources for current and future installed wind capacity per country

Initially, future installed capacity for onshore and offshore wind capacity was approached under scenarios until 2030 developed by WindEurope (Ngiem and Pineda, 2017). However, for offshore wind, many tenders and plans are available, and combined, these plans approach or even exceed the scenario-based values. This is covered in Section 4.2.1.1, Table 4.13. Therefore, all existing tenders and plans until 2030 are used for offshore wind development until 2030. In contrast, there is much less certainty and defined plans in terms of onshore wind development. Therefore, onshore wind development until 2030 is approached under three scenarios: from WindEurope, NECP, and based on the most plausible development (Komusanac et al., 2020b; Roelofs, 2020). However this had a negligible impact on the final results. Therefore, only the mid-scenario is adopted, which is 7 GW of installed capacity by 2030. This is interpolated linearly back from 2030 to 2020, similar to Lichtenegger et al. (2020), to determine the amount that must be installed each year.

More detailed analysis of the future installed capacity in each country can be found in Appendix E.

Dealing with missing or incomplete data

The dataset from *The Wind Power* was loaded into QGIS to select only those wind farms that fall within the scope of this research: offshore wind farms in the North Sea and the English Channel, and onshore wind farms in the Netherlands. This selection rendered a few errors in distinguishing between onshore and offshore turbines: 16 wind farms had been categorised as offshore but were in fact onshore, for instance on dikes or at the coast. Five of these were outside of the Netherlands

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[1] This is the Netherlands (offshore and onshore), Germany, Denmark, the UK, France and Belgium (only offshore)

and were thus removed from the analysis. The remaining eleven were moved to the onshore dataset.

Subsequently, the onshore dataset for the Netherlands consisted of 698 entries, totalling 3853 MW. Of these entries, 74 did not have coordinates (total of 575 MW), and eight of those were wind farms larger than 10 MW (total of 427 MW). For those eight wind farms, the coordinates were searched and found manually. The remaining 150 MW spread over 66 wind farms was removed from the analysis, as this is less than 4% of the total capacity.

From the most recent report on onshore wind in the Netherlands by RVO (2021a), it was found that in 2020, there was 4177 MW of onshore wind, whilst the dataset totalled to 3725 MW. This means that 12% was missing. It is assumed that this missing capacity is resultant from missing data over time from small and individual wind turbines that were not taken up by a central database. Therefore, all known onshore wind farms are scaled by the percentage difference to bridge this gap in installed capacity.

Only two wind farms did not have a commissioning date defined; these were only 0.6 MW and 0.85 MW in size and were therefore removed from the analysis.

For offshore wind farms, the dataset for current installed capacity was complete.

In terms of the circular strategy analysis, there was a lack of information on transport costs and economic value of the secondary material. These concepts have been defined through a combination of desk research, expert opinion and estimates based on known information. More elaboration on this is offered in Section 4.3.

More information on data cleansing, the filling in of missing data and the research approach can be found in Appendix C.

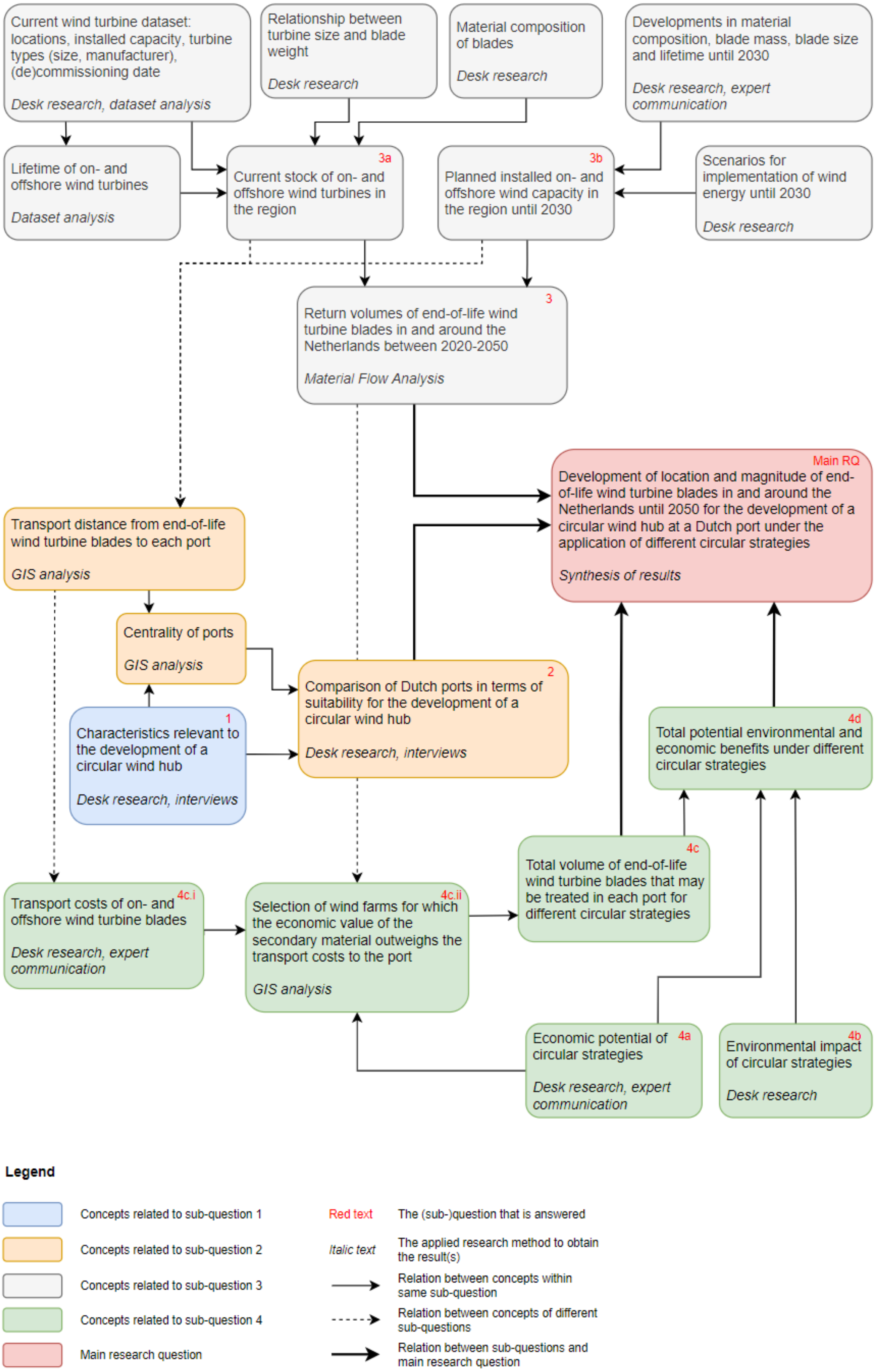

Figure 3.4: Data requirements for the research

4 RESULTS

This chapter presents the results to the research questions proposed in Section 1.4, obtained through the methods described in Chapter 3. The results are divided into three main parts, corresponding to the three main research objectives of this thesis. The first part is concerned with the location for the development of a circular wind hub: distinguishing important characteristics of a location and comparing Dutch ports accordingly. The second part covers the prospective material flows of return volumes of WTB, including the definition of the relevant concepts related to this. The third part focuses on the application of different circular strategies: the effect thereof on the volume of EoL WTB that may be treated in the hub and what economic and environmental benefits can be achieved by each strategy. At the end, the results are summarised and a synthesis of the results is offered.

4.1 COMPARISON OF PORTS FOR THE DEVELOPMENT OF A CIRCULAR WIND HUB

The first focus area of this thesis research is based on the suitability of ports for the development of a circular wind hub for EoL WTB. This section first introduces concepts and characteristics relevant to test this suitability, to arrive at a general framework that can be filled in for each port. This framework is then applied to five Dutch ports to help determine which port is more or less suitable to establish the circular wind hub.

4.1.1 Designing a framework to compare ports' suitability to develop a circular wind hub

From desk research and interviews with the five Dutch ports, a number of elements have been identified that are important to consider in determining a location's suitability for the development of a circular wind hub. These elements are introduced and explained, and a way of scoring a port's performance per element is offered.

First of all, the port must be open and willing to develop such a hub in the first place. Without this as a starting point, it is highly unlikely that the steps to develop the required infrastructure will be taken. Next, after Gjødvad and Ibsen (2016), there are a number of physical characteristics that a port must possess in order to be able to facilitate EoL treatment of wind turbines. These are:

- Adequate water depth to ensure accessibility;
- Sufficient load capacity;
- Enough space for storage and load-in facilities;
- Environmental permits[1];
- Facilities for hazardous materials.

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[1] In the Netherlands, these range from 1 - 6 where 6 is the highest, i.e. the most severe in terms of environmental impact.

Hence, it is desirable if the port has - or is in proximity to - companies, infrastructure and activities related to EoL treatment and/or the wind sector. That would namely ensure that there are already facilities and other aspects such as environmental permits in place. From the interviews with the ports, it has additionally come forward that it is important that secondary markets for the recovered materials are in proximity to the port.

The availability of space is important for two reasons. First of all, to be able to set up treatment facilities for the material, and second of all, to be able to handle the return volumes. The EoL material flow of wind turbines is of a discrete nature: at some moments in time, there will be no material, at another, an entire farm is dismantled and all this material becomes available at once. This is therefore not a continuous material flow and differs in magnitude each time.[2] Hence, it must be possible to accept the return volumes at the port and store the EoL WTB for a time.

With regard to the circular strategies and opportunities (Figures 1.1 and 2.6), it is valuable to analyse how the current activities or focus at each port fits inside these models. After all, activities that are higher up the circularity ladder are preferred, as has been indicated in Section 2.4. If ports are already specialising in a certain direction, this should also be taken into consideration. How these strategies compare in terms of their environmental impact and economic value when applied to EoL WTB is elaborated on in Section 4.3.1.

Furthermore, it is important that treatment facilities be developed in locations that are centrally-located with regard to current and future installed wind power (Andersen et al., 2016). This is valuable both from a logistical cost-perspective as well as from an ecological perspective, as minimised transport distance means minimised transport costs and associated emissions. Important to note is that this research does not explicitly consider emissions from transport; rather, the transport distance is used to represent this.

From these considerations, six main themes are identified as central categories to analyse for the development of a circular wind hub:

1. Port willingness to develop a circular wind hub;
2. Available space for storage and for the establishment of new infrastructure required for treatment facilities;
3. Current companies, infrastructure & activities at and in vicinity of the port related to the (reverse) wind supply chain;
4. Accessibility of the port in terms of potential future bottlenecks due to ever-growing blade sizes;
5. Port focus with respect to circular strategies;
6. Port centrality with regard to current and future wind farms.

Following the identification of relevant categories, an approach towards scoring each category is determined. This is summarised in Table 4.1. It is assumed that all six categories are equally important, i.e. there is no differentiation in weighting between them.

For the first four categories, an ordinal scale from 1 to 4 is applied, where 4 is the highest. This is because these elements are either difficult to quantify (e.g. willingness and existing companies), or the quantification is not always known (e.g. for available space). Hence an ordinal scale is assumed most fitting.

The circular strategy focus is based on an interval scale of 1-10, where 10 is the highest and associated with R0 from the circular strategies framework, and 1 the

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[2] The total blade mass outflow over time shown in Figure 4.8 gives a bit of distorted view in the sense that it gives the idea that the outflows are continuous and develop smoothly. In reality, a more jerky development is to be expected, as shown in Figure 4.12.

lowest, i.e. R9 from the circular strategies framework[3] (see Figure 2.6). This means that a score is given for the use of each circular strategy, and subsequently these are summed together - otherwise the weighing of this category would surpass 1. The use of this scale therefore approaches the scoring of circular strategies along the circular ladder to be of a linearly increasing fashion.

The port centrality is scored using a ratio scale based on the calculations introduced in Equations 3.4 and 3.5.

Category	Score method	Explanation
Port willingness	Ordinal, 1-4	1: not willing, 4: very willing
Available space	Ordinal, 1-4	1: very little, 4: plenty
Current companies, infrastructure & activities	Ordinal, 1-4	1: none, 4: plenty
Accessibility	Ordinal, 1-4	1: very difficult, 4: no difficulties
Circular strategy focus	Interval, 1-10	1: recovery (R9), 10: refuse (R0)
Centrality	Ratio	The higher, the more central

Table 4.1: Framework for determining port suitability for the development of a circular wind hub

As the categories have different scoring metrics and ranges of values, their scores must be normalised to a value between 0 and 1 to facilitate further comparison. A linear normalisation technique is applied, after Vafaei et al. (2018). For each category j and for each port i, the score of the port $r_{i,j}$ is divided by the maximum score in that category to arrive at a normalised score, i.e.:

$$n_{i,j} = \frac{r_{i,j}}{r_{max,j}} \tag{4.1}$$

Note that for port characteristics, the maximum score is 4; for circular strategies, the maximum score is 55[4], while centrality has no pre-determined maximum score and hence the maximum obtained score is used. Subsequently, all categories are summed to arrive at a final score for each port.

4.1.2 Applying the framework to Dutch ports

Now that the general framework has been designed, it is applied to the five Dutch ports. The findings from the interviews with the ports and desk research from their websites are summarised according to the first five categories from the framework. The websites consulted are Port of Amsterdam (nd); Port of Rotterdam (nd); Port of Den Helder (nd); Groningen Seaports (nd); North Sea Port (nd). Next, the sixth category, port location centrality, is calculated. Finally, a comparison of all the ports across all six categories is carried out.

4.1.2.1 *Conclusions per port*

The conclusions per port are split between categories 1-5 and category 6 from the framework. This is because the first five categories were determined based on the interviews and desk research, whilst the sixth category was calculated separately based on the transport distance and size of each wind farm to each port. The results are presented in this order.

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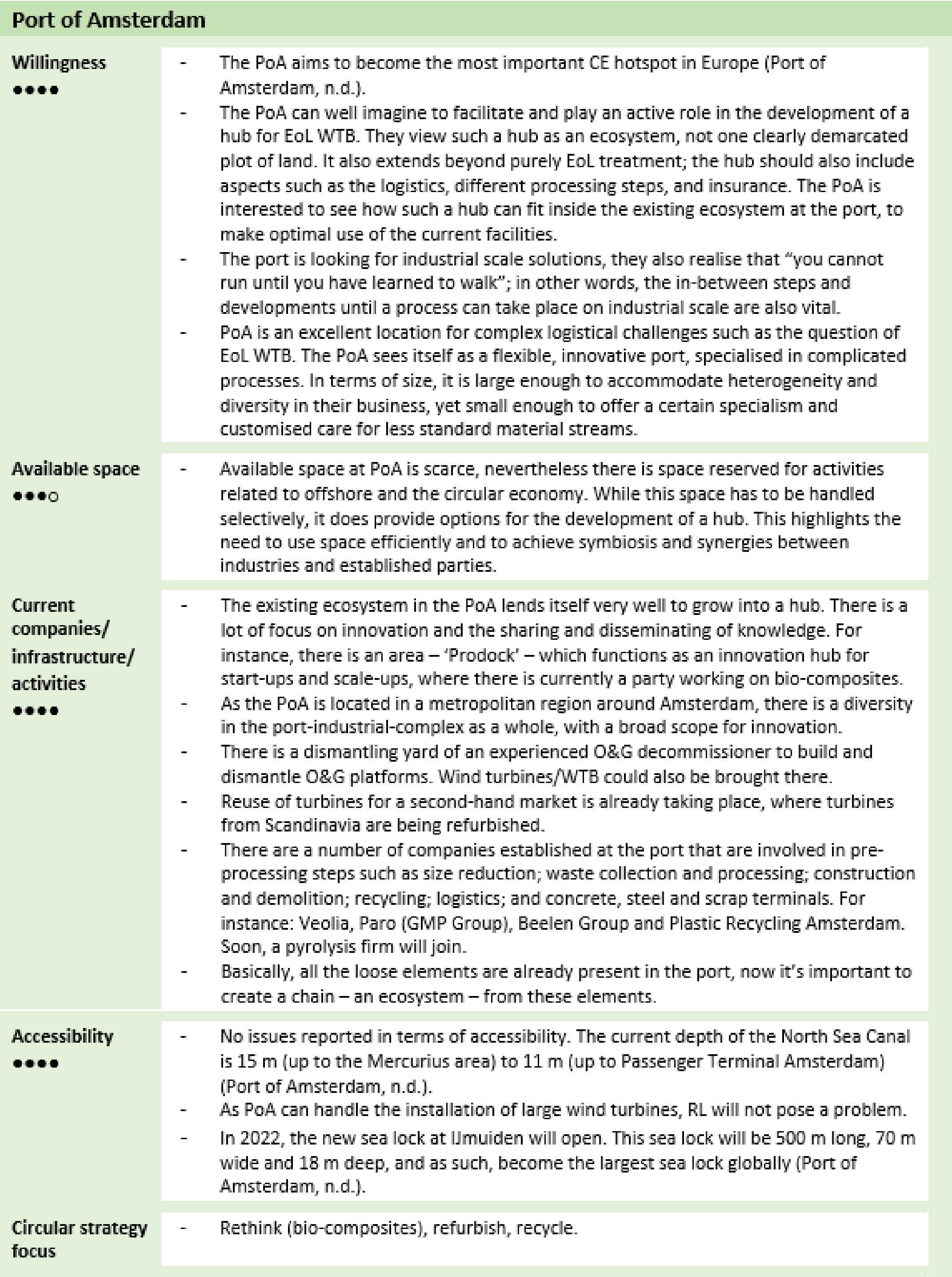
[3] A score of 0 would be given to disposal, which is not officially a strategy adopted in the circular ladder

[4] This is the sum of 10 (R0) + 9 (R1) + ... + 1 (R9)

Findings from interviews (categories 1 - 5)
The conclusions for each port for the first five categories are individually presented in tabular form. The PoA is outlined in Table 4.2; PoR in Table 4.3; PoDH in 4.4; GSP in Table 4.5; and NSP in Table 4.6.

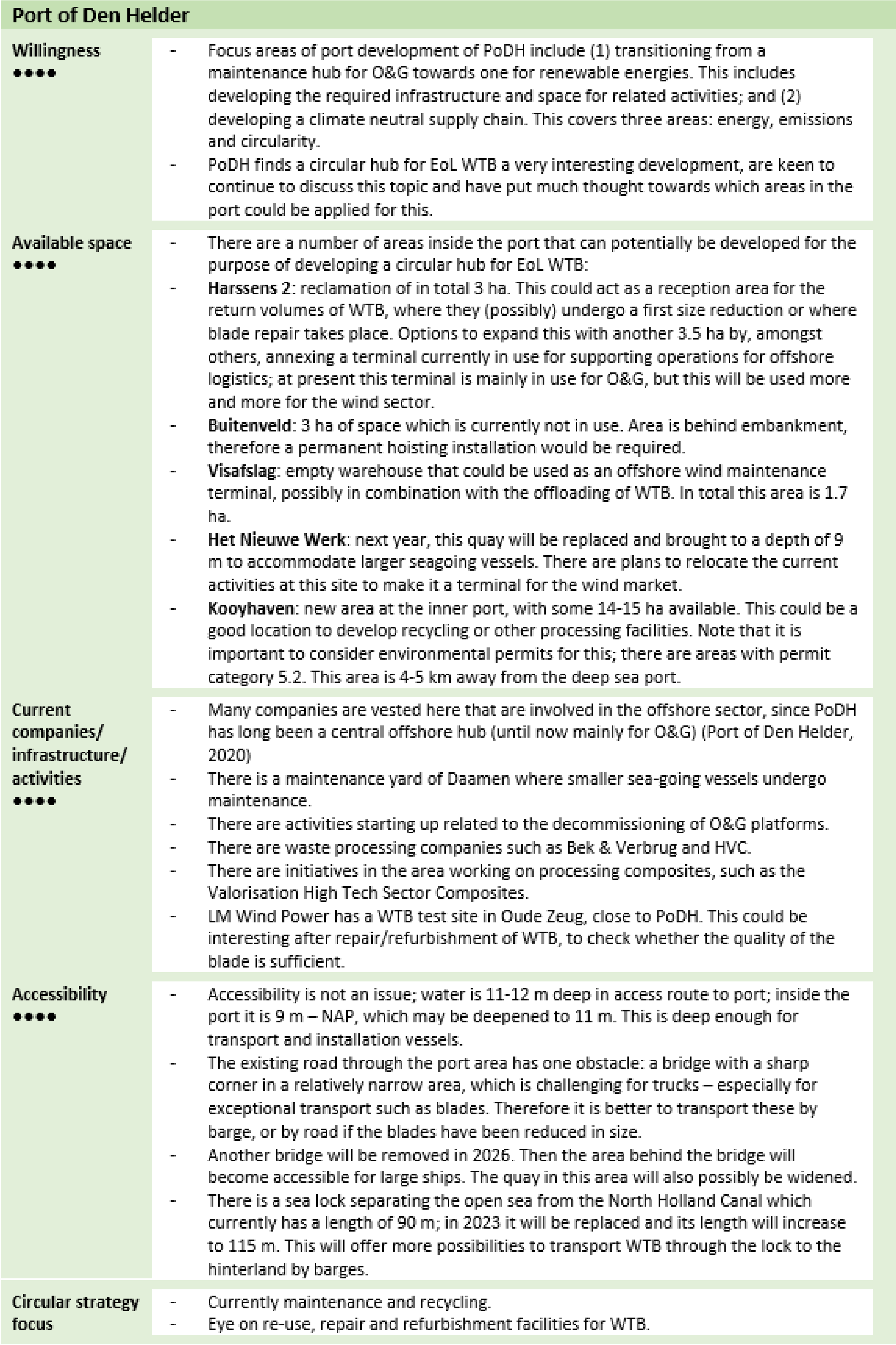


Port of Amsterdam	
Willingness ●●●●	- The PoA aims to become the most important CE hotspot in Europe (Port of Amsterdam, n.d.). - The PoA can well imagine to facilitate and play an active role in the development of a hub for EoL WTB. They view such a hub as an ecosystem, not one clearly demarcated plot of land. It also extends beyond purely EoL treatment; the hub should also include aspects such as the logistics, different processing steps, and insurance. The PoA is interested to see how such a hub can fit inside the existing ecosystem at the port, to make optimal use of the current facilities. - The port is looking for industrial scale solutions, they also realise that "you cannot run until you have learned to walk"; in other words, the in-between steps and developments until a process can take place on industrial scale are also vital. - PoA is an excellent location for complex logistical challenges such as the question of EoL WTB. The PoA sees itself as a flexible, innovative port, specialised in complicated processes. In terms of size, it is large enough to accommodate heterogeneity and diversity in their business, yet small enough to offer a certain specialism and customised care for less standard material streams.
Available space ●●●○	- Available space at PoA is scarce, nevertheless there is space reserved for activities related to offshore and the circular economy. While this space has to be handled selectively, it does provide options for the development of a hub. This highlights the need to use space efficiently and to achieve symbiosis and synergies between industries and established parties.
Current companies/ infrastructure/ activities ●●●●	- The existing ecosystem in the PoA lends itself very well to grow into a hub. There is a lot of focus on innovation and the sharing and disseminating of knowledge. For instance, there is an area – 'Prodock' – which functions as an innovation hub for start-ups and scale-ups, where there is currently a party working on bio-composites. - As the PoA is located in a metropolitan region around Amsterdam, there is a diversity in the port-industrial-complex as a whole, with a broad scope for innovation. - There is a dismantling yard of an experienced O&G decommissioner to build and dismantle O&G platforms. Wind turbines/WTB could also be brought there. - Reuse of turbines for a second-hand market is already taking place, where turbines from Scandinavia are being refurbished. - There are a number of companies established at the port that are involved in pre-processing steps such as size reduction; waste collection and processing; construction and demolition; recycling; logistics; and concrete, steel and scrap terminals. For instance: Veolia, Paro (GMP Group), Beelen Group and Plastic Recycling Amsterdam. Soon, a pyrolysis firm will join. - Basically, all the loose elements are already present in the port, now it's important to create a chain – an ecosystem – from these elements.
Accessibility ●●●●	- No issues reported in terms of accessibility. The current depth of the North Sea Canal is 15 m (up to the Mercurius area) to 11 m (up to Passenger Terminal Amsterdam) (Port of Amsterdam, n.d.). - As PoA can handle the installation of large wind turbines, RL will not pose a problem. - In 2022, the new sea lock at IJmuiden will open. This sea lock will be 500 m long, 70 m wide and 18 m deep, and as such, become the largest sea lock globally (Port of Amsterdam, n.d.).
Circular strategy focus	- Rethink (bio-composites), refurbish, recycle.

Table 4.2: Summary of port characteristics of Port of Amsterdam

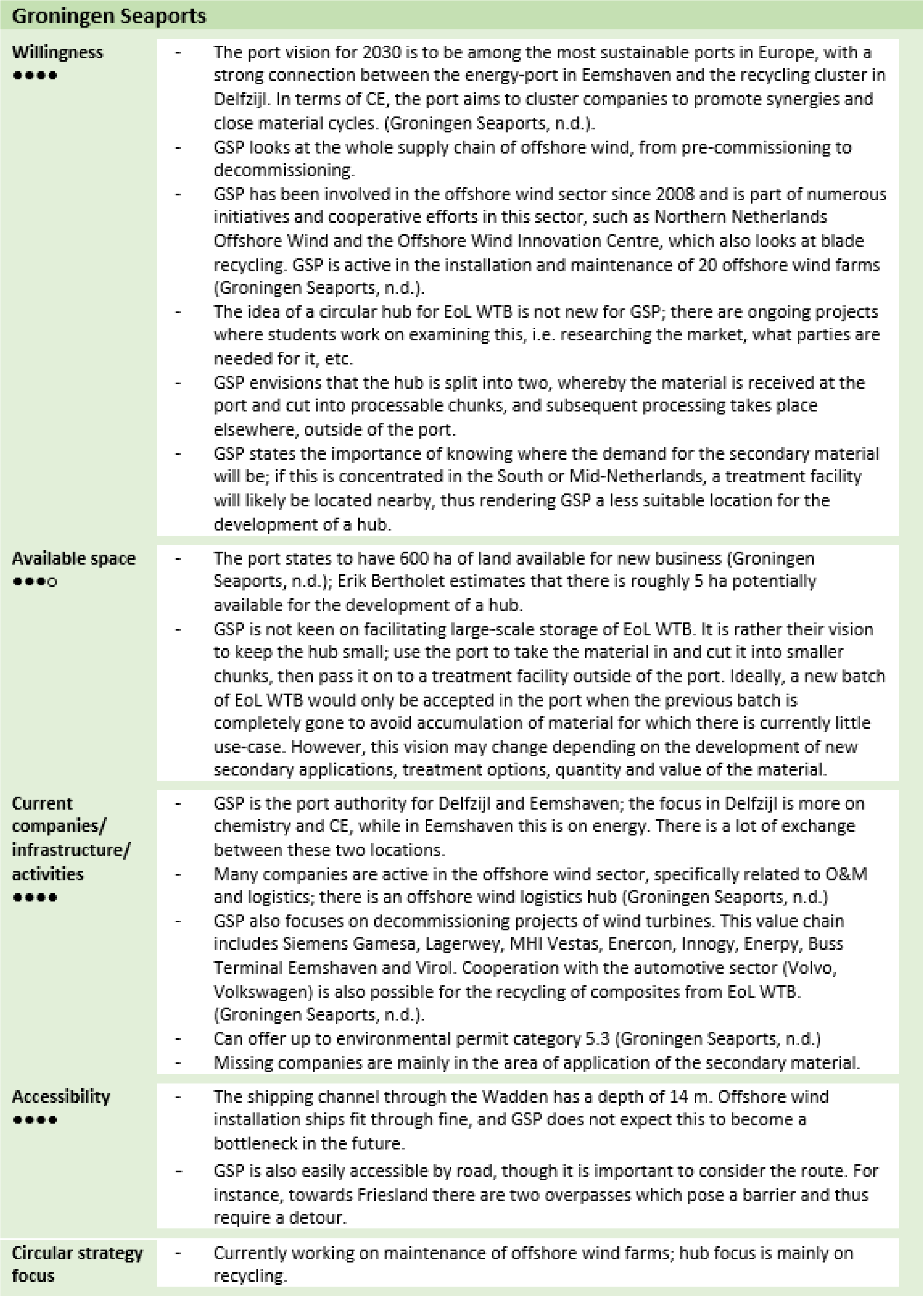
Port of Rotterdam	
Willingness ●●○○	- PoR aims to become the most sustainable port globally (Port of Rotterdam, n.d.) - Since 2015 there is a focus on offshore wind, with the development of an Offshore Wind Terminal as a hub for the installation of offshore wind (developed by Sif and Verbrugge). - Dismantling of wind turbines was initially not on the radar of PoR; this has gradually become something the port is looking at. - At present, PoR is at an investigative stage from an industry perspective: what is the current status of production technology and processing technologies, what are the developments, which parties are involved, and can EoL offshore wind act as sourcing for production processes? - PoR sees the development of a hub as something that could be spread throughout the whole of the Netherlands, with collaboration, cooperation and symbiosis between parties that are vested at different ports. There are no concrete ideas about such a hub yet; all ideas about this are still in an exploratory stage. - Due to current limitations, it is difficult for PoR to say yes to the development of a circular hub.
Available space ●○○○	- Space is very limited. The free space at Maasvlakte 2 has all been divided and reserved already, which means that these sites can be used temporarily until their strategic implementation takes place. This means that activities related to EoL WTB can happen project-wise for 5, maximum 15, years; setting up large treatment facilities that require large investments is not possible. - If the EoL WTB material reaches the port in shredded form, this offers more opportunities than if the WTB return in their original form, since the shredded material could then go directly to a recycling terminal for further processing. - Some companies have strategic reserves in the port; if it would be possible for these companies to use EoL WTB material as their sourcing, then these reserves could be used to store the WTB material. But these are theoretical ideas and introduce difficult questions with uncertain answers such as: which industries will still be at the port in 10-15 years, which ones are capable of transformation, and which ones will be able to see the processing of EoL WTB material as part of their core business? - Therefore, the possibilities are limited to whether these can be adopted within current facilities; it is not possible to develop new ones.
Current companies/ infrastructure/ activities ●●●●	- Sif has a terminal with a total area of 62 ha (incl. space for expansion), which is a production location for monopiles. If the space allows it, this could also be used for decommissioning of wind turbines, however this would only be applicable to monopiles, not other components. - Vested companies related to (decommissioning of) offshore wind include Rhenus, SIF, EMR, Jewo, AC Jansen, Beelen and Meuva. - In terms of environmental permits, PoR is a suitable location as it is an industrial area where such permits are already in place. - If the processed material of EoL components is used again for production of wind turbine components, it will go to production facilities for wind turbines, which are not located in the Netherlands. This therefore also influences the infrastructure development at the port.
Accessibility ●●●●	- Accessibility to the port is neither a problem for offshore or onshore transport. The port has a maximum depth of 24 m (Port of Rotterdam, n.d.). - There are good connections to the Maas and Rhine rivers.
Circular strategy focus	- No strong focus yet; from all circular strategies, most focus seems to be on recycling. - Aim to develop in facilitating maintenance (Port of Rotterdam, n.d.).

Table 4.3: Summary of port characteristics of Port of Rotterdam



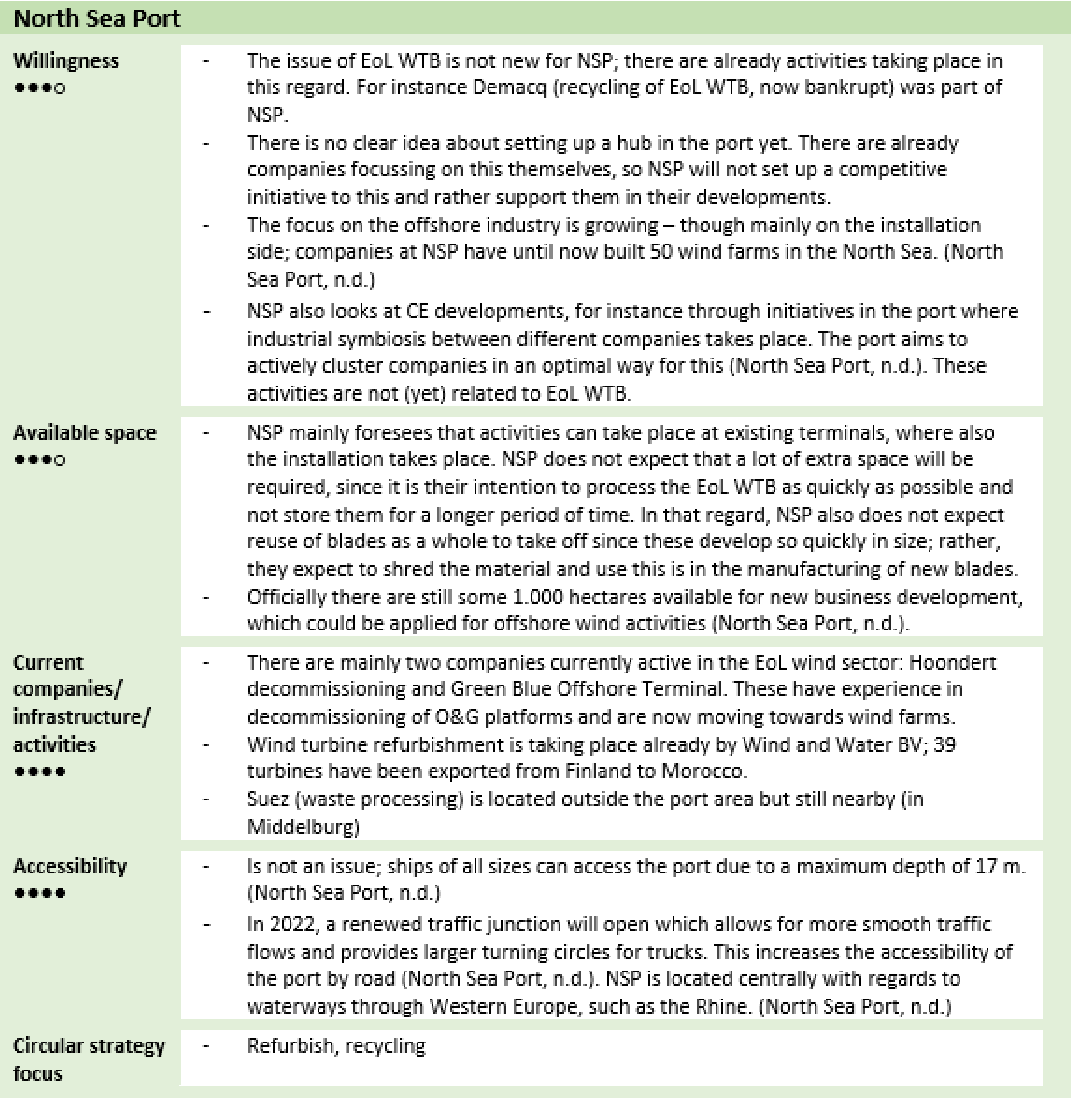
Port of Den Helder	
Willingness ●●●●	- Focus areas of port development of PoDH include (1) transitioning from a maintenance hub for O&G towards one for renewable energies. This includes developing the required infrastructure and space for related activities; and (2) developing a climate neutral supply chain. This covers three areas: energy, emissions and circularity. - PoDH finds a circular hub for EoL WTB a very interesting development, are keen to continue to discuss this topic and have put much thought towards which areas in the port could be applied for this.
Available space ●●●●	- There are a number of areas inside the port that can potentially be developed for the purpose of developing a circular hub for EoL WTB: - **Harssens 2**: reclamation of in total 3 ha. This could act as a reception area for the return volumes of WTB, where they (possibly) undergo a first size reduction or where blade repair takes place. Options to expand this with another 3.5 ha by, amongst others, annexing a terminal currently in use for supporting operations for offshore logistics; at present this terminal is mainly in use for O&G, but this will be used more and more for the wind sector. - **Buitenveld**: 3 ha of space which is currently not in use. Area is behind embankment, therefore a permanent hoisting installation would be required. - **Visafslag**: empty warehouse that could be used as an offshore wind maintenance terminal, possibly in combination with the offloading of WTB. In total this area is 1.7 ha. - **Het Nieuwe Werk**: next year, this quay will be replaced and brought to a depth of 9 m to accommodate larger seagoing vessels. There are plans to relocate the current activities at this site to make it a terminal for the wind market. - **Kooyhaven**: new area at the inner port, with some 14-15 ha available. This could be a good location to develop recycling or other processing facilities. Note that it is important to consider environmental permits for this; there are areas with permit category 5.2. This area is 4-5 km away from the deep sea port.
Current companies/ infrastructure/ activities ●●●●	- Many companies are vested here that are involved in the offshore sector, since PoDH has long been a central offshore hub (until now mainly for O&G) (Port of Den Helder, 2020) - There is a maintenance yard of Daamen where smaller sea-going vessels undergo maintenance. - There are activities starting up related to the decommissioning of O&G platforms. - There are waste processing companies such as Bek & Verbrug and HVC. - There are initiatives in the area working on processing composites, such as the Valorisation High Tech Sector Composites. - LM Wind Power has a WTB test site in Oude Zeug, close to PoDH. This could be interesting after repair/refurbishment of WTB, to check whether the quality of the blade is sufficient.
Accessibility ●●●●	- Accessibility is not an issue; water is 11-12 m deep in access route to port; inside the port it is 9 m – NAP, which may be deepened to 11 m. This is deep enough for transport and installation vessels. - The existing road through the port area has one obstacle: a bridge with a sharp corner in a relatively narrow area, which is challenging for trucks – especially for exceptional transport such as blades. Therefore it is better to transport these by barge, or by road if the blades have been reduced in size. - Another bridge will be removed in 2026. Then the area behind the bridge will become accessible for large ships. The quay in this area will also possibly be widened. - There is a sea lock separating the open sea from the North Holland Canal which currently has a length of 90 m; in 2023 it will be replaced and its length will increase to 115 m. This will offer more possibilities to transport WTB through the lock to the hinterland by barges.
Circular strategy focus	- Currently maintenance and recycling. - Eye on re-use, repair and refurbishment facilities for WTB.

Table 4.4: Summary of port characteristics of Port of Den Helder



Groningen Seaports	
Willingness ●●●●	- The port vision for 2030 is to be among the most sustainable ports in Europe, with a strong connection between the energy-port in Eemshaven and the recycling cluster in Delfzijl. In terms of CE, the port aims to cluster companies to promote synergies and close material cycles. (Groningen Seaports, n.d.). - GSP looks at the whole supply chain of offshore wind, from pre-commissioning to decommissioning. - GSP has been involved in the offshore wind sector since 2008 and is part of numerous initiatives and cooperative efforts in this sector, such as Northern Netherlands Offshore Wind and the Offshore Wind Innovation Centre, which also looks at blade recycling. GSP is active in the installation and maintenance of 20 offshore wind farms (Groningen Seaports, n.d.). - The idea of a circular hub for EoL WTB is not new for GSP; there are ongoing projects where students work on examining this, i.e. researching the market, what parties are needed for it, etc. - GSP envisions that the hub is split into two, whereby the material is received at the port and cut into processable chunks, and subsequent processing takes place elsewhere, outside of the port. - GSP states the importance of knowing where the demand for the secondary material will be; if this is concentrated in the South or Mid-Netherlands, a treatment facility will likely be located nearby, thus rendering GSP a less suitable location for the development of a hub.
Available space ●●●○	- The port states to have 600 ha of land available for new business (Groningen Seaports, n.d.); Erik Bertholet estimates that there is roughly 5 ha potentially available for the development of a hub. - GSP is not keen on facilitating large-scale storage of EoL WTB. It is rather their vision to keep the hub small; use the port to take the material in and cut it into smaller chunks, then pass it on to a treatment facility outside of the port. Ideally, a new batch of EoL WTB would only be accepted in the port when the previous batch is completely gone to avoid accumulation of material for which there is currently little use-case. However, this vision may change depending on the development of new secondary applications, treatment options, quantity and value of the material.
Current companies/ infrastructure/ activities ●●●●	- GSP is the port authority for Delfzijl and Eemshaven; the focus in Delfzijl is more on chemistry and CE, while in Eemshaven this is on energy. There is a lot of exchange between these two locations. - Many companies are active in the offshore wind sector, specifically related to O&M and logistics; there is an offshore wind logistics hub (Groningen Seaports, n.d.) - GSP also focuses on decommissioning projects of wind turbines. This value chain includes Siemens Gamesa, Lagerwey, MHI Vestas, Enercon, Innogy, Enerpy, Buss Terminal Eemshaven and Virol. Cooperation with the automotive sector (Volvo, Volkswagen) is also possible for the recycling of composites from EoL WTB. (Groningen Seaports, n.d.). - Can offer up to environmental permit category 5.3 (Groningen Seaports, n.d.) - Missing companies are mainly in the area of application of the secondary material.
Accessibility ●●●●	- The shipping channel through the Wadden has a depth of 14 m. Offshore wind installation ships fit through fine, and GSP does not expect this to become a bottleneck in the future. - GSP is also easily accessible by road, though it is important to consider the route. For instance, towards Friesland there are two overpasses which pose a barrier and thus require a detour.
Circular strategy focus	- Currently working on maintenance of offshore wind farms; hub focus is mainly on recycling.

Table 4.5: Summary of port characteristics of Groningen Seaports



North Sea Port	
Willingness ●●●○	- The issue of EoL WTB is not new for NSP; there are already activities taking place in this regard. For instance Demacq (recycling of EoL WTB, now bankrupt) was part of NSP. - There is no clear idea about setting up a hub in the port yet. There are already companies focussing on this themselves, so NSP will not set up a competitive initiative to this and rather support them in their developments. - The focus on the offshore industry is growing – though mainly on the installation side; companies at NSP have until now built 50 wind farms in the North Sea. (North Sea Port, n.d.) - NSP also looks at CE developments, for instance through initiatives in the port where industrial symbiosis between different companies takes place. The port aims to actively cluster companies in an optimal way for this (North Sea Port, n.d.). These activities are not (yet) related to EoL WTB.
Available space ●●●○	- NSP mainly foresees that activities can take place at existing terminals, where also the installation takes place. NSP does not expect that a lot of extra space will be required, since it is their intention to process the EoL WTB as quickly as possible and not store them for a longer period of time. In that regard, NSP also does not expect reuse of blades as a whole to take off since these develop so quickly in size; rather, they expect to shred the material and use this is in the manufacturing of new blades. - Officially there are still some 1.000 hectares available for new business development, which could be applied for offshore wind activities (North Sea Port, n.d.).
Current companies/ infrastructure/ activities ●●●●	- There are mainly two companies currently active in the EoL wind sector: Hoondert decommissioning and Green Blue Offshore Terminal. These have experience in decommissioning of O&G platforms and are now moving towards wind farms. - Wind turbine refurbishment is taking place already by Wind and Water BV; 39 turbines have been exported from Finland to Morocco. - Suez (waste processing) is located outside the port area but still nearby (in Middelburg)
Accessibility ●●●●	- Is not an issue; ships of all sizes can access the port due to a maximum depth of 17 m. (North Sea Port, n.d.) - In 2022, a renewed traffic junction will open which allows for more smooth traffic flows and provides larger turning circles for trucks. This increases the accessibility of the port by road (North Sea Port, n.d.). NSP is located centrally with regards to waterways through Western Europe, such as the Rhine. (North Sea Port, n.d.)
Circular strategy focus	- Refurbish, recycling

Table 4.6: Summary of port characteristics of North Sea Port

Port location centrality (category 6)
This subsection analyses the centrality of each port based on the transport distance and volume from on- and offshore EoL WTB. The material volumes per wind farm are used as a weighting factor next to the transport distance. This means that larger wind farms play a relatively larger role than smaller ones.

The distances between the wind farms and ports are calculated in QGIS using a Distance Matrix. This determines the straight-line distance between each wind farm and each port, based on the coordinates of these entities. More detailed information on the current and future locations of wind farms is offered in Section 4.2.1.2.

The closeness centrality of each port is determined according to equations 3.4 and 3.5. The total sum of distances from all wind farms to each port until 2050 is given in Table 4.7. This already gives a first indication in terms of how the ports compare with regard to their centrality.

Port	Total distance [km]
PoA	113,000
PoR	134,000
PoDH	116,000
GSP	168,000
NSP	190,000

Table 4.7: Total distance from all current and future wind farms to each port, aggregated over all years and rounded to the nearest whole kilometre

Since the lifetime of wind farms is assumed to follow a Normal probability distribution, it is not possible to conclude in which specific year a wind farm will be dismantled. For determination of the closeness of the ports, and specifically for analysing the development thereof over time, an assumption about when the wind farm will be decommissioned is required. Each wind farm is therefore assigned a lifetime based on the defined default Normal distribution from Section 4.2.1.7.

Based purely on the transport distance from all wind farms to be decommissioned until 2050 (equation 3.4), the following ranking in centrality is attained: PoA $>$ PoDH $>$ PoR $>$ GSP $>$ NSP, with their closeness scores reported in the first column of Table 4.8. While this gives some valuable insight, a more detailed understanding of the closeness of each port is achieved by incorporating the size of each wind farm. Enhancing this analysis with the size of the wind farms, i.e. how many turbines are installed and how large these turbines are, offers a more detailed idea of the centrality of these ports based on the magnitude of the expected return volumes of EoL WTB.

Determination of this weighted closeness is done by dividing the distance by the weight of material for each wind farm, summing these values per year, and subsequently taking its reciprocal (equation 3.5). These weighted closeness scores are reported in the second column of Table 4.8.

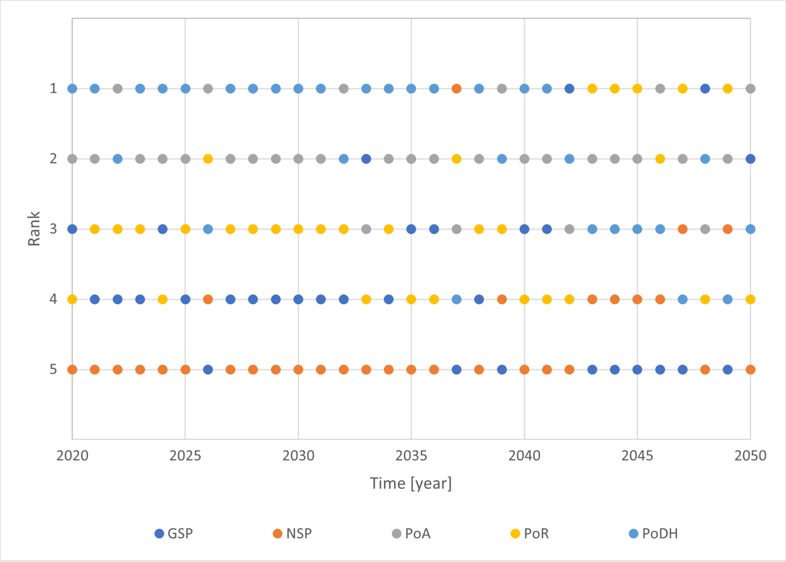
Port	Closeness centrality	Weighted closeness centrality
PoA	$8.8 \cdot 10^{-6}$	$1.8 \cdot 10^{-4}$
PoR	$7.5 \cdot 10^{-6}$	$1.2 \cdot 10^{-4}$
PoDH	$8.6 \cdot 10^{-6}$	$2.1 \cdot 10^{-4}$
GSP	$5.9 \cdot 10^{-6}$	$1.2 \cdot 10^{-4}$
NSP	$5.3 \cdot 10^{-6}$	$7.8 \cdot 10^{-5}$

Table 4.8: Closeness centrality of ports based first on distance, second on distance and material volume, aggregated over all years. The higher the value, the better: i.e. the more centrally located the port is

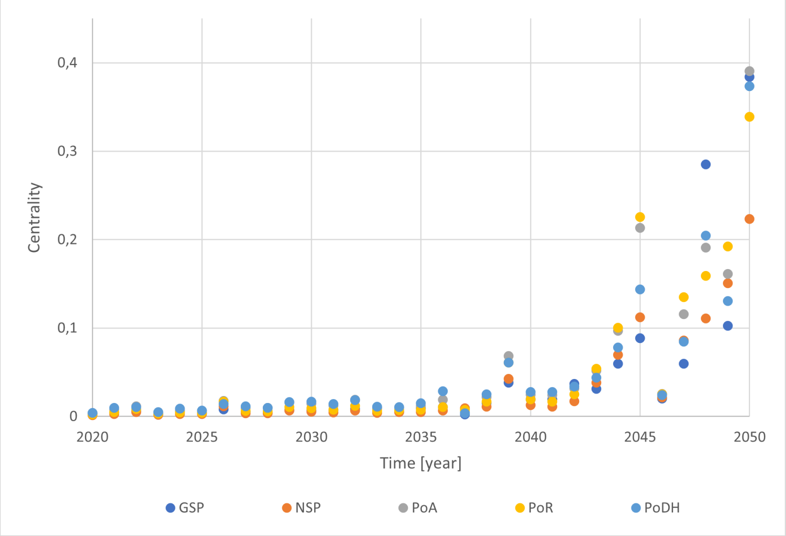
It should be noted here that in this way, the transport distance and material at the wind farm are compared as 1:1, i.e. each aspect is considered equally important. This could be adjusted by adding a scaling parameter. A final note on these centrality measures is that they are generated using the reciprocal of the distance, therefore it holds that the higher the value, the more central the port is. From this point forward, only the weighted closeness is further considered in the analysis.

The weighted closeness of the ports, both in ranking and in absolute value, per year, is shown in Figure 4.1. For visibility purposes, only years 2020 - 2050 are shown. Note that the highest rank is 1 and the lowest 5. It can be seen that over time, the PoDH, PoA and PoR generally score best, where the first two almost consistently occupy the highest and second-highest rank. The PoR starts playing a more principal role after 2040.

From the absolute values, it becomes clear that the closeness scores do not lie very far apart. Thus, although a differentiation can be made between the ports, it is not very distinctive - it becomes more distinctive in later years. Extending the analysis to include wind farm installations after 2030 could offer a more clear distinction. From the aggregated scores in Table 4.8, it can be concluded that PoDH is most centrally located based on wind farm locations and size built until 2030, with PoA in second place. Even though the differences may not be extreme, a more central location will still generate the least environmental impact and costs from logistics.



(a)



(b)

Figure 4.1: Closeness centrality of Dutch ports over time (a) ranked (1: most central, 5: least central) (b) as absolute values (the higher, the more central)

4.1.2.2 *Overall conclusions*

For each of the six categories defined in the framework, the general conclusions from all the five ports are presented below.

Port willingness
While none of the ports reject the idea of a circular hub, there is a clear distinction between ports who are more and less eager to take the lead in this and play an active role in it. PoR is still at an investigative and exploratory phase - and also has the most recent focus on offshore wind -, and NSP rather sees companies developing this themselves than taking the lead in this. There is general consensus on the idea that the circular hub need not necessarily be a clearly physically demarcated area at *one* port, but rather a larger area, with synergies and cooperation between existing industries and facilities, possibly even throughout the whole of the Netherlands.

Available space
For most ports, free space is relatively scarce, yet possibilities exist to implement activities related to the circular hub. The extent of these possibilities differs quite strongly between ports. The strongest bottleneck is at PoR, while PoDH has most clearly defined areas where hub activities can be developed.

Regarding the availability of space, it is also valuable to consider the fossil industry in the outlook towards 2050. The current analysis is based on the status quo in 2020 and the current plans and ideas of the ports; however a lot more space may become available as the fossil industry declines. For instance, the PoR has a significant petrochemical cluster including five oil refineries and the PoA is the largest gasoline port in the world. Changes in the port-industrial areas may thus offer new opportunities for available space to develop the hub area.

However, it is considered unlikely that these industries will actually disappear; these are big market players who will likely want to keep their terminal while they transition towards new business models, for instance based on bio-fuels. The PoA is already in contact with their customers to develop bio-fuels and hydrogen as alternative for the traditional liquid bulk (such as oil) (Port of Amsterdam, nd). The ports have ambitious sustainability goals, therefore it could be that they impose certain requirements towards these traditional petrochemical industries, but a complete disappearance of these terminals is considered unlikely. Nevertheless, it is valuable to stay aware of developments in this regard.

Current companies, infrastructure and activities
All ports have a reasonable amount of companies/infrastructure related to either the offshore sector or waste processing. This is most often currently related to oil & gas (O&G) and can be applied to EoL WTB. Furthermore, if certain activities develop for which the relevant companies are missing, numerous ports mentioned in the interview that these companies will come when required.

Accessibility
None of the ports foresee an issue related to (future) onshore and offshore accessibility of the port. Where there might be bottlenecks, these are already being addressed. The maximum water depth at each port is sufficient.

Circular strategies
Most focus across the ports is still on recycling; to shred the material as quickly as possible and move it out of the port. From Figure 2.6, this is one of the lowest circular strategies. Focus directed towards strategies higher on the circularity ladder is mainly present at PoDH and PoA. There is also a focus on the maintenance of offshore wind farms at PoR, PoDH and GSP. However, this is not a circular strategy applicable to the EoL stream; rather it is an O&M activity that falls outside of the

scope of this research. Nevertheless, it is valuable to beware of since it keeps blades in operation for a longer time.

Centrality

The differences in port centrality are minor until around 2040; after this, as time progresses, the differences become more established. Nevertheless, over time, a distinct ranking between the ports can be determined, with ports that are overall more centrally located, and others less so. The PoDH and PoA come forward as most centrally located, with the PoR starting to play a more principal role after 2040. The ports' normalised scores offer a relative comparison from which the differences can be more clearly observed.

The ports additionally mention a number of aspects that are important for them to know prior to developing a hub. These include:

- Expected return volumes of EoL WTB and how long these would remain in the port.
- What markets exist for the secondary material and where these markets are. This also determines in what form the material must be delivered. If this is in crushed form, it makes RL much easier.
- Who is responsible for the material. In the case of O&G, for instance, it became a matter of national responsibility, i.e. that each country had to take back its own installations to process these. If similar regulations are implemented for wind farms, it would have significant impact on the development of a hub for EoL WTB, since a lot of the material would come from other countries.

The top two aspects are (partially) resolved by this thesis research. See Sections 4.2 and 4.3, respectively.

4.1.2.3 *Port comparison*

From the analysis of the six main categories, a full comparison between the Dutch ports can be made. The absolute scores of each port based on the findings described in the previous sections is offered in Table 4.9; the normalised scores and a subsequent total score per port can be found in Table 4.10. From the total scores in Table 4.10, the PoDH and PoA come forward as most suitable locations, followed by GSP.

A recurring element from the interviews was the idea that a hub need not be limited to a single location. Rather than a clearly physically demarcated area at one port, it could span a wider area, with synergies and cooperation between existing industries and facilities.

As numerous ports have shown notable willingness and since the ports have various focus areas in terms of circular strategy application, it might be interesting to encourage collaboration between these ports to conjointly develop a circular hub. This collaboration should be measured against the increase in required logistical operations and thus logistical costs and emissions that would be required in this case.

For this study, as the Netherlands is a small country, it could even be spread throughout the entire country, using each port's specialised focus. This might be especially valuable for the PoDH and PoA, as these two ports come forward as the most suitable locations and are located in close proximity to each other. In this way, each port can apply their expertise to the hub: the PoA can for instance offer innovation and the Amsterdam metropolitan area to focus more on R0-R2; the PoDH can offer space to set up treatment facilities for R3-R8, test the blades at the LM test site, and offer maintenance activities, with possible assistance from GSP.

	Port of Amsterdam	Port of Rotterdam	Port of Den Helder	Groningen Seaports	North Sea Port
Port characteristics (range 1-4*)*					
Port willingness	4	2	4	4	3
Available space	3	1	4	4	3
Companies, infrastructure, activities	4	4	4	4	4
Accessibility	4	4	4	4	4
Circular strategies (range 1-10*)*					
R0 Refuse					
R1 Rethink	9				
R2 Reduce					
R3 Re-use			7		
R4 Repair			6		
R5 Refurbish	5		5		5
R6 Remanufacture					
R7 Repurpose					
R8 Recycle	2	2	2	2	2
R9 Recover					
Sum	16	2	20	2	7
Centrality					
Centrality (weighted)	$1.8 \cdot 10^{-4}$	$1.2 \cdot 10^{-4}$	$2.1 \cdot 10^{-4}$	$1.2 \cdot 10^{-4}$	$7.8 \cdot 10^{-5}$

Table 4.9: Summary of absolute port scores for the suitability to develop a circular wind hub

	Port of Amsterdam	Port of Rotterdam	Port of Den Helder	Groningen Seaports	North Sea Port
Port willingness	1	0.5	1	1	0.75
Available space	0.75	0.25	1	1	0.75
Companies, infrastructure, activities	1	1	1	1	1
Accessibility	1	1	1	1	1
Circular strategies	0.29	0.04	0.36	0.04	0.13
Centrality (weighted)	0.85	0.58	1.00	0.59	0.37
Total	4.9	3.4	5.4	4.6	4.0

Table 4.10: Summary of normalised port scores for the suitability to develop a circular wind hub. The maximum possible score is 6

Finally, there a number of considerations in the EoL treatment options mentioned by the ports that are valuable to be aware of. These are:

- There must be a scale solution possible, not just incidental projects.
- It is important to consider decommissioning already in the production phase. For instance, by introducing a kind of deposit system for the blades for the manufacturer (as a form of Extended Producer Responsibility (EPR)).
- For refurbishment, it is important to differentiate between generations of turbines, since each new generation is improved compared to the last in terms of quality. For offshore turbines, specifically, it is important to consider that the blades have much to endure in an offshore environment. The question stands whether it is feasible to consistently reuse these offshore blades. Furthermore, experience at sea is limited, so there is little information available in terms of material degradation, quality development, and what the possibilities are for reusing the blades. Besides this, there is the issue of the availability of a maintenance history and who has access to this information. More research will be required in terms of what the options for reuse of the turbine or turbine components are after some 20 years in an offshore environment.
- It would also be interesting to look into the refurbishing of components instead of replacing them and disposing of the damaged component. A challenge for this is that wind turbine manufacturers do not necessarily manufacture all the components themselves. Yet, once they receive a component, it is given a new ID tag, meaning that at EoL it is difficult to determine where the component originally came from. Solving this can be done in two ways: either by enforcing more transparency, or if producers do not want this, by requiring them to take back their own products at EoL. It would be valuable to investigate how this is managed in for instance the aircraft or automotive industry, to compare and learn from these.
- Ideally, there is high-quality resource recovery, i.e. treatment options that are highest on the circularity ladder (see Figure 2.6). This includes redesign of WTB to facilitate EoL treatment of new/future WTB. While this is desirable, it also makes the material stream even more complex, for instance when some materials cannot go through the same recycling process.

4.2 RETURN VOLUMES OF END-OF-LIFE WIND TURBINE BLADES

The second focus area of the research is concerned with the dMFA model: defining and localising the material flows of EoL WTB in and around the Netherlands between 2020-2050. In Section 3.4, several concepts were introduced that require consideration: the current and future installed wind capacity, design of the blades - in material composition, size and mass -, locations of the wind farms, and the lifetime of the blades. This section first elaborates on these concepts to define them for their current and future values, and secondly presents the results from the dMFA.

4.2.1 Defining the key parameters: current and future values

This section describes the key parameters or concepts related to the dMFA. They are defined in terms of their current value as well as their development over time until 2030.

4.2.1.1 Installed capacity

The current installed capacity is composed of offshore wind in the Netherlands, Germany, Denmark, the UK, France and Belgium, and onshore wind in the Netherlands. A comparison is drawn between the reported installed capacities in these countries from WindEurope (Komusanac et al., 2021) and the installed capacity from the sum of all wind farms per country in the dataset. The results can be seen in Tables 4.11 and 4.12. For offshore wind in the Netherlands, France and Belgium there is no notable data discrepancy. For Germany, Denmark and the UK there is - however this is explained by the fact that these countries also have wind farms in other water basins than the North Sea. For onshore wind in the Netherlands, there is also a significant data gap of 12%. This missing data has been filled as described in Section 3.4.

	Reported offshore capacity [MW]	Offshore capacity in dataset [MW]
the Netherlands	2,611	2,604
Germany	7,689	6,749
Denmark	1,703	826
the UK	10,428	7,511
France	2	0
Belgium	2,261	2,262

Table 4.11: Installed offshore capacity in 2020 (Komusanac et al., 2021)

	Reported onshore capacity [MW]	Onshore capacity in dataset [MW]
the Netherlands	4,177	3,725

Table 4.12: Installed onshore capacity in 2020 (RVO, 2021a)

For wind capacity development, a range of scenarios exist. Ngiem and Pineda (2017) developed a low, mid and high scenario for European on- and offshore wind power development. However, the figures from these scenarios are a bit outdated already, since these were published in 2017 and recent news updates indicate new targets, where Germany has increased its offshore targets from 15 to 20 GW in 2030 (Reve, 2020) and so too the UK, from 30 to 40 GW (Reve, 2019). Therefore, a renewed version was published in 2020, whereby the WindEurope low scenario has been updated and an NECP scenario introduced (Pineda et al., 2020). These scenarios are elaborated on for onshore and offshore, separately.

Onshore wind

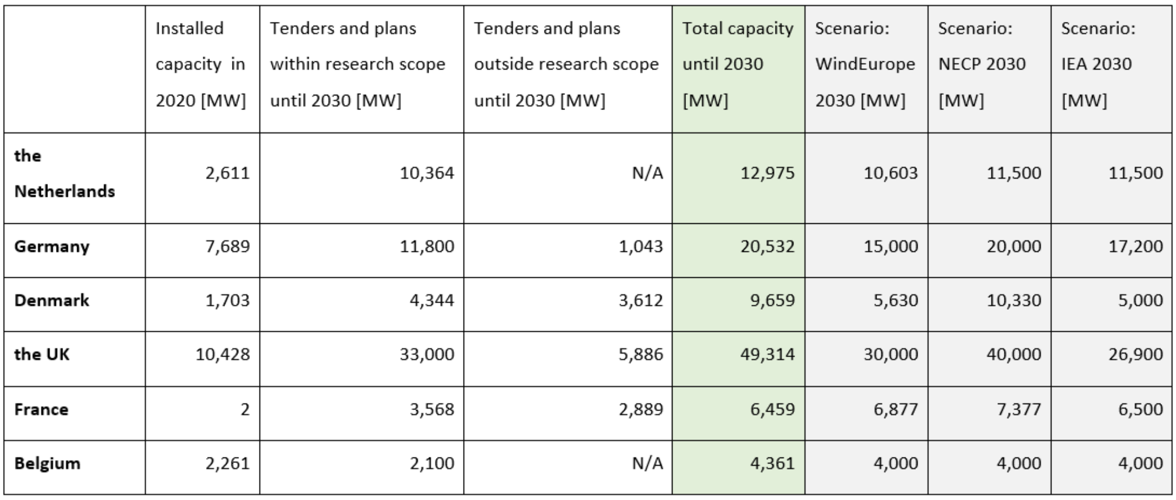
Onshore wind development is compared under different published scenarios from Dutch agencies. In Roelofs (2020), a variety of scenarios for installed wind capacity in the Netherlands in the coming decades is summarised. For onshore wind until 2030, this varies between roughly 5 GW to 10 GW. Onshore wind development faces a number of issues such as the availability of space on land and social challenges. The impact of public opinion on the development of onshore wind has become apparent recently, whereby the standards and norms around aspects like noise and shadows from wind turbines on land must be re-evaluated (Raad van State, 2021). This will cause a potentially significant delay in the installation of onshore wind capacity in the Netherlands.

Ultimately, three scenarios for onshore wind are evaluated in the research: 6 GW, 7 GW (WindEurope low scenario) and 9 GW (NECP scenario) by 2030. It is assumed that these capacities are reached according to a linear pathway from today.

Adoption of these three scenarios in the model reveals that the different scenarios yield very similar results. While onshore wind makes up a significant share of total capacity until around 2010, it is quickly taken over by offshore wind which claims some 80% of capacity inflows after 2012 and even 95% after 2026. Naturally, this is due to the fact that offshore wind in this research is composed of six countries, whilst onshore wind is only considered for the Netherlands - which is simultaneously a rather small country for onshore wind compared to for instance Germany, the UK or France. Since the difference in results is so limited, only the mid-scenario of 7 GW by 2030 is adopted.

Offshore wind

Offshore wind development is completed with the IEA outlook to 2030 (IEA, 2019) next to the WindEurope and NECP predictions. The development of offshore wind is first approached by analysing the existing tenders and planned projects in the North Sea and English Channel. Next, the sum of these plans are compared with the aforementioned scenarios. The outcome of this can be seen in Table 4.13.



	Installed capacity in 2020 [MW]	Tenders and plans within research scope until 2030 [MW]	Tenders and plans outside research scope until 2030 [MW]	Total capacity until 2030 [MW]	Scenario: WindEurope 2030 [MW]	Scenario: NECP 2030 [MW]	Scenario: IEA 2030 [MW]
the Netherlands	2,611	10,364	N/A	12,975	10,603	11,500	11,500
Germany	7,689	11,800	1,043	20,532	15,000	20,000	17,200
Denmark	1,703	4,344	3,612	9,659	5,630	10,330	5,000
the UK	10,428	33,000	5,886	49,314	30,000	40,000	26,900
France	2	3,568	2,889	6,459	6,877	7,377	6,500
Belgium	2,261	2,100	N/A	4,361	4,000	4,000	4,000

Table 4.13: Offshore wind capacity development by 2030. The current and planned capacity per country up to 2030 is compared to different scenarios for offshore wind capacity in 2030

It can be seen that the sum of current installed capacity in 2020 with the tenders and projects in the North Sea and other water basins until 2030 (the first three columns, summed in the fourth column) exceed the scenario capacity (the final columns) for four of the six countries; for Denmark and France, it is just a bit below the scenario capacities. However, these differences are considered minor and not significant to require further scenario implementation. Besides, it may also well be possible that the remaining capacity is installed (at least partially) in other water bodies. Therefore, the development of installed offshore wind capacity until 2030 in this research is considered based on the tenders and planned projects within the geographical scope.

The total capacity inflows in the model until 2030 for offshore and onshore turbines is illustrated in Figure 4.2.

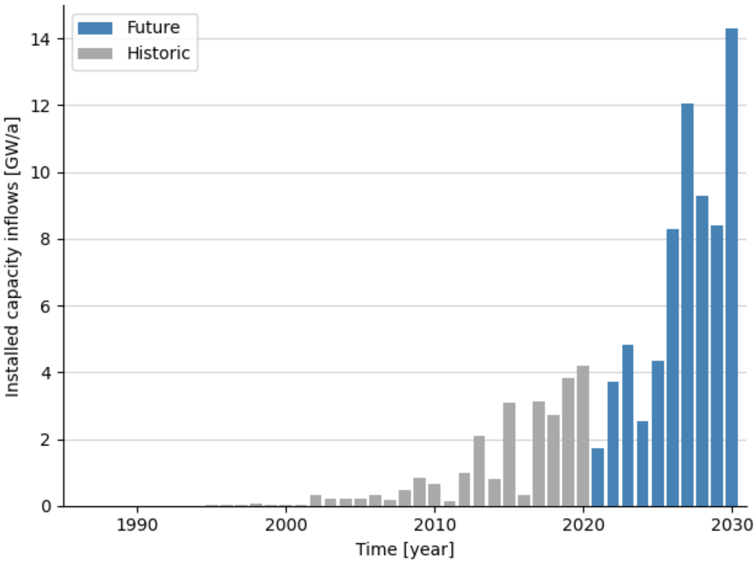


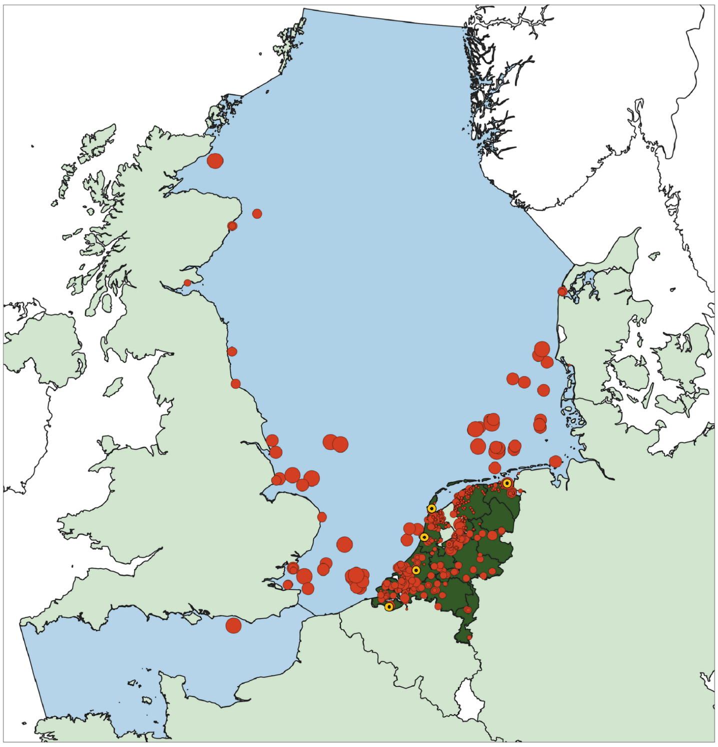
Figure 4.2: Annual installed capacity inflows within the defined region until 2030

4.2.1.2 *Locations of wind farms*

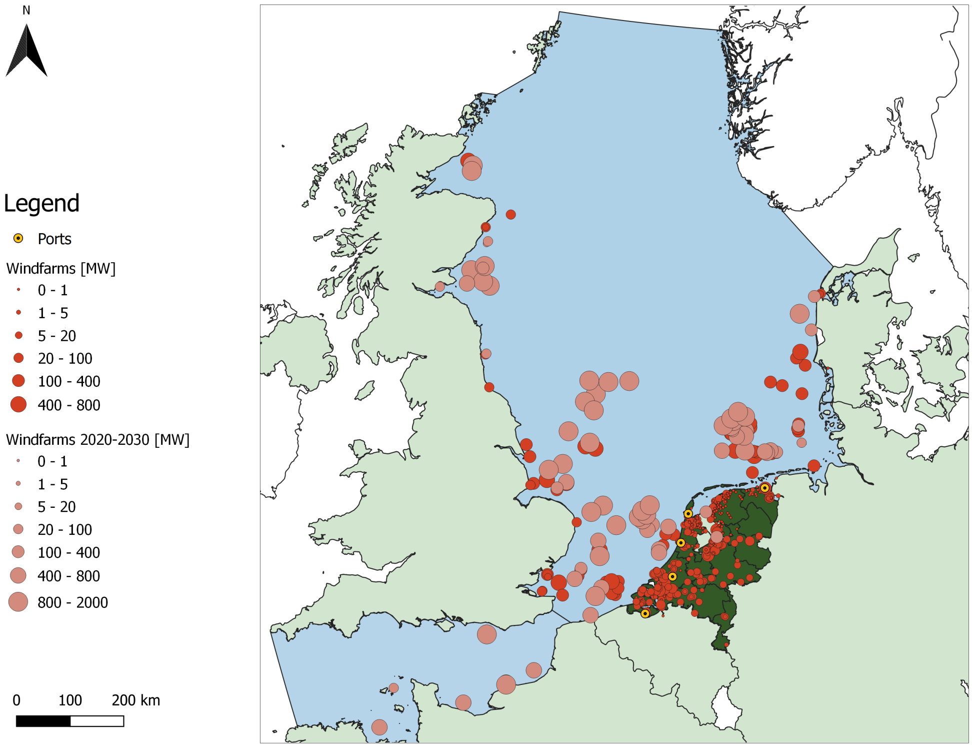
In Figure 4.3a, the current installed wind farms are visualised. As the North Sea held 79% of all European offshore wind in 2020, compared to 12% in the Irish Sea, 9% in the Baltic Sea, and ≤1% in the Atlantic Ocean (Ramírez et al., 2021), this sea basin clearly plays the largest role in the offshore wind sector. Therefore, only the North Sea with extension to the English Channel is considered for offshore locations.

The coordinates for future offshore wind farms were found by several steps. The latitude was given by (4COffshore, 2021); the corresponding longitude was found by consulting webpages of the wind farm or the responsible government agency in that country, by comparing it to known locations of other wind farms nearby, or by plotting it on Google Maps. These coordinates correspond to a central location within the wind farm. For onshore wind, there is much less certainty regarding the specific locations for the wind farms; the plans for this are still being finalised. Therefore, the centroid of each province in the Netherlands is taken as a proxy for wind farm locations, and the capacity development under the different scenarios is divided according to the regional distribution between the provinces that is currently in place. More information on this can be found in Appendix D.1 and E.1.

The development of offshore wind between 2020-2030 can be seen in Figure 4.3b. Over time, a trend can be seen of installations reaching deeper waters and wind farms becoming larger in size. Still, new wind farms seem to develop in relative proximity of current installations. Offshore developments in France can also be clearly noticed, with zero wind farms in 2020 to five in the English Channel by 2030.



(a) Windfarms in 2020



(b) Windfarms by 2030

Figure 4.3: Current and future installed wind farms under analysis
Blue*: offshore extents (English Channel and North Sea),* ***dark green****: onshore extents (the Netherlands),* ***light green****: countries whose offshore area is included,* ***red****: existing wind farms in 2020,* ***pink****: new offshore wind farms until 2030*
Projection: EPSG:4326

4.2.1.3 Turbine manufacturers

In 2019, the share of manufacturers in the European wind industry was distributed as follows: Vestas 29%, SGRE 26%, Enercon 19%, Senvion 11%, Nordex-Acciona 8%, GE 6% (IRENA, 2019). For offshore, specifically, Vestas and SGRE combined make up an even larger share, with 24% and 68% in 2020, respectively. The share of GE in the European offshore sector was only 1.4% (Ramírez et al., 2021).

The share of manufacturers in onshore wind is distributed differently. Analysis by (Roelofs, 2020) shows the following distribution: Enercon 38%, Vestas 27%, SGRE 6%, Nordex 8%, Neg Micon 8%, Senvion 6%, Lagerwey 2%, and others 6%. Lagerwey has since been taken over by Enercon.

This share - for both onshore and offshore - is assumed to remain the same until 2030.

4.2.1.4 Material composition of blades

As discussed in Section 2.3, the WTB consist mainly of resin (the polymer matrix) and glass fibres. With the growth in blade size, the growth in weight of the blade must be limited. This is often done by combining the glass fibres with carbon fibres as these are lighter (Beauson and Brøndsted, 2016). Thus, a small percentage of the GF is replaced by CF (Zimmermann et al., 2013; Andersen, 2015); around 6% (Lefeuvre et al., 2019). The use of CF remains limited due to their high costs (Zimmermann et al., 2013). These higher costs are brought about due to the use of more costly raw materials in CF compared to GF, and a significantly higher energy demand to produce the CF: 183-286 MJ/kg vs. 13-32 MJ/kg for GF (Olivieux et al., 2015).

The following assumptions regarding the use of CF in blade manufacturing are adopted in this research, following Lefeuvre et al. (2019):

- There is no CF in WTB of turbines prior to 2010 or turbines smaller than 2 MW since these turbines are limited in size;
- When used, the CF makes up 6% of the blade mass.

The material composition of a 1.5 MW blade is given by Liu and Barlow (2016)[5]:

Material	Weight-percent
Fibre (glass, carbon)	60.4%
Resin	32.3%
Steel	1.1%
Copper	0.3%
Aluminium	0.0%
Balsa	2.3%
PVC	1.7%
Paint	0.9%
Putty	0.7%
Spray adhesives	0.0%

Table 4.14: Material composition (in weight-percent) of a 1.5 MW wind turbine blade (Liu and Barlow, 2016)

Other overviews state that in weight-percentage, the blade is made of 95% composite material, 3% steel or iron and 0.3% aluminium (Tota-Maharaj and McMahon, 2020), or 80-95% GFRP, 0-10% CFRP, 0-15% plastics, 2-9% steel and 0-1% aluminium (Andersen, 2015). These values correspond well to the overview from Table 4.14. From these overviews it becomes clear that the role of materials other than the fibres and resin is extremely limited. Therefore, some studies have chosen to omit these other materials and assume the blade is completely made of composite material,

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[5] Aluminium and spray adhesives are given as 0.0% as the original source also only reports 1 decimal place.

where the ratio of resin/fibre is 35/65 (Sommer and Walther, 2021; Tota-Maharaj and McMahon, 2020). Detailed bills of materials of blades are not generally publicly available and blade manufacturers are hesitant in sharing this information. Therefore, even though it is based on a 1.5 MW blade, this research will adopt the values of Table 4.14 as best estimate for the material composition of WTB.

The share of CF may change in the future as blades continue to grow in size. For instance, the New Energy Externalities Developments for Sustainability predicted in 2008 that the share of CF in fibres used in blades could reach 50% by 2025 (Liu and Barlow, 2016). However, Zimmermann et al. (2013) mention that a significant increase in the use of CF has not been observed, and this is reinforced by personal communications with Julie Teuwen, SGRE and LM Wind Power. A slight increase in the share of CF may be expected, but it will not likely exceed 7% in the turbines installed in the next 10 years (personal communication with Julie Teuwen). As this is such a minimal change, the share of CF is kept constant at 6% in this research. This is also supported by the fact that CF is more expensive than GF, while the wind sector is mainly cost-driven. Hence the share of CF will not likely increase much.

In Section 2.4.1, a number of developments in WTB design are described. The most important and high potential development is the usage of thermoplastics as opposed to thermosets. While these developments are noteworthy and promising, the analysis has found it unrealistic that they will be implemented on a significant scale before 2030. This is supported by personal communications with Julie Teuwen. Therefore, the general material composition as described in Table 4.14 will remain the same for all blades in this research.

The resin type is a distinctive choice for manufacturers. The main choice is between epoxy and polyester. While epoxy outperforms polyester in terms of emissions from solvents (Vestas, 2002) and mechanical characteristics (Kuipers, 2019), it is also two to three times more expensive (Stewart, 2012; Kuipers, 2019). The use of resin is an important aspect to be aware of since this influences the EoL treatment: solvolysis works better for polyester than epoxy (Olivieux et al., 2015) and in the fluidised bed process, polyester requires lower temperatures (Yang et al., 2012). Moreover, the newly-established CETEC research consortium looks at a new way of recycling specifically epoxy-based blades (Nehls, 2021). While this thesis research does not look in further detail at these recycling techniques (for more information, see Section 4.3.1.3), having the differentiation in resin type in the current analysis does offer a valuable stepping stone for further research.

To shed light on the use of resin, the manufacturer shares from Section 4.2.1.3 are applied to the outflows of EoL WTB. This then sheds light on the differences in resin usage.

From consulting manufacturers' websites and specifications of their turbines, as well as from personal communications with SGRE and LM Wind Power, it has been found that in general, Vestas, SGRE and Enercon use epoxy, while LM Wind Power uses polyester and Nordex seems to use both. For the remaining manufacturers, a 50/50 use of epoxy/polyester is assumed. Given the manufacturer shares, it is assumed in the research that 95.3% of all offshore turbines and 85.5% of all onshore turbines contain epoxy.

It should be noted that this is a rough estimation. There are also distinctions to be found in epoxy or polyester type, and furthermore LM Wind Power may also manufacture blades for Vestas and SGRE. Hence it is not so easily or clearly defined which blades have which resin. Therefore more detailed analysis would be required to approach this more accurately. This is outside the scope of this research.

4.2.1.5 *Size of blades*

In 2020, newly installed turbines in Europe had an average capacity of 8.2 MW for offshore turbines and 3.3 MW for onshore turbines (Komusanac et al., 2021). Of course, each year a range of models is installed; for offshore wind farms in

Europe in 2018, this was between 3.5 and 8.8 MW (IRENA, 2019). The distribution of turbine sizes of the current stock of turbines within the scope of this research can be seen in Table 4.15. Two things become instantly apparent: first of all, that most turbines are still relatively small (<4 MW); and secondly, that offshore turbines are generally larger than onshore ones. For offshore turbines, the maximum turbine power rating is 9.5 MW; for onshore this is 7.5 MW (the actual largest turbine is the 12 MW Haliade X, which is a demonstration turbine intended for the offshore environment).

Power rating [MW]	Frequency: onshore	Frequency: offshore
$0 \leq P \leq 1$	765	4
$1 < P \leq 2$	267	0
$2 < P \leq 3$	518	753
$3 < P \leq 4$	275	1,412
$4 < P \leq 5$	22	213
$5 < P \leq 10$	27	1,635
$10 < P \leq 20$	1	0

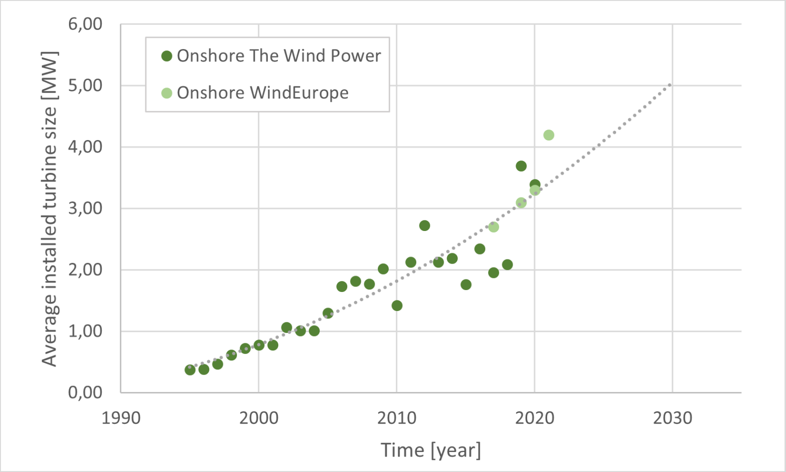
Table 4.15: Power rating of currently installed onshore and offshore turbines in the analysis

In terms of future developments in blade size, the general trend thus far has been a consistent growth in rotor diameter as wind turbines have reached higher power ratings. This is illustrated in Figure 2.5.

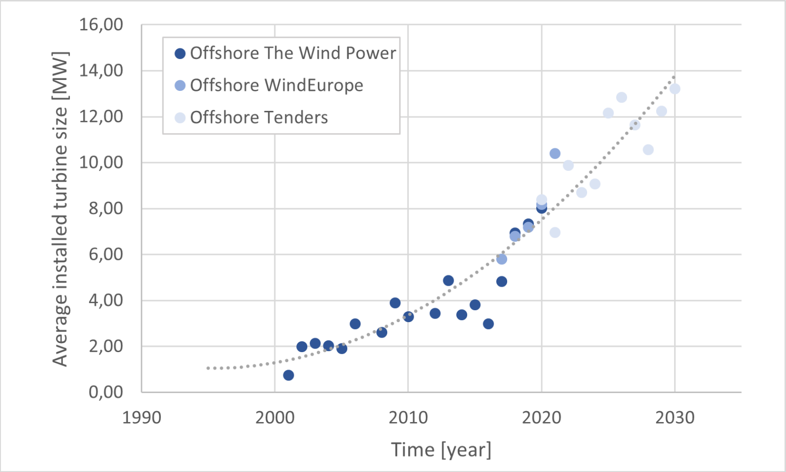
While the average offshore turbine size in 2020 was 8.2 MW, new orders placed in that year already included 10-13 MW turbines, which are expected for projects after 2022 (Ramírez et al., 2021). The feasibility of a 20 MW turbine is already mentioned by Agora Energiewende (2017) and IRENA (2019). From personal communications with SGRE and LM Wind Power, it seems that manufacturers do not see a clear cap on blade size from a technical viewpoint. However, there must still be a business case in it as it creates other challenges, for instance in developing a suitable supply chain and proper logistics. Zimmermann et al. (2013) mention that onshore transport of blades will become very difficult due to carrying limits of bridges and other infrastructure. They therefore expect onshore wind turbines to stay below 4 MW with a maximum rotor diameter of 100 m. Modular blades would help resolve this obstacle; such blades have entered the testing phase, however the concept is not yet cost-competitive and it remains difficult to predict whether they will really enter the market (Agora Energiewende, 2017). Alternatively, transport for onshore turbines could - as much as possible - be moved from road to waterways.

The question remains how the average turbine size will develop over time. Naturally, each year a range of turbine sizes will be installed. Therefore, a trend is drawn based on historic data taken from the database from *The Wind Power*, whereby the earliest years (1989, 1993 and 1994) were left out of the analysis as these only included 1 or 2 turbines. This data was complemented with what is known from external analyses (Fraile and Mbistrova, 2018; Komusanac et al., 2020a, 2021) and from defined tenders from 4COffshore (2021). The found trend fits relatively well to the average turbine power rating over time provided by Fraile et al. (2021), and can be seen in Figure 4.4.

While some of the tenders for offshore wind include the turbine size that will be installed at the wind farm, some only include the total capacity of the planned wind farm. For those tenders, the average turbine size per year from Figure 4.4b is used to fill this data gap. Similarly, for onshore wind development, the average turbine size per year from Figure 4.4a is applied.



(a) Onshore



(b) Offshore

Figure 4.4: Average turbine power rating development until 2030, based on *The Wind Power*-dataset, WindEurope reports and known tenders. (a) For onshore turbines (b) For offshore turbines

4.2.1.6 Mass of blades

Blades of wind turbines of different rated power will also differ in their mass. Oftentimes, an average value of around 10 tonnes of blade material per MW is adopted (Andersen et al., 2014; Lefeuvre et al., 2019; Sultan et al., 2018). However, analysis of 56 wind turbine models by Liu and Barlow (2017) shows how the mass of the blades is dependent on the turbine size, as shown in Figure 4.5. The decrease in blade mass for models $\geq$ 5 MW can be explained by improvements in design, material use and manufacturing technique.

A limitation here is that this overview groups all larger models under $\geq$5 MW. As there are now developments for 15-20 MW turbines, it was investigated whether further categorisation for larger models is required. However, there is very limited information openly available for larger turbines and their blade mass. For the data that is available, the blade mass intensity of 12.58 t/MW as defined by Liu and Barlow (2017) is compared to the provided mass intensity of the turbines. This can be seen in Table 4.16. From this, it can be concluded that the blade mass intensity from Liu and Barlow (2017) is a reasonable fit, with a deviation of >10% in only one case. The blade mass intensity of Liu and Barlow (2017) has additionally been validated by Roelofs (2020) and will therefore be used in the research. Nevertheless, when more data is available, this categorisation could be extended and refined for larger models.

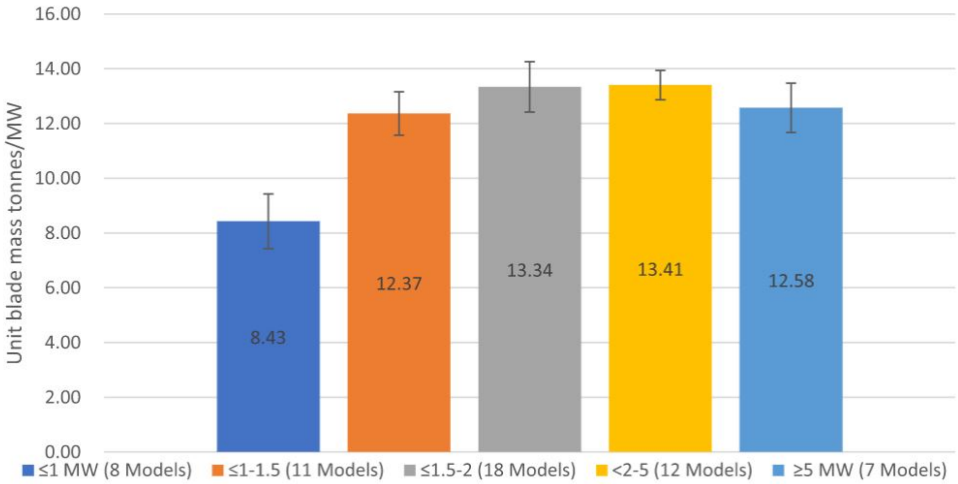


Figure 4.5: Blade mass vs. turbine rated power (Liu and Barlow, 2017, p. 232)

Turbine power rating [MW]	Type	Mass intensity of blades [t/MW]	% deviation from expected mass intensity
8	LEANWIND 8 MW reference wind turbine	13.13	4.3
9.5	MHI Vestas Offshore V164-9.5	11.05	-12.1
9.5	MHI Vestas Offshore V174-9.5	11.37	-9.6
10	DTU 10 MW reference wind turbine	12.51	-0.5
12	GE General Electric Haliade-X 12 MW	13.75	9.3
15	IEA reference wind turbine	13.00	3.3

Table 4.16: Blade mass intensity for larger turbine models, compared to expected blade mass intensity of 12.58 t/MW from Liu and Barlow (2017)

Manufacturers may apply different production processes and have differences in material usage in their blades. For instance, SGRE design and manufacture their blades in such a way that the blade is created in one piece, thereby eliminating the need for any joints (Siemens Gamesa Renewable Energy, 2021). This also means the blade is lighter than other models. Personal communication with SGRE has revealed that their blades are roughly 2-3% lighter than blades from other manufacturers, though the overall material composition is the same. While no full comparison has taken place with all blade types, it can generally be assumed that no joints means lower mass.

For onshore wind, Section 4.2.1.3 has shown that SGRE has a 6% share; for offshore wind, it is 68%. Applying these percentages to the 2-3% lower mass of SGRE blades means that the total mass of offshore WTB would be 1.3-2% lower, while for onshore WTB it would be 0.12-0.18% lower. This means that the total calculated EoL volume of WTB would be 1.42-2.18% lower, which is deemed insignificant for implementation in the model.

4.2.1.7 Lifetime of turbines

Design lifetimes for onshore turbines are often 20 years (Razdan and Garrett, 2019; Siemens, 2014), and for offshore turbines 25 years (Siemens Gamesa Renewable Energy, nd), or even 30 years (Kruse, 2019). However, these are design lifetimes; in real life, the lifetime will deviate from this since no turbine can be completely failure-free (Papadakis et al., 2010). Specifically for offshore turbines, there has been too little actual experience with wind farms reaching their EoL to support these claims, especially for large-scale wind farms. Historical data on the lifetime of wind turbines is based mainly on small-scale onshore turbines, which is not very accurate for an industry that develops at such a fast pace and that is moving further and further offshore. The lack of experience with dismantling large-scale offshore wind farms also makes it difficult to say something about the possibilities for lifetime extension (Liu and Barlow, 2017). For WTB, it is expected that 27 years is the limit for operational life; after this time they will have experienced too much fatigue or defects that it is no longer feasible to repair them (Liu and Barlow, 2017).

The choice or need to dismantle a wind farm depends on numerous factors. These include the wearing down of the components, repair costs, legal aspects and economic considerations such as the availability of funding (Kruse, 2019) or the choice to repower the wind farm with larger turbine models. For these reasons, a wind farm is oftentimes dismantled at a different time than its design lifetime. From personal communications with numerous experts, it was revealed that it is becoming more common that a wind farm is dismantled at an earlier date because replacing it with new, larger models is economically appealing. These dismantled turbines may then serve another decade orso in an immature market (see Section 2.4.2). At the same time, the Netherlands have recently proposed to extend the permits of wind farms to last another 20 years, thus potentially totalling to a total of around 40 years of operational life (Durakovic, 2020c).

In many previously performed studies on the quantification of EoL WTB material, the lifetime of the blades is considered to be of static nature. It is often estimated to be 20 years (Andersen et al., 2016; Cooperman et al., 2021; Liu and Barlow, 2015; Kruse, 2019) or 25 years (Lefeuvre et al., 2019; Sultan et al., 2018). In another study, Liu and Barlow (2017) assume three different scenarios where the lifetime varies between 18, 20 and 25 years. Other studies may assume an even more optimistic estimate, reaching up to 30 years (Sultan et al., 2018).

Due to the above-mentioned factors, the time after which a wind farm may need (or is chosen) to be dismantled can vary and is influenced by a variety of factors. Therefore, it does not seem an accurate approach to model the lifetime as a static value, but rather as a continuous probability distribution function. Alternatives in literature are a Weibull function (Cao et al., 2019; Lichtenegger et al., 2020; Zimmermann et al., 2013) and a Normal distribution (Sacchi et al., 2019; Roelofs, 2020). A Weibull distribution is often used in reliability analysis to approach the *technical* lifetime of products. Since the choice to dismantle is not only dependent on technical failure, the Weibull function is not deemed to be fitting.

A Normal distribution better encompasses the variety of reasons why a wind farm might be dismantled earlier or later than its design lifetime. Sacchi et al. (2019) use a Normal distribution with a mean, μ, of 18.42 and standard deviation, σ, of 4. Roelofs (2020) applies a Normal distribution with an increasing mean until 2030; from 18 to 20 to 22 years for onshore turbines, and from 18 to 24 years for offshore turbines. Historic and future turbines are given a standard deviation of 5.3 and 4, respectively.

It should be noted that lifetime is not the sole relevant indicator for waste streams of EoL WTB material. After Liu and Barlow (2017), manufacturing and service waste of WTB also play a role. While these streams are not unimportant, this research only considers the EoL stream. Background on these waste streams is provided in Appendix A.3.

Analysis of the lifetime of dismantled wind farms in the dataset used in this research gives a Normal distribution defined by the parameters given in Table 4.17. There were only 20 offshore wind turbines in the dataset that had been dismantled and for which the commissioning and decommissioning dates were known. This is too small a sample to draw conclusions from. Therefore, the lifetime of turbines up to and including 2020 is approached by a Normal distribution based on the parameters from the combined onshore and offshore dataset, i.e. a mean (μ) of 18 years (rounded) with a standard deviation (σ) of 5.32, based on 2028 decommissioned turbines for which the commissioning and decommissioning year was known. This is in line with Sacchi et al. (2019) and Roelofs (2020). The distribution is shown in Figure 4.6.

μ	σ	N
18	5.32	2028

Table 4.17: Normal distribution parameters of lifetime of dismantled onshore and offshore turbines

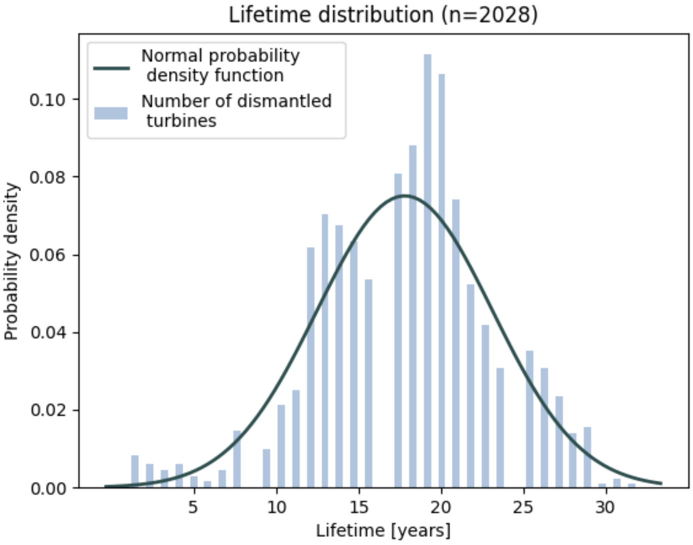


Figure 4.6: Normal distribution of lifetime of dismantled on- and offshore turbines. Based on turbines in the dataset for which commissioning and decommissioning dates were known

It is assumed that the mean lifetime of wind farms until 2030 develops as in Table 4.18. The mean lifetime of new offshore wind farms is considered to be a bit longer than onshore turbines, due to the high costs for installation and decommissioning in the offshore environment. At the same time, it is assumed that the standard deviation for both on- and offshore turbines will decrease slightly as more experience is expected to bring about more uniformity. For all years after 2020, the standard deviation is assumed to be 4, in line with Sacchi et al. (2019) and Roelofs (2020). The mean lifetime is modelled under different scenarios: the default scenario based on historic data and the reasoning mentioned here; a low scenario where this is decreased by 20%; and a high scenario where this is increased by 20%.

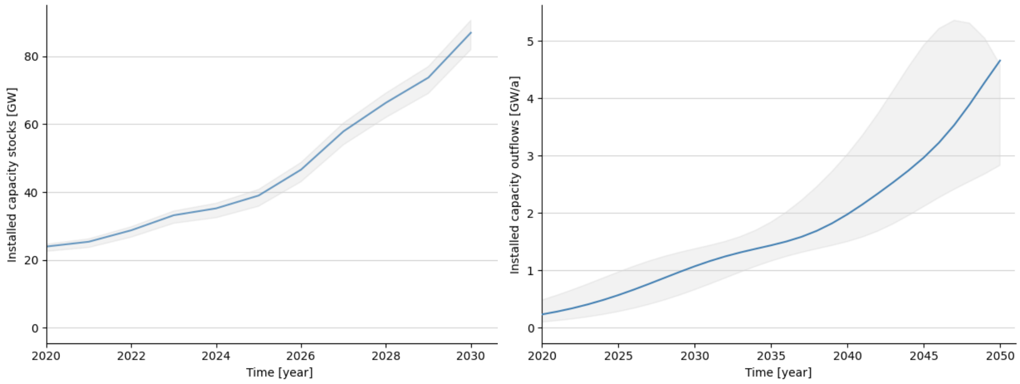
		< 2020	≤ 2025	> 2025
Low	Onshore	14	16	18
	Offshore	14	18	20
Default	Onshore	18	20	22
	Offshore	18	22	25
High	Onshore	22	24	26
	Offshore	22	26	30

Table 4.18: Scenarios for average lifetime development for onshore and offshore turbines

4.2.2 Material flows of end-of-life wind turbine blades between 2020-2050

This section offers the results from the dMFA. Since inflows (installed capacity) only go up to 2030 and are set to 0 after this time, inflows and stocks are only shown up to 2030. Outflows are relevant until 2050.

The total installed capacity stock and outflows develop as shown in Figure 4.7a and 4.7b. The middle line illustrates the default lifetime scenario while the grey cloud around this line shows the spread between the high and low lifetime scenarios. The upper boundary of the cloud illustrates the low-lifetime scenario, whilst the lower boundary illustrates the high-lifetime one. This is the case for all the upcoming graphs.

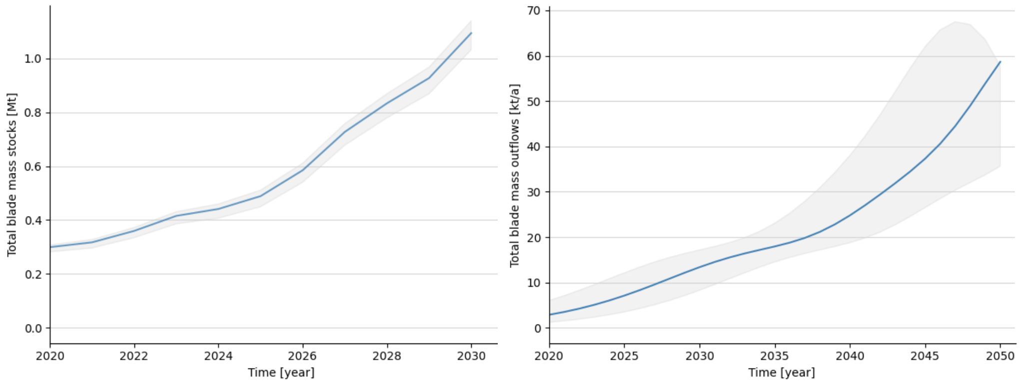


(a) Capacity stock

(b) Capacity outflows

Figure 4.7: Wind capacity development (a) Stocks until 2030 (b) Annual outflows until 2050

The blade mass stock and annual outflows are shown in Figure 4.8. These logically follow a similar pattern as the total capacity outflow. The annual outflow reaches 59 kt per annum in 2050. The total cumulative outflows per material up to 2050 in each scenario are summarised in Table 4.19.



(a) Blade mass stock

(b) Blade mass outflows

Figure 4.8: Blade mass development (a) Stocks until 2030 (b) Annual outflows until 2050

A 20% shorter average lifetime goes paired with higher outflows until 2046 (where the cloud reaches a peak), after which it experiences a steep decline. The consistently higher outflows in this scenario are explained by the fact that with a lower average lifetime, wind farms are decommissioned sooner. Meanwhile, the inflow of capacity has remained the same, hence the same amount of material enters the system, but leaves the system quicker, meaning that in the final years, there is less material available. In other words, the consistently higher outflow is being offset in the final years by experiencing a sharp decrease. If capacity inflow is included post-2030, this decrease should not be observed. A 20% higher average lifetime (the lower limit of the cloud) follows a to-be expected trend, namely consistently lower outflows than the default scenario, with a delayed response owing to the prolonged average lifetime.

The total blade mass is composed of numerous materials as described in Section 4.2.1.4. The outflow of composites (GF, resin, CF) and minor materials is shown in Figure 4.9. The annual outflow of composites (the sum of GF, CF and resin) amounts to around 54 kt per annum in 2050. As mentioned in Section 4.2.1.3, there is a divide between manufacturers that apply epoxy and manufacturers that apply polyester as resin. By far, the majority of blades is manufactured with epoxy. This differentiation can be seen in Figure 4.10. It is therefore advisable that most research or advancements in treatment techniques be focused on epoxy. It can also be clearly seen that the minor materials play a very small role; these make up <10% of the total blade mass.

A noticeable trend in these outflows is the flattening of the curve between 2030-2036. This is explained by a decrease in onshore inflows between 2013-2018 and strongly fluctuating offshore inflows in these years. Meanwhile, onshore wind still makes up some 20-30% of inflows in this time frame. With an average lifetime of 18 years for turbines installed prior to 2020, this lower inflow will indeed show its effects around 2031-2036, as is observed.

	Low lifetime [kt]	Default [kt]	High lifetime [kt]
Total blade mass	995	689	469
Glass fibre	563	390	266
Resin	321	223	151
Carbon fibre	38	26	17
Balsa	23	16	11
PVC	17	12	8
Steel	11	8	5
Paint	9	6	4
Putty	7	5	3
Copper	3	2	1

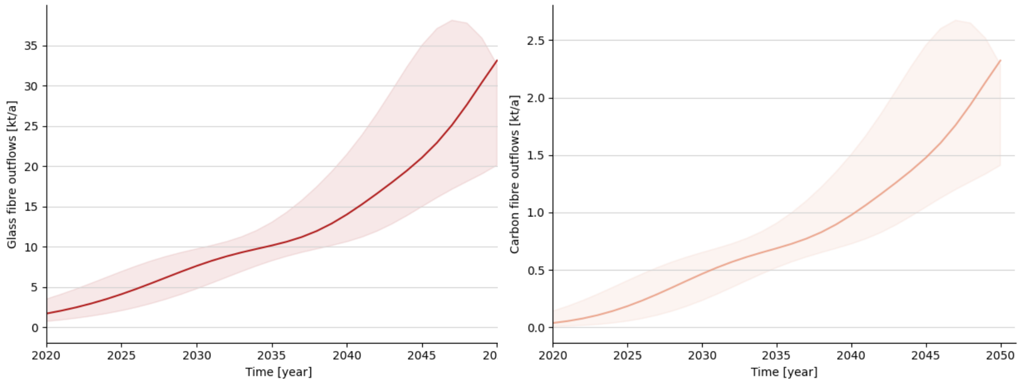
Table 4.19: Cumulative material outflows by 2050 under each lifetime scenario

The results are compared to past analyses to ascertain whether they are plausible. Lichtenegger et al. (2020) calculate around 180 kt and 320 kt of blade waste in Europe in 2030 and 2050, respectively. The ratio between onshore/offshore in their analysis is around 80/20. For onshore wind capacity, the Netherlands constitutes around 2% of the countries in their study; for offshore wind, the countries in this analysis constitute around 90%. Scaling the original results of Lichtenegger et al. (2020) to correspond to the same scope as this research then results in an annual outflow of EoL WTB material of 30 kt in 2030, which grows to around 77 kt in 2050.

Liu and Barlow (2017) report a global annual EoL WTB material outflow of around 500 kt in 2030 and almost 2 Mt in 2050. Europe makes up around 25% of this flow. Applying the ratios derived from Lichtenegger et al. (2020) results in an annual outflow of 25 kt in 2030, which grows to around 98 kt in 2050.

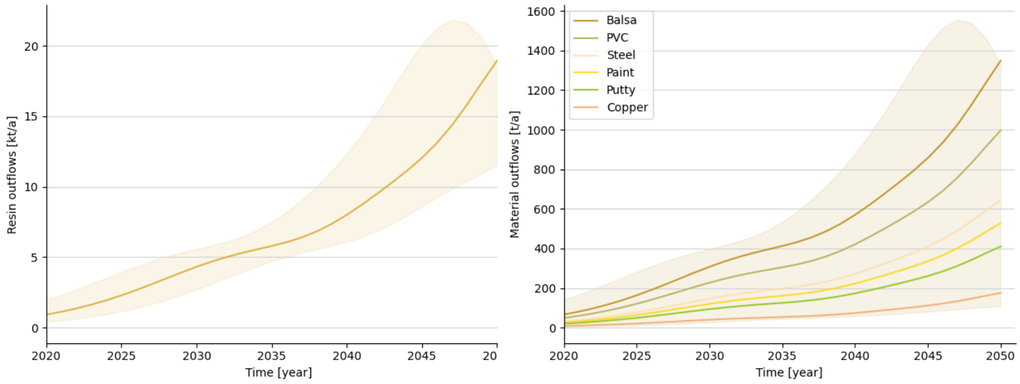
A recent study by van der Meulen et al. (2020b) predict the material flows from EoL offshore wind turbines from 2020 to 2050 in the North Sea. They estimate a steadily increasing annual material flow of composites that reaches between 40 to 50 kilotonnes in 2050 (van der Meulen et al., 2020b).

Roelofs (2020) calculates a composite outflow between 4 kt (low scenario), 14 kt (mid scenario) and 30 kt (high scenario) in 2050 for combined onshore and offshore wind in the Netherlands. In this study, the Netherlands makes up around 24% of total installed capacity. The mid-value calculated by Roelofs (2020) - 14 kt - is roughly 26% of the 54 kt of composites from this research. This therefore fits quite well.



(a) Glass fibre

(b) Carbon fibre



(c) Resin

(d) Minor materials

Figure 4.9: Annual material outflows until 2050 (a) Glass fibre (b) Carbon fibre (c) Resin (d) Minor materials

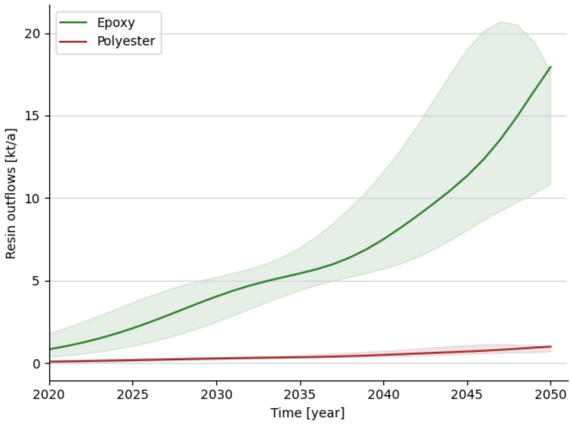


Figure 4.10: Annual epoxy and polyester outflows until 2050

The higher results found by Lichtenegger et al. (2020) and Liu and Barlow (2017) are partially explained by the use of different scenarios and lifetime modelling. Furthermore, these studies also consider other waste flows than solely EoL, such as repowering and manufacturing and service waste. Looking only at the outflows from Lichtenegger et al. (2020) that are resultant from decommissioning, these reach 20 kt in 2030 and 53 kt in 2050, which is fairly similar to the results from this study. Hence, the results of this study (15 kt in 2030, 59 kt in 2050) seem plausible.

In order to investigate the impact of the chosen average lifetimes and turbine size developments, these variables were increased and decreased by 10%. Sensitivity analysis of the change in turbine size showed that the effect thereof was negligible.

Comparisons of the default scenario with a ±10% change in average lifetime yields changes in annual and cumulative blade mass outflows significantly greater than 10% in almost all years. In all cases, the magnitude of the percentage change decreases over time. Table 4.20 shows the final % change in cumulative blade mass outflows by 2050 for each scenario in the sensitivity analysis. The complete results can be found in Appendix G.1.

In each scenario, the sensitivity analysis is significant, though the low average lifetime scenario shows the least response, especially in the case of -10%. For the default and high average lifetime scenarios, the % changes are significantly higher. In these two scenarios, the percentage change is in all cases higher under the -10% sensitivity compared to +10%. In other words, a shortened lifetime has a stronger effect on the total blade mass outflows than a longer lifetime. Nevertheless, in both directions the changes are significant. Since the model results show strong sensitivity to changes in average lifetime, this is an important parameter to be aware of.

	Cumulative blade mass [kt]	% change
Low lifetime	995	
+10%	876	−12%
−10%	1084	+9%
Default lifetime	689	
+10%	558	−19%
−10%	847	+23%
High lifetime	469	
+10%	381	−19%
−10%	587	+25%

Table 4.20: Cumulative blade mass outflows by 2050 under sensitivity analysis of average lifetime, rounded to whole numbers

4.3 EFFECT OF CIRCULAR STRATEGIES ON VOLUME & ECONOMIC AND ENVIRONMENTAL BENEFITS

This section considers the effect of different circular strategies on the expected return volume of EoL WTB that may be treated at each port, and the associated economic and environmental benefits that may be achieved. First, the available circular strategies are described and analysed in terms of their economic potential. Subsequently, the environmental impact of each circular strategy is assessed, based on a mutual comparison as well as compared to the material it replaces in each case. Following this, the transport cost of EoL WTB is determined. Based on both the transport cost and the economic value of the secondary WTB material, a study is done for each wind farm to establish whether it is economically viable to transport the EoL material to each port, under each circular strategy. As such, the final volume of EoL WTB that could be treated at each hub is determined. For the sake of theoretical insight, it is considered that each of the three circular strategies is applied to 100% of the blade material. In reality, there is no one-size-fits-all, and a combination of EoL strategies will need to be applied (FORCE Technology, 2017). Finally, the potential economic and environmental benefits under application of each circular strategy are estimated.

4.3.1 Economic potential of circular strategies

As introduced in Section 2.4, the three strategies under consideration are:

- Circular strategies based on reusing (reuse);
- Circular strategies based on repurposing (repurpose); and
- Circular strategies based on recycling (recycle) the WTB.

Each strategy is described in terms of the opportunities and limitations the strategy faces, what is required for market development and what the potential size of the market may be, as well as the economic value of the secondary material. For background information on each of the circular strategies, the reader is referred back to Section 2.4.

Determining the monetary value is a challenge since this depends on the market that can absorb the material, and this not yet been properly mapped out - especially for repurpose and recycle. A market-oriented approach is important to consider already now, since a producer requires resource-security in aspects such as price, quality, quantity and frequency of supply (personal communications with Anne Velenturf). An important note is that this research defines the economic value of the secondary material under the assumption that there *is* a market and that the market *can* absorb the material. While this is often not the case yet - or only to a limited extent - this non-existence of a market can turn around very quickly once a business case is developed.

While the analysis of the economic value is based on the assumption that a market exists, a critical reflection of the market potential under each circular strategy is offered.

4.3.1.1 Reuse

Under reuse, the blade is reused in its current form and for the same purpose. It may be the case that remanufacturing, refurbishment or repair is required prior to re-installing the blade for its second lifetime, to ensure that its quality is sufficient. This offers a high value product at relatively low costs (Jensen and Skelton, 2018).

Opportunities
The resale of used wind turbine components, including the blades, is commonly taking place through e-platforms (FORCE Technology, 2017). Examples of such platforms are Business in Wind, Spares in Motion and Reusable Parts. These platforms are at present limited to (generally small-sized) onshore turbines. Refurbishment of wind turbines and subsequent installation in less mature market is already happening (Cooperman et al., 2021), and has also come forward in the interviews with the ports as something they have had experience with. This offers another 10-15 years of operation. Wind turbine manufacturers are also taking this into their own hands: GE has for instance set up its own RePower programme whereby their onshore turbines are refurbished and repowered to last another 10+ years (GE, 2021).

Limitations
Reusing WTB also faces a number of challenges. The wind industry is developing at a very quick pace (Sultan et al., 2018), which limits this strategy to less mature markets, where wind power is only just starting up. While this market is not inexhaustible, there are a significant number of countries where wind power is only just developing - or has not developed yet (IRENA, 2021). An important aspect that deserves consideration in this case is to prevent a problem shift when the blades ultimately reach EoL in a country where much less stringent environmental regulations are in place, as this yields the risk that the WTB would still be incinerated or landfilled. As offshore wind is still relatively new and few offshore turbines have

been dismantled, there is little experience with refurbishing offshore turbines. It is unclear to what extent the quality of the blades has degraded after some 20 years in the offshore environment. Therefore, this is currently limited to onshore turbines only. Time and research will tell whether this is also feasible for offshore WTB.

Application of a used WTB for a second lifetime faces a number of barriers. First of all, proper documentation of the blade is required (FORCE Technology, 2017) which offers information with regard to material use, blade design and specifications. This differs per manufacturer and blade model, hence each blade will be slightly different. To achieve more transparency in this aspect creates tension with intellectual property and confidential information of manufacturers. In reality, this therefore limits reuse to that of the entire turbine and not individual blades. Furthermore, blades will differ in terms of quality at the time of decommissioning and there is a higher risk of blade failure (Liu et al., 2019). It is therefore a challenge to match the requirements for size, quality and remaining lifetime with a used blade (FORCE Technology, 2017). Especially for offshore WTB, the fear and expectation exists that the quality of the blades will have degraded too much that a sufficient quality can no longer be guaranteed.

Requirements for market development

To help progress the reusing of EoL WTB, two aspects are key. First of all, to arrive at more transparency in the wind sector. In order for the blade to be able to be properly reused, it is imperative that information on its quality (for which monitoring will be important), maintenance history, specifications and material composition are available to the interested parties. Clear agreements will have to be made for this. Second of all, more research is required on the development of offshore WTB and how well these are still able to perform in a new offshore environment - if at all. Since the offshore wind sector will grow significantly, a substantial amount of offshore WTB will become available for this.

Potential size of market

The potential of this market could theoretically be rather sizeable. In 2020, there were 74 countries worldwide with <100 MW of wind capacity installed (onshore and offshore combined), and many more with no offshore capacity at all (IRENA, 2021). Thus, there are plenty of countries with immature wind markets. Naturally, not all of these countries are applicable; perhaps they are not looking to expand their wind market, are wind conditions undesirable there, or perhaps they are located too far away that it does not make sense to transport the used blades so far. Still, Northern Africa, Eastern Europe and Central Asia could be applicable for this. As climate change mitigation becomes more and more pressing, one can imagine that purchasing second-hand turbines becomes more and more attractive. It is unlikely that blades will be reused individually since they differ per manufacturer and model; therefore this is limited to reusing the turbine in its entirety. With a lack of quality guarantees at present and a strong growth in wind turbine development, it seems unrealistic that this market will really take off.

Economic value

A second-hand wind turbine is estimated to be sold at half the original price, according to Ortegon et al. (2013). A recent study by Bortolotti et al. (2019) estimates the blade cost of three turbine models. The turbine models and blade cost are reported in Table 4.21. Other blade cost estimates are provided by TPI Composites (2003) and Red (2008). Their estimates are almost twice as high the ones provided by Bortolotti et al. (2019), even after accounting for the fact that their studies include transport costs, which make up around 7% of the total blade cost (TPI Composites, 2003), which the study by Bortolotti et al. (2019) does not include. Another potential reason why their cost estimates are significantly higher is that TPI Composites (2003) and Red (2008) are from 2003 and 2008, respectively, whilst the study by

Bortolotti et al. (2019) is much more recent. Since the wind industry undergoes such rapid developments, it is chosen to adopt the most recent reported figures. A simplified approach is adopted by assuming the average of the reported figures for all WTB - regardless of size and whether it is an onshore or offshore turbine -, i.e. $40,000/MW, or €34,000/MW for a new blade.

This research adopts the estimation of Ortegon et al. (2013) that a second-hand wind turbine is sold at half its original price.[6] Following this approach, the economic value of the EoL WTB would be set at €17,000/MW. The prices asked on websites where second-hand wind turbine parts such as blades are sold, e.g. Spares in Motion and Wind-Turbine-Models, are much lower than this. Though it varies a lot, some examples include €3252/MW, €1300/MW and €4625/MW. It should be noted that the blades sold on these websites are in general onshore turbines of ≤1 MW, which is not very representative of the material flow in this research. Nevertheless, €17,000/MW seems quite optimistic, especially considering that potential refurbishing or repair would still need to take place. While this aspect is beyond the scope of this research, it can be considered to a limited extent by decreasing the economic value to €10,000/MW. Taking a simplistic approach for the specific blade mass of 10 tonnes/MW, as described in Section 4.2.1.5, this then amounts to €1000/tonne.

Turbine model	Capacity [MW]	Blade length [m]	Total costs [$]	Cost per MW [$/MW]
WindPACT	1.5	33	52,146	34,764
IEA Wind Task 37	3.4	63	15,4090	45,321
SNL-100-03	13.2	100	547,723	41,494

Table 4.21: Blade cost for different wind turbine models (Bortolotti et al., 2019)

Assumptions in the further analysis of reusing WTB in this research are:

- Costs and material requirements for potential remanufacturing, refurbishing or repair activities are not considered;
- The economic value of the blades is assumed to be €1000 per tonne;
- What happens when these second-hand blades reach EoL after another 10-15 years of operational life (Ortegon et al., 2013; Tota-Maharaj and McMahon, 2020) is outside the scope of this research.

4.3.1.2 *Repurpose*

Repurposing means using the waste material in its existing form for a new purpose or application (Jensen and Skelton, 2018; ETIPWind, 2019). This offers a high value end product, against relatively little energy requirements for processing (Jensen and Skelton, 2018).

Opportunities
There are a fair number of opportunities around for the repurposing of EoL WTB. The Re-Wind project has indicated a significant amount of demonstration projects and opportunities for WTB in this respect: a wide range of applications for blades of varying sizes, ranging from furniture to bridges, tiles, facades and noise barriers - to name a few examples (Bank et al., 2018). Generally speaking, the blades still have much structural integrity left and show good mechanical quality even after a full service life (Joustra et al., 2021b; André et al., 2020).

Research by Joustra et al. (2021a) illustrated the feasibility of cutting the blade into structural elements, i.e. construction panels and table parts. This offers the chance to use the segmented parts for different applications. The segmented parts (beams,

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[6] Even though this is based on an entire wind turbine and not individual parts, this estimation is adopted for lack of better estimates.

panels) showed very good performance in terms of stiffness and strength compared to traditional building materials such as steel, aluminium and wood (Joustra et al., 2021b). This segmentation does, however, subject the core materials of the blade to exterior conditions such as UV radiation and moisture; supplementary surface treatment of the segmented elements is therefore required (Joustra et al., 2021a).

Another option is to use the blades as much as possible in their current form for urban projects. Superuse Studios is an architecture firm that has completed several projects in this regard. They have for instance developed two playgrounds and street furniture using blade parts. The projects are currently still on an incidental basis; if such projects would happen more structurally, standardised solutions and products could be offered, which would reduce the final costs. Currently, Superuse's playground built with EoL WTB is already cost-competitive with a conventional design playground. (personal communications with Jos de Krieger).

Other potential applications for repurposed blades include a pedestrian bridge, housing, or transmission line poles (ORE Catapult, 2021). Numerous design concepts have been developed for full blades as load-carrying structures in a bridge, though further research here is required (André et al., 2020). The first bridge made from actual EoL blades is to be built in Ireland this year (Mavrokefalidis, 2021). Gentry et al. (2020) show the possibility of applying a 100 metre blade as a roof for a small house; research results indicate that the performance of the roof falls within specified structural limits. The same holds for repurpose as a transmission pole: Alshannaq et al. (2021) show that also in this application (for 230 kV transmission), the blades can handle the loads and that deflections fall within the specified limits. Transmission poles made from composites are already being developed, and are presumed to have significantly higher durability than steel, concrete or wood - conventional materials for these poles. While the initial test results are promising, more research with regard to limit states and material deterioration is required (Alshannaq et al., 2021).

For more inspiration with regard to opportunities for repurposing WTB, the reader is referred to the Re-Wind Design Atlas (Bank et al., 2018).

This indicates that the possibilities for repurposing EoL WTB - albeit small-scale projects at present - are in abundance.

Limitations

Despite this abundance of opportunities, large-scale application of repurposing still faces significant barriers.

The most important limitation is the issue of a lack of standardisation and documentation of WTB (Jensen and Skelton, 2018). The mechanical characteristics differ per blade since blades from different manufacturers and models have varying designs and specifications - and this information is mostly confidential (Joustra et al., 2021b). If the blade was manufactured as a segmented blade or as an integrated one determines whether there are bonding areas which impacts subsequent segmentation patterns (Joustra et al., 2021b). Furthermore, knowing the mechanical characteristics is crucial for use in a secondary application; this therefore requires additional time and costs to test the blades (ORE Catapult, 2021). Standardisation in repurpose is also made difficult due to the large variety in blades: solutions for a 25 metre blade are very different compared to a 100 metre blade (ORE Catapult, 2021). For industrial solutions, a steady material supply of constant dimensions would actually be required (Beauson and Brøndsted, 2016); EoL WTB cannot offer this.

Furthermore, repurposing of blades faces similar limitations as reusing them: there is little information available with regards to the blade quality at EoL and how much remaining lifespan the blade has. This asks for developments in monitoring and inspection during the use-phase so that this can be better kept track of (Joustra et al., 2021b).

Due to the variability in blade specifications (size, shape, material composition), availability over time, and quality, in combination with a lack of documentation, it is difficult to properly match EoL blades with designers (Jensen and Skelton, 2018).

Another limitation is that repurposing blades - while it offers a lot of value - is in a way merely a delay of the ultimate problem of treatment of this material (André et al., 2020). Once the repurposed blades reach EoL, there will still need to be solutions developed to handle this.

Ideas differ about at which TRL repurposing is currently. van der Meulen et al. (2020b) state a TRL of 4-5, while ORE Catapult (2021) report a TRL of 8 - nevertheless mentioning that the scale is still very small.

Requirements for market development

Since blades differ in size and shape, it is imperative for market parties that more transparency is developed in terms of which blades are used where. If it is known what type of blade will be released when, one can better anticipate the material output and as such, develop better-fitting designs and solutions for their secondary life. Hence, good insight into the material flows is important in order to generate appropriate solutions. (personal communications with Jos de Krieger). A balance must be found between the supply, processing capacity and market demand (personal communications with Jelle Joustra).

Next to more insight in the quantity and type of blades that will become available when, it is important that more transparent documentation becomes available - both in terms of original blade specifications as well as monitoring data during the blade's use phase. This will require cooperation and the sharing of information throughout the value chain (Joustra et al., 2021b).

Potential size of market

The Re-Wind project, together with the other developments mentioned under *Opportunities*, show that there are many options available for end-markets. While these individual markets perhaps do not offer the scalability required, their combination could. In this way, blades of different size, weight and quality could be matched with a best-fit secondary application. Still, the challenge of matching market demand with supply remains.

To give an idea of the potential size of one of the potential markets, the repurposing of a WTB as a bridge is considered. The demonstration of a bridge made of blades by (André et al., 2020) showed concepts of bridges made with two to four blades. The authors state that in Sweden, there are currently 2,500 bridges that require deck replacement. This would then result in 5,000 - 10,000 blades, i.e. some 1,600 - 3,300 turbines. In this research, the cumulative outflow up to 2050 results in around 9,800 turbines; three to six times the amount that would be required for all of Sweden's bridges - assuming that every bridge would be replaced with WTB. Apart from replacement, the blade-bridge can also be applied to new pedestrian and bicycle paths, which will be increasingly developed as more focus is being directed towards low-carbon transport (Deeney et al., 2021).

Research by Nagle (2021) states that full repurposing of all blades will not be feasible with regard to market applications. However, it is estimated that repurposing of 20% of annual blade return volumes is feasible, which would still offer significant environmental gains, which Section 4.3.2 elaborates on.

There will not be one market that can absorb all the return volumes of EoL WTB over time. However, the amount of design concepts and demonstration projects to date is impressive and indicates that there are a lot of opportunities when the most important barriers have been overcome and the required additional research has been performed. The initial results from these projects are all promising.

Economic value

The economic value of blades meant for repurposing is challenging to define. Since most repurposing projects until now have been demonstration projects, there is no clear market indication of their economic value, yet. Superuse Studios reported that the blades they have purchased for their projects ranged in costs from <€0 to €2000 per blade (excluding transport and storage), however this does not indicate the monetary value after the blades have been repurposed in architectural projects. The price they pay for the blades varies strongly per project and depends, amongst others, on the supply of blades at that moment and the urgency with which the owner must do away with them.

The monetary value of the repurposed blades furthermore depends on the type of material that they replace and may therefore differ per sector. An estimation of their monetary value can therefore be made based on what materials the repurposed blades replace. Since Joustra et al. (2021b) have shown that EoL WTB segments can be repurposed as construction material and as such, compete very well with traditional construction materials, the potential economic value of the secondary material is compared to the average costs of these traditional construction materials. In €/tonnes, aluminium, steel and lumber are estimated at 1500, 565 and 0.00035 (IndexMundi, nd; MEPS, 2021; MarketsInsider, 2021). Clearly, this is a very large price range. The average price of these three materials is taken (roughly €688/tonne) and subsequently, it is assumed that the price of EoL WTB material is a bit below this. This research therefore adopts a rough estimate of an average of €500/tonne.

Assumptions in the further analysis of repurposing WTB in this research are:

- In total, 55% of the blade can be used for repurposing (Joustra et al., 2021b);
- The monetary value of these blades is set at €500 per tonne;
- The delayed material flow of when these repurposed blades reach EoL is outside the scope of this research.

4.3.1.3 Recycle

Recycling means using the waste material in a new application (Jensen and Skelton, 2018), thereby (partially) replacing virgin materials. It is the category where most developments are being made, though still it is at its infancy. While there numerous recycling techniques available and under development, this research only considers mechanical recycling. From all the techniques available, mechanical recycling has the highest TRL for GFRP and the highest combination TRL of GFRP-CFRP[7] (ORE Catapult, 2021). Under mechanical recycling, though, the resultant material is of low value and cannot be substituted for virgin material. Typically it is used for much less demanding applications (Cherrington et al., 2012).

Opportunities
Mechanical recycling implies cutting the material into flakes or strips and/or grinding this into a powder or granulate. This can subsequently be used as reinforcement or filler in other products (Bax & Company, 2019). The strips or flakes can be used in building panels or as riverbank protection (ten Busschen, 2016, 2018). Research by Mamanpush et al. (2018) shows how the recycled WTB material can be used in items such as floor tiles or roadblocks. The composite panels showed good mechanical properties and better water resistance than their wood-alternatives (Mamanpush et al., 2018).

A potential market for the shredded material, in the form of flakes, is in river bank protection or as sheet piles. Research at Windesheim University of Applied Sciences has illustrated this. The core of the sheet pile (70%) is made of the flakes while the remaining 30% must still be virgin material - similar to paper production.

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[7] Namely, a TRL of 9 for GFRP and 6 for CFRP. For a definition of TRL, see Section 2.4.4

At EoL, the sheet piles can be shredded and the flakes can be used again for the construction of new sheet piles. Thus, even though the composites cannot be applied again in WTB, they can be applied within sheet piles indefinitely, rendering this a circular product in that sense. In quality, these sheet piles compete with traditional hardwood ones. While the price is 10-30% higher (if industrially made), the lifespan is much longer (>60 vs. 20-30 years) and as it is a circular product, local governments are generally prepared to pay a higher price for this. For this application, the material must not be shredded into too small pieces in order to retain as much strength and rigidity as possible. If it is ground too small, for instance into dust, then the material loses its strength and can only be applied as filler, no longer as a reinforcing material. (personal communications with Albert ten Busschen).

Research by ten Busschen (2020) has additionally shown the potential of mechanically recycled WTB in retaining walls, guiding structures for boats, crane mats and bridge decks. The recycled composite material has a remarkable performance to weather conditions and offers a long lifetime. Demonstration projects in this regard have shown very positive results. For instance, EoL composites were used in the manufacture of retaining walls in Almere; these resulted in the same bending strength as the conventional azobé wood ones and after two years of use (2017-2019), no signs of material deterioration were detected. Another example is the development of guiding structures with EoL composites in Delfzijl in 2019, where these replaced tropical hardwood ones. Again, the structures showed very good performance and were not subjected to fungi attacks, unlike the tropical hardwood beams. (ten Busschen, 2020). Shredded composites have also been applied in manufacture of a new bridge deck in Friesland, with positive mechanical properties as a result (ten Busschen et al., 2019).

A Danish company, Miljøskærm®, founded in 2015, recycles GF from WTB to be used in noise barriers for traffic. These barriers contain >90% recycled material and have been installed in numerous projects throughout Denmark (Miljøskærm®, 2021).

Limitations

While mechanical grinding has a high TRL and low processing costs compared to the other recycling techniques available, it still goes paired with a number of challenges. A review by Beauson et al. (2014) indicates that manufacturing new composites with partly recovered glass fibres or shredded composites leads to inferior product quality compared to manufacturing with purely virgin materials. Personal communication with Markku Vilkki from Conenor Ltd, a company specialised in utilising shredded composites, indicates that the shredded material they received from a recycling company was of very low quality and was not sorted, rendering it a low-grade feedstock material for further application. The issue of quality is supported by Jelle Joustra; the shredded material is composed of a mix of materials and it is not readily known what exactly it is made up of and how strong it is. This can be seen in Figure 4.11, where two batches of shredded EoL WTB are shown.

Due to the limited quality and potential irregularity of supply, markets that have relatively low quality and quantity requirements may lend themselves well for absorbing this material. For instance, sports equipment or garden furniture (personal communications with Anne Velenturf). This, however, offers additional challenges for future recycling when the material is dispersed over many applications and/or locations (personal communications with Jelle Joustra).

The low quality of the recycled material means that using purely the recycled material will result more rapidly in creep and fatigue. Therefore, virgin composites are needed as reinforcement to prevent this (ten Busschen, 2020). Using recycling composites will therefore always still require a virgin supply. Furthermore, mechanical recycling produces microplastics and dust which are undesirable by-products (ORE Catapult, 2021). Hence, improvements in this recycling technique are welcome.

Figure 4.11: Batches of shredded EoL WTB from Jelle Joustra (own photo)

Requirements for market development

While the current value of the shredded material may not be high, there are already plenty of options demonstrated to use it as reinforcement or filler material, most often replacing wood alternatives. It seems better to shred the material than to grind it, as this retains as much as possible the strong mechanical properties of the GFRP and CFRP.

Challenging aspects for mechanical recycling are the low-grade feedstock it produces, as well as the irregularity of material supply, similar to the challenge faced by repurposing and reusing blades. To improve the end-quality, documentation of the blades is required so that it is known what materials - and in what proportion - are shredded. Higher quality of the shredded flakes or strips might reduce the need for virgin reinforcement and offer a wider variety of secondary applications. Finally, the low price of virgin GF (Mishnaevsky et al., 2017) further stymies the market adoption of shredded ones.

Potential size of market

As mentioned, shredded composites have been used to manufacture sheet piles. Sheet piles can be applied as flood protection measure; in the UK, for instance, a >100-metre sheet pile construction was built as river bank protection for 33,000 households around the river Thames (ArcelorMittal, 2017). As recent events have illustrated in the Netherlands, Belgium and Germany, flooding of rivers will become an increasing risk in Europe due to climate change (IPCC, 2021). Increased use of such structures might therefore be expected.

Per sheet pile, 16.8 kg of composite flakes are used. A project for a harbour in the Netherlands used 80 sheet piles, i.e. 1340 kg of composite flakes (ten Busschen et al., 2019). This research yields a cumulative amount of 689 kilotonnes of EoL WTB waste by 2050 (see Section 4.2.2). Applying a final yield rate after mechanical recycling of 55%, this would result in 379 kilotonnes of useful shredded material between 2020-2050, i.e. around 280 times the amount required for such a sheet pile project. Of course, the return volumes grow over time, as indicated by Figure 4.8b, so it will be less in the early years and more later. However, on average, this translates to around 10 sheet pile projects per year, which - over the entire geographical scope of this research - seems more than reasonable. Since shredded flakes have additionally shown promise in noise barriers, panels, furniture, construction applications, support beams and bridge decks, it may be assumed that the return volumes can be absorbed quite well in the market.

Economic value
The economic value of recycled GF is very limited. It is estimated to be €250/tonne[8] (Bax & Company, 2019; Sommer and Walther, 2021; Dong et al., 2018). The monetary value of recycled CF is higher than that of GF: estimates range from €2500/tonne (Sommer and Walther, 2021) to €4500/tonne (Bax & Company, 2019). However, in a hybrid blade it is not possible to differentiate between CF and GF since these are mixed together, and pure CF blades do not exist. Therefore, the monetary value of GF will be applied.

Assumptions in the further analysis of recycling WTB in this research are:

- The minimum capacity of a mechanical grinding plant is set at four thousand tonnes per annum (Sommer and Walther, 2021; Dong et al., 2018). The expected return volumes are placed in context of this minimum required capacity;
- The final yield rate is estimated at 55% (Liu et al., 2019);
- The monetary value of recycled composites is €250 per tonne (Bax & Company, 2019; Sommer and Walther, 2021; Dong et al., 2018).

4.3.2 Environmental impact of circular strategies

While the three circular strategies under consideration in this research have been analysed in terms of their opportunities, limitations, potential markets and economic value, it is also important to consider their environmental impact. As described in Section 2.3.1, there are many possible categories to measure environmental impact; this study limits itself to the energy consumption or energy intensity of the materials or processes. Other impact categories are disregarded, though the occasional reference to another sustainability score is made if this information is known. The circular strategies are first discussed separately; subsequently, a mutual comparison of the strategies in terms of energy consumption is offered.

Reuse
Reusing EoL WTB obliterates the need to manufacture a new blade. Table 4.22 (repeated from Section 2.3.1) shows the energy consumption and carbon emissions from the manufacturing of two types of WTB. Assuming a unit blade weight of 13.34 t/MW (after Figure 4.5), this results in an energy intensity of 39.75 MJ/kg for the GF blade and 44.72 MJ/kg for the hybrid GF-CF blade. Taking a conservative approach that all blades have an energy consumption that is the average of these two values - 42.24 MJ/kg - this would imply that reuse of a blade saves some 42 MJ/kg, since another blade need not be newly manufactured. This estimate does not take into account transport and repair/refurbish/remanufacture activities to improve the quality of the used blade, however it can still be concluded that significant energy savings can be achieved.

	GF blade	Hybrid GF-CF blade
Turbine capacity [MW]	1.5	2.0
Blade length [m]	45.2	45.3
Energy consumption [GJ]	795.0	1194.0
CO_2 emissions [ton]	42.1	67.7

Table 4.22: Environmental impact of blade manufacturing for two types of blade (Liu and Barlow, 2016; Liu et al., 2019)

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[8] Again, this value is based on the condition that there is a market for this material

Repurpose
Through repurpose, the WTB oftentimes replace conventional building materials such as aluminium and steel. There is general consensus that repurposing blades requires less effort than recycling them (Joustra et al., 2021b). The energy demand for mechanical recycling varies, though the maximum is reported at around 5 MJ/kg (ORE Catapult, 2021), hence for repurposing it is assumed to be a bit below this; between 3-4 MJ/kg for segmenting the blade into useful parts. Simultaneously, reported energy intensities for the production of conventional building materials are significantly higher than this: between 196-257 MJ/kg for aluminium, 110-210 MJ/kg for stainless steel and 30-60 MJ/kg for steel (Olivieux et al., 2015). In terms of carbon footprint, this is even more compelling. Using repurposed blades as opposed to steel could save between 4,685 - 6,845 kg CO_2-eq. per tonne of blade waste; for concrete this is 617 kg CO_2-eq. and for wood 440 kg CO_2-eq (Nagle, 2021). Hence, significant environmental impact can be gained here. This is also illustrated by Superuse Studio's Blade Made playground, which has achieved a 90% CO_2 reduction compared to other playgrounds of the same size built with FSC certified wood and stainless steel.

Recycling
For mechanical recycling, the energy demand of the process depends on the processing rate. Under a lower processing rate (10 kg/h), the energy demand is 2.03 MJ/kg; under a higher processing rate (150 kg/h), it is 0.27 MJ/kg (Howarth et al., 2014). Other estimates give 0.1 - 4.8 MJ/kg as range for energy demand for mechanical recycling (ORE Catapult, 2021). The energy intensity for producing virgin GF is 13-32 MJ/kg and virgin CF 183-286 MJ/kg (from Section 2.3.1); clearly much higher than the energy demand of recycling. Thus, even if the resulting mechanical properties of the recycled fibres are much lower than that of virgin ones, the significant energy difference suggests that it is beneficial to use recycled fibres when mechanical performance is less important (Howarth et al., 2014; Shuaib and Mativenga, 2016). The recycled fibre reinforced polymer (FRP) will not always substitute virgin FRP; it may also substitute other materials. Jensen (2018) mentions that estimations of energy savings compared to other filler materials may reach 19 MJ/kg. The noise barriers developed by Miljøskærm® are said to save on 60% CO_2 emissions compared to traditional noise barriers made from aluminium or mineral wool (Wind Denmark, 2019).

Mutual comparison of the three strategies
Research by Liu et al. (2019) has compared different EoL options for WTB. For each strategy, the net energy consumption (in GJ) is determined and compared to that of the benchmark, landfill. The net energy consumption consists of the energy required for manufacturing, transport, O&M, and for carrying out the EoL strategy, minus the energy saved through the EoL strategy (i.e. the benefits). If the net energy consumption of the EoL strategy is less than that of landfill, then this results in environmental benefits. The results, in percentage compared to landfill, are summarised in Table 4.23.

The results indicate that all of the considered treatment options are preferred over landfill, and that life extension, which may be considered a form of reusing blades, offers the most environmental benefits, especially when applied for a longer period of time. This is supported by FORCE Technology (2017), which states that reusing blades is the most desirable EoL strategy from an environmental perspective since it avoids a new blade from being manufactured and keeps the energy and materials in the current blade in use for a longer time.

	Full GF	Hybdrid GF-CF
Landfill	100%	100%
Mechanical recycling	90%	88%
Life extension 2 years	90%	90%
Life extension 5 years	76%	76%
Life extension 10 years	52%	52%

Table 4.23: Net energy consumption of EoL strategies for two types of WTB, compared to landfill as baseline (Liu et al., 2019). The lower the percentage, the lower the net energy consumption

Deeney et al. (2021) have performed a similar type of study, comparing landfill with incineration, co-processing, furniture making and bridge fabrication (both repurposing strategies). The research scores each strategy based on economic, societal and environmental indicators to arrive at an integrated sustainability score. In this case, bridge fabrication comes forward as most sustainable strategy, with furniture making following closely behind. These two repurposing options score significantly higher than the others. The authors apply different methods for integrating the sustainability scores, however each method yields the same general conclusion. For instance, the *PROMETHEE*-method they apply gives the final sustainability score reported in Table 4.24 (it holds that the more positive the score, the better it is).

	Sustainability score
Landfill	-0.59
Incineration	-0.32
Co-processing	-0.10
Furniture making (repurpose)	0.45
Bridge fabrication (repurpose)	0.57

Table 4.24: Sustainability score of EoL strategies for WTB (Deeney et al., 2021). The higher the score, the more sustainable

Following the research by Liu et al. (2019), the specific energy consumption of different EoL strategies is determined. Repurposing blades is not originally included in the analysis, hence a value between recycling and reusing them is chosen for this strategy. For reuse, the value of 10-year life extension is adopted. The specific energy consumption is determined by subtracting the benefits of the EoL strategy from the energy demand required to carry it out, and dividing this by the weight of the blade. The original analysis compares a full GF blade with a blade reinforced with CF; since two-thirds of all manufacturers are estimated to use CF in their blades (see Section 4.2.1.4), an intermediate value is adopted whereby the full GF blade counts twice and the hybrid GF-CF blade once. This results in estimations for the specific energy consumption as summarised in the first column of Table 4.25. From this, it can be inferred that the energy savings achieved by applying reuse and repurpose are more than four times and more than two times that of applying recycle, respectively. When applied to the cumulative return volume from the default lifetime scenario, total energy savings as summarised in the second column of Table 4.25 can be achieved.

	Specific energy consumption [MJ/kg]	Total energy savings [PJ]
Recycle	-14	10
Repurpose	-30	21
Reuse	-60	41

Table 4.25: Specific energy consumption for different EoL strategies based on Liu et al. (2019), and total resultant energy savings based on calculated material outflows in this research. Negative values indicate that the benefits (energy savings) from applying the strategy outweigh the energy demand

4.3.3 Transport costs of blades

To be able to determine for which wind farms it is ultimately economically viable to transport the EoL material to the port, the transport costs must be determined.

The cost of transport is difficult to generalise as it differs per route and is customised for each required transport (Peeters et al., 2017). Moreover, it depends on the type of material that is being transported: whether these are blades in their entirety, in parts, or already in crushed form at the wind site to reduce transportation costs as much as possible (Cooperman et al., 2021). This of course depends on the type of secondary application and therefore on the choice of treatment- or processing technique. Other variables that influence the costs include the location of the wind farm, the vessel type and equipment required depending on turbine type, weather patterns, and land-based waste treatment facilities (van der Meulen et al., 2020b). This research therefore assumes a range of average values for onshore and offshore transport of blades. Furthermore, it is assumed that for onshore transport, the blades are either transported as a whole (for reuse and repurpose), or in crushed form (for recycle); for offshore transport it is assumed all blades are transported as a whole, regardless of which circular strategy is applied. Developments in blade transport until 2050 are not considered.

4.3.3.1 Onshore transport

Onshore transport of blades can be done by truck, rail or barge. Transport by rail, however, is much more limited: it allows for a maximum blade length of 27.4 metres, whilst transport by truck allows up to 45.7 metres under regular transport, and up to around 61 metres for oversized and specialised transport (Peeters et al., 2017). The difficulty lies in making turns, driving through narrow passageways, over bridges and underneath overpasses - due to their size as well as weight (Cotrell et al., 2014). Reported costs of transport by truck exist in quite a large range. The average transport costs found in literature and reports[9] are summarised in Table 4.26.

	Average transport cost
James and Goodrich (2013)	€7.22-11.34/km for a 40-45m blade
TPI Composites (2003)	€3.01/km for a 50m blade
Smith (2001)	€2.84/km for a 24.5m blade
	€2.84/km for a 32.4m blade
	€2.44/km for a 41.7m blade
	€4.90/km for a 41.7m blade
	€5.67/km for a 58.8m blade
Smith and Griffin (2019)	€26.05/km for a 65m blade

Table 4.26: Onshore transport costs by truck

The value given by Smith and Griffin (2019) stands out here, and is based on quite a rough estimate of the travelled distance. On the other hand, the costs provided by Smith (2001) and TPI Composites (2003) are from some twenty years ago, and their applicability to today is therefore doubtful. Considering the large range in reported transport costs, three scenarios for transport costs by truck are implemented: (1) €3/km, (2) €10/km and (3) €25/km. From personal communications with a transport company specialised in abnormal loads such as those of WTB, it has become clear that the rates for onshore transport of WTB are confidential information and remain with the customer. It is therefore unfortunately not possible to validate this with market players.

In crushed form, the transport costs are significantly lower, namely €0.0619/ton-km (Cooperman et al., 2021). For mechanical recycling, it can therefore be expected

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[9] These are mainly estimates from the United States. However, with a lack of information these costs are assumed to be similar for Europe, i.e. the Netherlands

that the blades are already crushed at location, since they are not required to remain in original material form.

Transport of WTB for onshore turbines can also be done using barges on waterways. This will likely become more common as onshore turbines reach larger sizes. Peeters et al. (2017) report a maximum blade length of 76.2 metres for barges. Smith (2001) mentions that barges are not used for blades of turbines below 5 MW. Following James and Goodrich (2013), transport by barge costs on average $15.000 per blade for 1100 miles, which amounts to €7.20/km per blade. James and Goodrich (2013) also mention that transport by barge is generally less costly over large distances than by truck - the average transport cost value by barge therefore fits to the costs per truck described above.

4.3.3.2 *Offshore transport*

To better understand the offshore transport of WTB, personal communication has taken place with Twan Kolkert, Commercial Manager of the Business Unit Wind at Heerema Marine Contractors. The offshore transport of WTB is generally done by the turbine installation vessel itself. This is a jack-up vessel which carries multiple sets of wind turbines per trip. The jack-up vessel will load the turbine sets, sail to the offshore site for installation, and return to the port to load new sets of turbines. This is a repetitive cycle. On average, jack-ups can carry four sets of wind turbines per trip. Each set consists of the tower, nacelle, and the three blades. For an overview of the different wind turbine components, the reader is referred to Figure 2.3.

A simple approach to establish the total cost for offshore transport is therefore made up of the time to load the sets onto the vessel, the time to transport it to the offshore location, and the time to return to the port. The costs of such a jack-up vessel range between €175,000 - €200,000 per day; hence an average value of €187,000 is taken. It takes roughly 0.8 days to load one turbine set onto the jack-up vessel, hence the total loading time at the port is 3.2 days for the four sets. The vessel speed is roughly 10 knots, i.e. 18.52 km/h.

As the vessel transports the tower, nacelle and blade assembly, the transport costs must be distributed over these components for the purpose of this research. One approach is to distribute the transport cost in proportion to the mass of these components. Based on Wang et al. (2019), the blades are assumed to make up around 10% of the total mass of the tower, nacelle and blade assembly combined. This means that the total transport cost is multiplied by a factor of 0.1. As this corresponds to the transport of twelve blades (four sets with three blades each), the costs are additionally divided by twelve to give an indication of the costs per blade.

Thus the total transport costs for one blade are given by:

$$\left[3.2[\text{day}] + 2 \cdot \frac{distance[\text{km}]}{18.52[\frac{\text{km}}{\text{h}}] \cdot 24[\frac{\text{h}}{\text{day}}]}\right] \cdot 187,000[\frac{€}{\text{day}}] \cdot 0.1 \cdot \frac{1}{12} \tag{4.2}$$

4.3.3.3 *Overview of costs*

Since it is difficult to approach the transport costs with a generalised, average value, three scenarios are applied with low, mid and high transport costs. For onshore transport by truck, a range was already defined, with €3/km, €10/km and €25/km. These three values are roughly a factor 3 apart. Therefore, the determined transport costs of truck with shredded material, barge, and jack-up vessel are divided (low scenario) or multiplied (high scenario) with a factor 3 to arrive at a range for each transport method. The three scenarios are therefore:

Transport method	Low	Mid	High	Unit
Offshore (jack-up vessel)	62,333.33	187,000.00	561,000.00	€/day
Truck (entire blade)	3.00	10.00	25.00	€/blade-km
Truck (shredded blade)	0.02	0.06	0.19	€/blade-km
Barge	2.40	7.20	21.60	€/blade-km

Table 4.27: Transport costs under a low, mid and high transport cost scenario for different transport methods

4.3.4 Final potential volume treated at each port

Now that both the monetary value of the secondary material under different circular strategies and the transport costs have been defined, the final volume that may be treated at each port can be determined. This volume is comprised of those wind farms for which the economic value of the secondary material outweighs the transport costs of the WTB to the port. Of course, this approach is quite limited as these are not the only relevant economic aspects. Significant costs also go paired with decommissioning, setting up and running treatment facilities and the processing of the material. However, while this is not a thorough economic analysis, it does provide insight on how the circular strategies compare to each other and what financial margins can be achieved under application of each one.

From Section 4.3.1, the monetary value under different circular strategies is defined as summarised in Table 4.28 below; the transport costs are summarised in Table 4.27.

	Economic value	% of material for secondary application
Reuse	€1.000/tonne	100
Repurpose	€500/tonne	55
Recycle	€250/tonne	55

Table 4.28: Monetary value of secondary material under different circular strategies

For each port, the final potential volume is determined under different conditions:

- Scenarios for transport costs (low, mid, high);
- Scenarios for applied circular strategy (reuse, repurpose, recycle).

Each wind farm is assigned a decommissioning date based on the Normal distribution[10] defined in Section 4.2.1.7. This yields a more realistic return flow as shown in Figure 4.12, since it is to be expected that return volumes will become available as batches at irregular times rather than developing smoothly. Assigning a definite decommissioning date to each wind farm is an incorrect prediction per individual wind farm, but since these are drawn from the same Normal distribution, on average it is correct. Nevertheless, a discrepancy exists: the cumulative outflows by 2050 now reach 641 kt versus 689 kt by means of the dMFA. This is 7% lower and is therefore considered an acceptable discrepancy.

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[10] Based on the default lifetime development

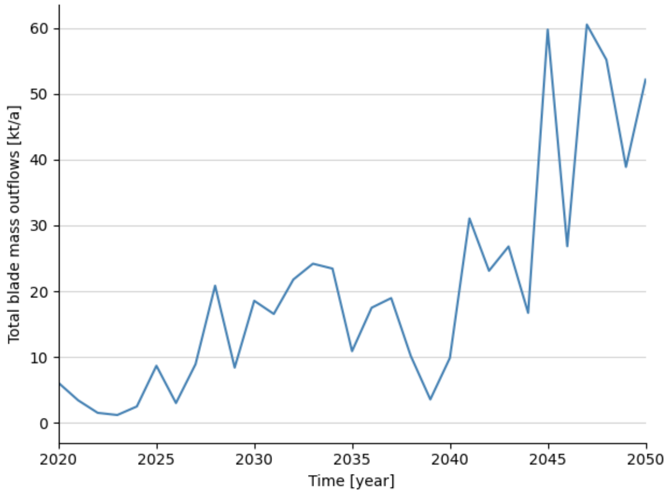

Figure 4.12: Annual blade mass outflows until 2050 with defined decommissioning dates for wind farms

For this analysis, it is important to consider the number of trips required to transport all the material from the wind farm to the port. Each transport method has a maximum capacity, hence depending on the size of the wind farm, the distance from the wind farm to the port will need to be completed multiple times. The maximum capacity of each transport method is as follows:

- Offshore jack-up vessel: four wind turbine sets per vessel (from Section 4.3.3.2)
- Onshore truck (entire blade): one blade per trip (Ortegon et al., 2013; Liu and Barlow, 2016)
- Onshore truck (shredded blade): 33 tonnes per truck (International Transport Forum, 2013)
- Onshore barge: four blades per trip[11]

Based on this, the closeness centrality of the ports is re-assessed and the outcomes shown in Table 4.29. There is a differentiation between the circular strategies[12] since recycling of the blades enables the transport of shredded material, which generates different results than transport of whole blades. The same conclusions hold as the analysis of the weighted centrality from Section 4.1.2.1, with PoDH and PoA as most centrally located, and only the PoR and GSP switched in order.

Port	Closeness centrality (reuse, repurpose)	Closeness centrality (recycle)
PoA	$5.2 \cdot 10^{-5}$	$1.5 \cdot 10^{-4}$
PoR	$3.6 \cdot 10^{-5}$	$1.1 \cdot 10^{-4}$
PoDH	$5.8 \cdot 10^{-5}$	$1.7 \cdot 10^{-4}$
GSP	$3.3 \cdot 10^{-5}$	$1.0 \cdot 10^{-4}$
NSP	$2.3 \cdot 10^{-5}$	$6.9 \cdot 10^{-5}$

Table 4.29: Closeness centrality of ports based on the total number of trips required for the transport of EoL WTB, aggregated over all years. The higher the value, the better: i.e. the more centrally located the port is

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[11] Based on different reported figures: 1 blade (Williams Shipping, 2021), 2 blades (Smith, 2001), 6 blades (PacVan, 2019)

[12] The values for reusing and repurposing the blades are the same as their transport is assumed to be identical

Table 4.30 summarises for each port the cumulative amount of blade material for which it is economically viable to transport it to the port until 2050, and what percentage this is of the total amount of blade material. A more detailed overview of this can be found in Appendix F.1, where the total volumes are divided between onshore and offshore material. The total viable volume over time (in kt per annum) for each port, under each cost scenario and for each circular strategy can be found in Appendix F.2.

	Reuse		Repurpose		Recycle	
	[kt]	[%]	[kt]	[%]	[kt]	[%]
Low transport cost						
PoA	512	80	220	34	177	28
PoR	500	78	198	31	169	26
PoDH	540	84	225	35	160	25
GSP	498	78	208	32	157	24
NSP	488	76	157	25	134	21
Mid transport cost						
PoA	263	41	31	5	60	9
PoR	234	36	27	4	63	10
PoDH	278	43	21	3	62	10
GSP	234	37	24	4	53	8
NSP	194	30	21	3	56	9
High transport cost						
PoA	45	7	3	0.5	38	6
PoR	44	7	5	0.8	42	7
PoDH	28	4	1	0.2	28	4
GSP	40	6	4	0.6	26	4
NSP	38	6	1	0.2	30	5

Table 4.30: Total amount of blade mass for which it is economically viable to be transported to each port under application of different circular strategies, aggregated until 2050. In black the amount in kilotonnes; in grey the percentage that this is of all wind farms in the analysis

Under application of the circular strategies, it can be concluded that the viable volumes at each port no longer follow the trend of centrality of the ports, per se. The economic value of the material is limited, while the transport costs are sizeable - and for some wind farms even need to be made multiple times as a result of the size of the wind farm. Therefore, the viable volume at each port becomes much less dependent on the entire area, and much more so on individual wind farms, i.e. which wind farms happen to be in vicinity to the ports. This is especially the case in the high transport cost scenario.

For reuse and repurpose strategies, most of the material stems from offshore wind farms. Onshore transport of full blades is expensive, especially since only one blade can be transported by truck per trip. For recycle, on the other hand, most of the material comes from onshore wind farms, since transport by truck is much less expensive for the material in crushed form. Simultaneously, the monetary value of the recycled material is low, meaning that in most cases, this does not cover the higher transport costs from offshore wind farms.

The largest volumes are found - unsurprisingly - in the low transport cost scenario. In this scenario, under reuse, the division between the ports does follow the centrality score of the ports. The monetary value of the material sufficiently high to cover a larger transport distance. As such, it is less influenced by which individual wind farms lie in direct vicinity to the port. Between the circular strategies, the viable volumes follow the same trend as the economic value of the secondary blade material: moving from most under reuse, to least under the recycle strategy. The transport costs are low enough that even circular strategies based on recycling, which tend to generate the lowest economic value, can still be cost-effective for offshore wind farms.

For the mid and high transport cost scenarios, recycle is no longer a cost-effective strategy for offshore wind farms, hence the volume stems solely from onshore wind. Still, more material can be treated when the blades are recycled compared to repurposed, since the recycling of blades allows for transport in shredded form. For the high transport cost scenario, repurpose is also no longer a cost-effective strategy for offshore wind farms. Due to the high transport costs, only onshore wind farms in the direct neighbourhood of the port are economically viable to be treated at the port.

It can be concluded that all three circular strategies are responsive to a change in transport costs. The repurpose and recycle strategies show most receptiveness to this, with very low viable volumes already in the mid transport cost scenario. This is explained by the lower revenue from these strategies, combined with the fact that only 55% of the return volume can be used for the secondary application. This has as result that for reuse, the margin between revenue and transport cost is much larger - though it is still limited.

For the recycling of blades, it was found that the minimum required throughput volume for a mechanical grinding facility is 4 kilotonnes per annum. While the *total* volume from EoL WTB in the analysed region already reaches this volume in 2022[13], this is not the case when the analysis is extended to the *economically viable* volume. In this case, the minimum required throughput is only reached around 2040 in the low transport cost scenario, and not at all in the mid- and high costs scenario[14]. This is illustrated in Figure 4.13, with PoDH as example. The ports follow similar developments over time; for clarity, only one of the ports is illustrated here. An overview with all ports can be found in Appendix F.3.

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[13] In the default lifetime scenario

[14] In the mid transport cost scenario, the threshold of 4 kt/a is passed shortly, but this is not sufficient

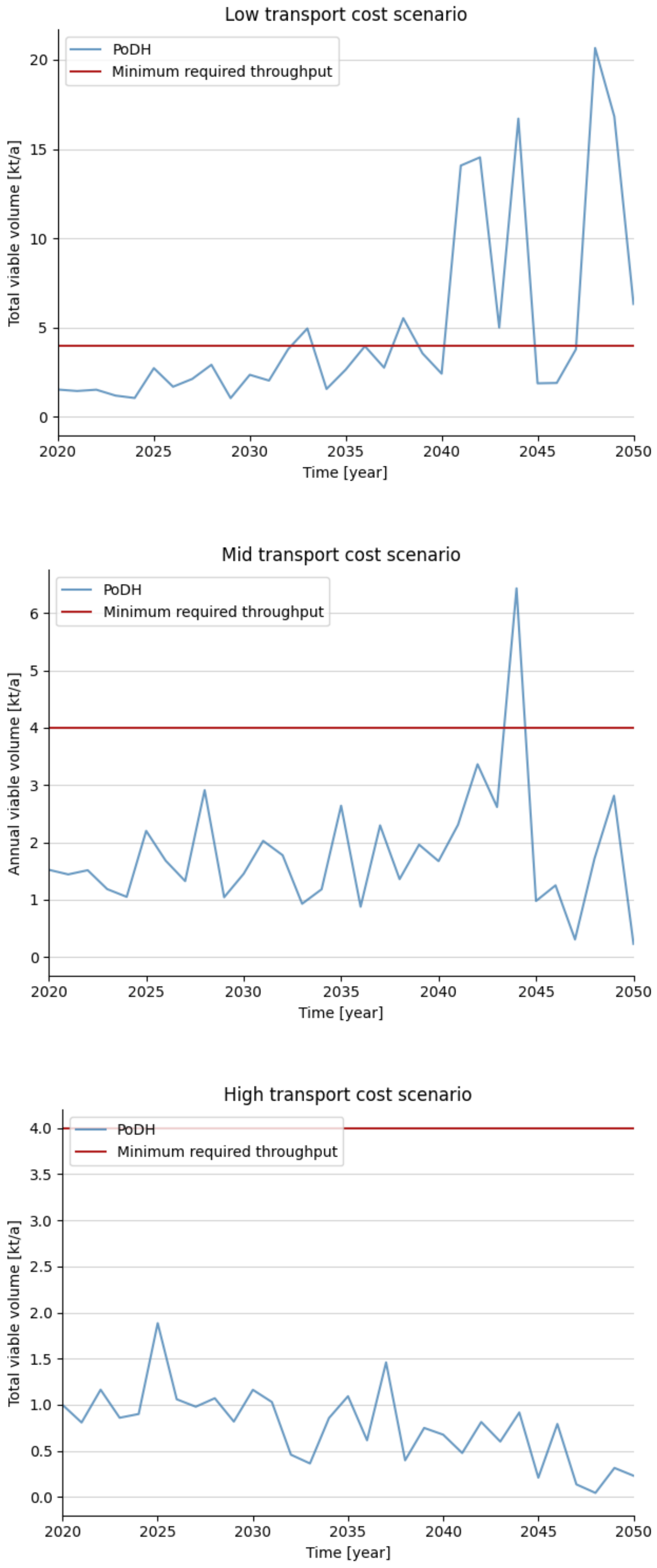

Figure 4.13: Viable volume vs. minimum required throughput for recycling the WTB in the low, mid and high transport cost scenario; PoDH used as illustration as each port follows a similar trend

The findings are analysed with regard to their sensitivity to the model parameters. Both the transport costs and economic value of the secondary material are increased and decreased by 10%. From the transport cost scenarios (Table 4.30), it has already become clear that the final potential volume to be treated at each port is highly dependent on this; it remains to determine how much impact a small change in transport costs generates. The results of the sensitivity analysis are reported in Table 4.31. The full results per port can be found in Appendix G.2 for transport costs and in Appendix G.3 for the economic value.

	Reuse [%]		Repurpose [%]		Recycle [%]	
Transport costs ±10%						
Low cost	-8.2	5.0	-19.8	17.6	-17.5	18.4
Mid cost	-17.1	15.2	-53.2	52.8	-4.1	5.7
High cost	-29.1	95.6	-28.0	11.3	-19.1	24.7
Economic value ±10%						
Low cost	-8.2	4.3	-19.9	16.3	-21.9	14.7
Mid cost	-17.1	14.1	-53.2	52.6	-5.4	5.0
High cost	-29.5	93.3	-46.3	11.3	-19.6	24.3

Table 4.31: Summary of minimum and maximum percentage change of all ports in the total viable volume to treat at the hub under sensitivity analysis of transport costs and economic value

The sensitivity analysis for changes in transport costs and economic value show very similar results. The outcome in viable volume shows a very strong response to a ±10% change in both cases. The only exceptions with sensitivity below 10% are reuse in the low transport cost scenario, and recycle in the mid transport cost scenario. This indicates that the generated results are strongly dependent on the definition of these parameters, and they must therefore be interpreted in light of this. However, despite this, the main conclusions between the circular strategies still hold. Furthermore, the strong influence of these parameters suggests that policy interventions on these are advised. For instance, by enhancing the economic value of the secondary material.

4.3.5 Economic and environmental benefits under each circular strategy

Considering the final potential volume that may be treated at each port, the total potential economic and environmental benefits can be determined under application of each circular strategy. The economic benefits are determined by taking the sum of the difference of the economic value and the transport costs for each wind farm. The environmental benefits are approached by evaluation of the energy savings yielded by each circular strategy, as summarised in Table 4.25.

The results are shown in Figures 4.14 and 4.15 for the economic and environmental benefits, respectively. These follow the same trends as the viable volume at each port. It can be concluded that the choice of circular strategy has a much stronger influence on the results than the choice of port location, especially in the low and mid transport cost scenarios. The average economic and environmental benefits from all ports is summarised in Table 4.32.

	Economic benefits [M€]			Energy savings [PJ]		
	Reuse	Repurpose	Recycle	Reuse	Repurpose	Recycle
Low cost	307	22	11	30	6	2
Mid cost	105	2	5	14	0.7	0.8
High cost	12	0.3	2	3	0.1	0.5

Table 4.32: Average potential economic benefits and energy savings under application of each circular strategy, aggregated until 2050. Results rounded to whole numbers

According to Sommer and Walther (2021), the variable costs of a mechanical grinding plant are 100 € per tonne of material. In the low, mid and high transport cost scenarios for recycling the blades, the average cumulative viable volume is 159 kt, 59 kt and 33 kt, respectively. This then translates to a total amount of variable costs until 2050 of 15.9 M€, 5.9 M€ and 3.3 M€, respectively. The economic benefits offered by recycling do not cover this - especially considering the fact that substantial investments and fixed costs will also need to be made. However, it is promising that, as a first step, the economic benefits approximate the variable costs to a substantial extent.[15]

Most energy savings can be realised in the low transport cost scenario through reusing the blades, where total energy savings of 30 PJ over a 30-year timeframe can be achieved. This amounts to, on average, 1 PJ of energy saved per year. This is equal to the energy required to power 15,000 households for a year (Klimaatakkoord, nd). For the 2 PJ energy savings from recycling the blades over the same time period, this would translate to around 1,000 households, making a clear case for choosing a higher circular strategy. From Table 4.25, the total achievable energy savings for all the material in the region are 41 PJ for reuse, 21 PJ for repurpose and 10 PJ for recycle. Hence a lot more environmental benefit could be realised if the percentage of material treated in the hub is increased. Of course, energy is also required for the subsequent processing of the recovered material into new products, but the benefits of a circular hub - especially under application of higher circular strategies -, as opposed to landfill, become apparent.

As mentioned before, it is important to note that this analysis is limited. The environmental benefits have only considered energy demand and energy savings of applying the EoL strategy, thus disregarding other relevant environmental indicators. The economic analysis disregards the costs that must be made for decommissioning itself, initial investments to set up treatment facilities and the fixed and operating costs of these facilities. Nevertheless, these first insights offer a clear case for the development of a circular wind hub - and the importance to decrease transport costs or increase the economic value of the material to increase the amount of material that may be treated at the hub.

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[15] For reusing and repurposing blades, it is much more difficult to define processing costs since it considers individual projects each time. Therefore this indication of economic benefits is done solely for a recycling plant

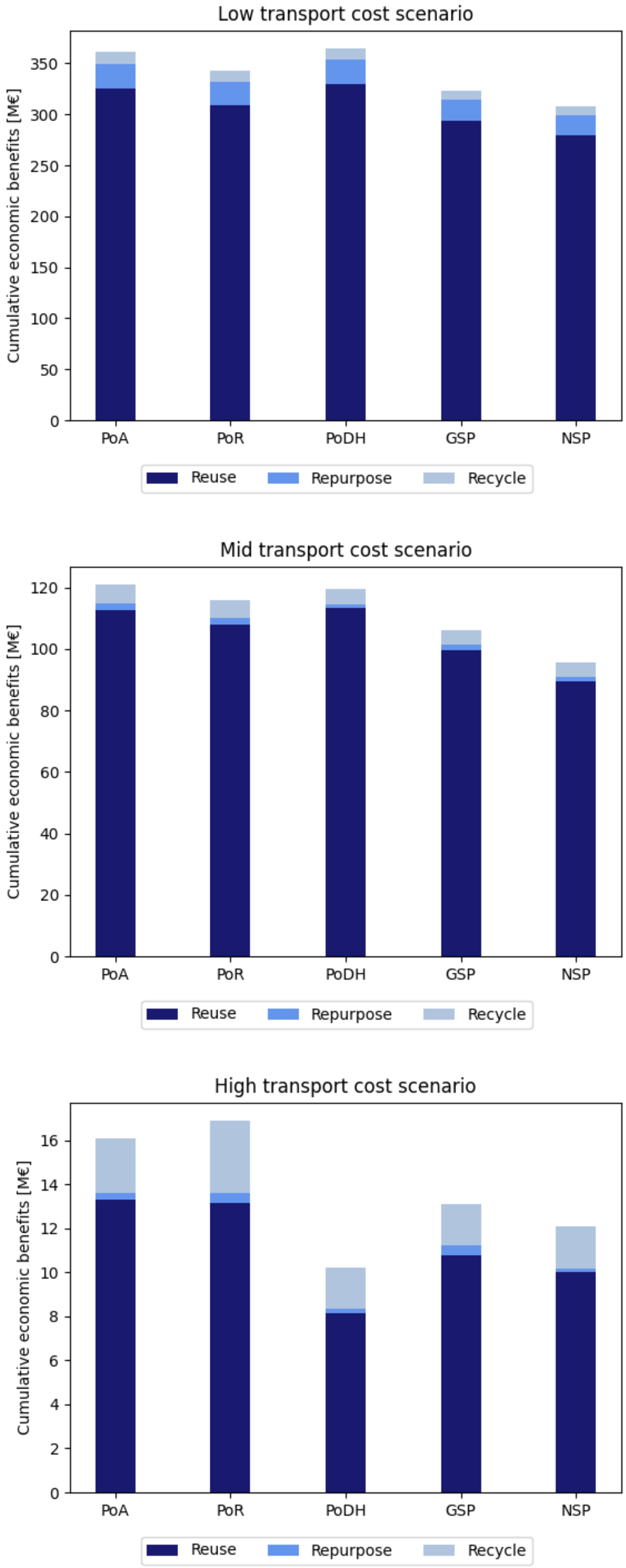

Figure 4.14: Economic benefits in million € at each port under application of each circular strategy, in the low, mid and high transport cost scenario, aggregated until 2050

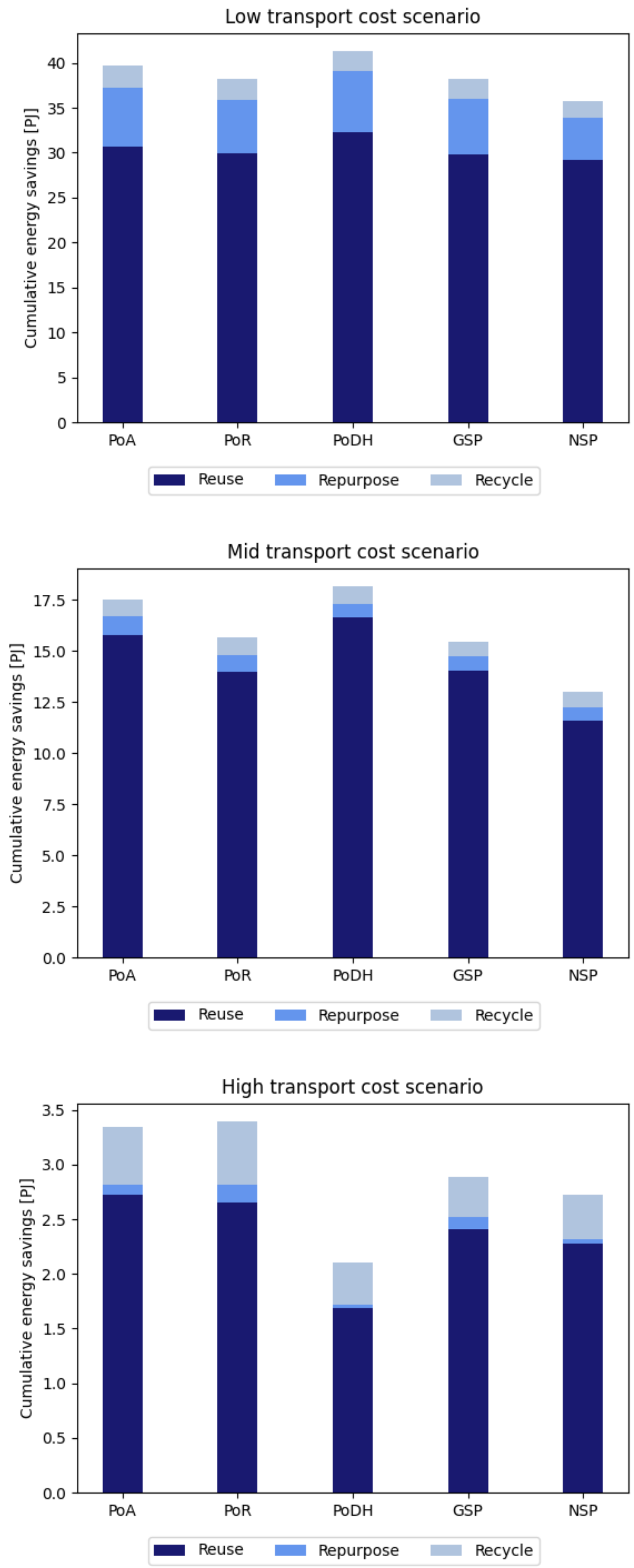

Figure 4.15: Energy savings in petajoule at each port under application of each circular strategy, in the low, mid and high transport cost scenario, aggregated until 2050

4.4 SUMMARY OF RESULTS

This chapter has offered an extensive amount of information. A summary of the findings is offered here.

Firstly, a framework has been designed whereby six main categories of characteristics that are important for a location to possess for the development of a circular wind hub have been distinguished. These are: (1) willingness to develop such a hub; (2) available space; (3) current companies, infrastructure and activities; (4) accessibility; (5) focus on circular strategies; and (6) centrality with regard to current and future wind farms.

With this framework, five Dutch ports have been compared in terms of their suitability for the development of a circular wind hub. This comparison has brought PoDH and PoA forward as most suitable locations: these ports are most centrally located, have shown the clearest willingness to develop such a hub and have the space available to develop new facilities for this. That being said, all five ports already have a focus on the challenge of EoL WTB, have infrastructure and companies available that are already (indirectly) involved in the required reverse supply chain, and foresee no bottlenecks with regard to future accessibility to the port. For an overview of how the characteristics of these ports compare, the reader is referred back to Table 4.9.

Secondly, the material flows from EoL WTB that may be expected in the region until 2050 have been studied. The total blade mass stocks reach over 1 Mt in 2030, and the annual outflow may reach around 60 kt in 2050. The cumulative outflows by 2050 reach around 690 kt. Assuming all material is treated in the hub, the minimum required volume for a feasible recycling facility - 4 kt/a - is already reached in 2022. Under the lifetime scenarios, this date is pushed forward to 2018 (shorter average lifetime) or pushed backward to 2026 (longer average lifetime). In any case, the minimum required annual volume is reached relatively soon. While the sensitivity analysis on average lifetime yields significant changes in material outflows of >10%, the 4 kt/a threshold only changes by ±2 years.

Finally, possible circular strategies to be applied to the EoL WTB have been evaluated. Circular strategies based on reusing, repurposing and recycling the blades have been analysed in terms of their economic potential, the monetary value of the generated secondary material, and their environmental impact. Each circular strategy shows potential in terms of market application, however the markets are still at an immature stage. Overall, the most potential for material absorption in the market is offered by recycle, next by repurpose, and least by reuse.

Consideration of the monetary value with the expected material return volumes versus the transport costs has provided insight into the final volume of material that may be treated at each port. For an overview of the viable volume aggregated over time for the different scenarios, the reader is referred back to Table 4.30. A clear division is observed between reuse, repurpose and recycle. Generally speaking, since more circular strategies generate a material with a higher economic value, this allows for the transport costs - and thus transport distance - to increase.

For the low and high transport cost scenarios, expected developments are observed: under low cost, much more material may be treated at each port; under high cost, much less. In the high transport cost scenario, the viable volume is at maximum only 10% of the total amount of all wind farms, meaning that much can be gained here. In the mid and high transport cost scenarios, recycling blades offers a larger viable volume than repurposing them. This means that the higher transport costs for full blades as opposed to shredded material weigh larger than the higher revenue from repurposed blades than from recycled ones.

In the analysis of the application of different circular strategies, the group of wind farms for which it is economically viable to transport them to the ports is a subset of the total installed amount of wind farms. Therefore, the time when the minimum throughput capacity for a recycling plant is reached, lies further in the future. Under the low transport cost scenario, this is around 2040; in the mid and high transport cost scenarios it does not happen. Economic incentives to increase the market price of shredded blade material or subsidies to cover the transport expenses would likely improve this.

The potential economic and environmental benefits that may be achieved by treating the viable volume in a circular wind hub are most significant in the low transport cost scenario. The total economic benefits of these three strategies reach 11 M€, 22 M€ and 307 M€, respectively. These are not sufficient to cover the variable costs of a recycling plant, let alone the fixed costs and required investments. The economic benefits in the mid and high transport cost scenario are significantly lower. Interestingly, the potential market size for the secondary material seems to be largest for recycle and smallest for reuse, while the potential economic and environmental benefits are largest for reuse and much smaller for recycle. Regulation to balance this disparity is therefore recommended.

The environmental benefits are addressed as energy savings, which in the low transport cost scenario total to around 2 PJ, 6 PJ and 30 PJ by 2050 as a result of recycling, repurposing and reusing the blades, respectively. In the other scenarios, the energy savings are significantly lower. The energy savings from processing the complete return volume of EoL WTB could reach 10 PJ under recycle, 21 PJ under repurpose and 41 PJ under reuse. Hence, much can still be gained here by increasing the viable volume.

5 CONCLUSIONS AND DISCUSSION

This chapter offers conclusions to the research questions defined in Section 1.4 and presents a discussion wherein the contribution to academic literature is outlined, and the obtained conclusions and results are reviewed and placed in context of the research limitations. Finally, recommendations are offered, for further research as well as for the industry and policy-makers.

5.1 CONCLUSIONS

This research paper has investigated the following main research question:

How do Dutch ports compare in terms of suitability for the development of a circular wind hub, and what return volumes of end-of-life wind turbine blades in and around the Netherlands may be treated there until 2050 under application of different circular strategies?

The research was based on a threefold of objectives: (1) to distinguish specific characteristics that deem a location feasible for the development of a circular wind hub, and compare Dutch ports accordingly; (2) to shed light on the total expected return volumes of EoL WTB in the defined region by means of a geographic explicit quantification; and (3) to compare different circular strategies with regard to their potential economic and environmental benefits, and the final volume that may be treated at the hub in each case. Altogether, these three research objectives melt into a singular goal of this research, namely to aid the development of a circular wind hub in the Netherlands.

First, each of the sub-questions of the main research question is answered; subsequently, an overall conclusion is offered.

5.1.1 Conclusions per sub-question

The main research question has been split into four main sub-questions, each of which is answered separately below.

1. What characteristics are important for a location to possess for the development of a circular wind hub to treat the return volumes of end-of-life wind turbine blades?

For the potential development of a circular wind hub to centrally treat the EoL WTB, six relevant categories have been distinguished through interviews and literature consultation. These are: (1) port willingness; (2) available space; (3) current companies, infrastructure and activities that are already (indirectly) involved in the wind industry or reverse supply chain; (4) accessibility of the port; (5) the main circular strategies they presently focus on or aim to focus on; and (6) the centrality of the port based on the expected return volume. A way of scoring each category has been defined and as these scoring metrics vary, they are normalised to allow for ultimate comparison of the ports. For an overview of the scoring metrics per category, the reader is referred to Table 4.1.

2. *How do Dutch ports compare in terms of suitability for the development of a circular wind hub?*

Five Dutch ports have been compared in terms of their suitability to develop a circular wind hub according to the framework developed in sub-question 1. The analysis reveals that the PoDH and the PoA score the highest. Since these ports are located in proximity to each other, it could be of value to explore the idea of setting up a broader-defined hub in cooperation. The results and normalised scores of each port are summarised in Table 5.1. The complete results can be found in Table 4.30.

There is general consensus between the ports on the idea that the circular hub need not necessarily be a clearly physically demarcated area at one port; rather, it could be a larger area, with synergies and cooperation between existing industries and facilities, possibly even throughout the whole of the Netherlands. In this way, optimal use can be made of existing facilities and the involved ports can each direct their focus to a certain area of expertise or specialism.

3. *What return volumes of end-of-life wind turbine blades can be expected in and around the Netherlands between 2020 – 2050?*

The magnitude and location of EoL WTB that falls within the geographic demarcation of this research will clearly increase the coming decades. In the default lifetime scenario, the total stock of WTB reaches over 1 Mt in 2030 and annual outflows reach 59 kt in 2050. These results fit within the output range derived from similar studies. This material flow is almost completely made up of composite materials, which total to around 54 kt in 2050. The resin use in this composite flow is dominated by epoxy compared to polyester; it may therefore be advised that developments in recycling technique that are targeted at specific materials have their focus on epoxy. Cumulatively, the blade mass outflows reach 690 kt by 2050.

The minimum required throughput capacity for a mechanical recycling plant of 4 kt/a is already reached in 2022. This supports the urgency to develop a circular wind hub, and indicates that through interregional collaboration, the viability of the hub is enhanced. A minimum required throughput for reuse and repurpose strategies has not been identified.

The annual blade mass outflow over time is shown in Figure 5.1. As wind capacity development after 2030 is not considered in this analysis, these annual outflows may in effect be expected to further increase.

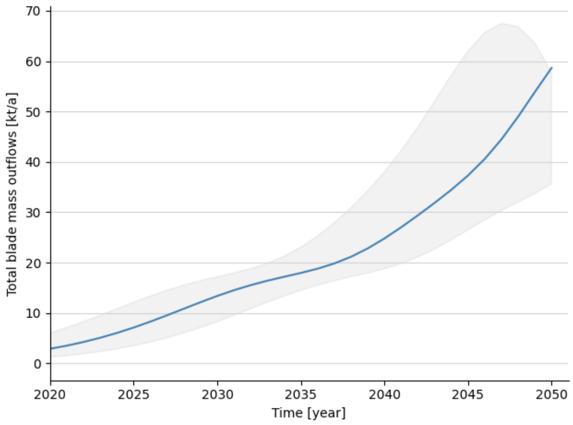

Figure 5.1: Annual blade mass outflows until 2050 from the dMFA

Under an increased lifetime of 20%, the annual material outflows are lower, and hence more environmental benefits may be expected since the generation of waste is decreased and fewer turbines need to be replaced (assuming that the location is reused as a wind farm site). The opposite conclusion holds for a decreased lifetime of 20%.

4. How does the choice of circular strategy influence the final volume of end-of-life wind turbine blades to be treated at a circular wind hub and what environmental and economic implications does this have?

The total estimated return volume from sub-question 3 represents the total amount of material that could theoretically be treated in the circular wind hub. However, it is not self-evident that the entire capacity of EoL WTB will be transported to the ports for EoL treatment. Therefore, an indication has been made for which wind farms it is economically viable to transport the blades to each port under the application of the different circular strategies, and what this means in terms of economic potential and environmental impact. This analysis was performed based on the default lifetime scenario only, and on three scenarios for transport costs.

In all three transport cost scenarios, the viable volume is limited. This is especially the case for circular strategies based on repurposing (repurpose) and circular strategies based on recycling (recycle), where the cumulative viable volume stays below 40% of the total volume in all scenarios, and even below 10% in the mid and high transport cost scenarios. The only exception where a substantial volume is reached is for circular strategies based on reusing (reuse) in the low transport cost scenario, with viable volumes ranging between 75 – 85%. Following the mid transport cost scenario, reuse would offer a cumulative amount of on average 240 kt by 2050; repurpose 25 kt; and recycling 59 kt.

This reduced amount of to-be treated blade material is also reflected in the time when the minimum threshold of 4 kt/a for a recycling plant is reached. In the low transport cost scenario, this is only around 2040; in the mid and high transport cost scenarios, the threshold is not reached at all.

The results show a strong response to a marginal change in the transport costs and economic value of the secondary material. This means that the definition of these parameters is of large influence on the final results, and means that policy interventions on these are advised. Despite this influence on the generated results, the overall conclusions remain the same.

The total economic benefits that can be achieved by treatment of these volumes for each circular strategy differ substantially, depending on circular strategy and the transport cost scenario. In the mid transport cost scenario, they amount to 105 M€ for reuse, 2 M€ for repurpose and 5 M€ for recycle by 2050. The cumulative economic benefits generated by recycling the blades in each scenario are not sufficient to cover the total expected variable costs of a recycling plant, let alone the required fixed costs and investments. Furthermore, there is a mismatch between expected revenues and potential market size: most economic benefits are generated under reuse, whilst the market potential is largest for recycle and lowest for reuse. This disparity calls for regulation.

The energy demand of each circular strategy is set against the energy savings the strategy yields. This results in a negative energy consumption - energy savings - of almost 60 MJ/kg for reuse; 30 MJ/kg for repurpose; and roughly 14 MJ/kg for recycle. Considering the complete volume of EoL WTB in the region, total energy savings of 41 PJ through reuse, 21 PJ through repurpose and 10 PJ through recycle could be realised. However, considering the cumulative viable return volumes, the actual realised energy savings would be much lower. In the mid transport cost scenario, these would be 14 PJ through reuse, 0.7 PJ through repurpose and 0.8 PJ through recycle. This illustrates the case for choosing a higher circular strategy, and suggests that significantly larger environmental benefits can be realised if the viable volume is increased to reach the total volume in the region.

5.1.2 Overall conclusion

To answer the main research question, it may be concluded that the PoDH and PoA come forward as most suitable locations for the development of a circular wind hub, in that order. Collaboration between the ports to conjointly develop a hub is suggested to make optimal use of each port's strengths and existing facilities.

The application of different circular strategies significantly influences the to-be treated volumes of WTB at the hub and the economic and environmental gains that can be achieved in this way. In each scenario, the viable volume is very limited compared to the total return volume in the region. Only for reuse in the low transport cost scenario, a substantial viable volume of on average 507 kt is reached. A summary of the results per port is offered in Table 5.1[1].

The total return volumes in this region already surpass the minimum required throughput capacity for a mechanical recycling plant of 4 kt/a in 2022. This supports the urgency to develop a circular wind hub, and indicates that through interregional collaboration, the viability of the hub is enhanced. Considering the viable volumes, the 4 kt/a threshold is only passed around 2040 in the low transport cost scenario, and not at all in the mid and high transport cost scenarios. This reinforces the urgency to increase the viable return volumes.

The research findings have shown that without any intervention, the to-be processed volumes at the hub - and the associated economic and environmental benefits - are limited. It is only viable to transport the EoL WTB to the hub for a small amount of wind farms, which is highly dependent on which wind farms are in direct vicinity to the port. The results therefore suggest that incentives are required to enhance the economic value of the secondary material so that the financial margin between economic value and transport cost is increased and hence, transport distances can increase. This would allow for a higher volume of material to be treated at the hub.

Alternatively, collaboration could be expanded to other composite sectors, such as the aviation and automotive sector, so that the annual material throughput is increased. This, however, brings along other challenges such as an even more heterogeneous material flow. Note that this would only be applicable for recycling as an EoL strategy and not for repurposing or reusing the blades. Furthermore, a push is needed so that the markets may develop more thoroughly. Transparent documentation of WTB and the monitoring of their quality development during the use-phase - especially for offshore WTB with which there is very little experience - is crucial.

The findings indicate that in terms of financial margin and environmental impact, most can be achieved by reusing the blades and least by recycling and repurposing them, depending on the scenario. Conversely, the potential market size seems highest for recycling the blades and lowest for reusing them. This imbalance asks for regulation. Additionally, while this research rests on the assumption that each circular strategy is applied to 100% of the return volumes of WTB, a combination of strategies is vital. There is no market that can fully absorb all the expected EoL WTB and it is unrealistic that this will develop over time. Furthermore, since return volumes are comprised of a variety of blade sizes and designs, a combination of EoL strategies will be required. Especially for repurposing blades, a wide variety of markets exist that each have a limited capacity for WTB. Hence, a hub could ideally offer the space and facilities required to offer a mix of strategies, and to store the material if market demand and supply for a certain strategy do not coincide. Strong collaboration is required to match WTB supply with demands in the different markets.

In conclusion, this research has offered a more concrete and tangible analysis of the challenge of EoL WTB in the geographical region relevant to the Netherlands

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[1] The application of circular strategies in this table is only shown for the mid transport cost scenario

until 2050. The return volumes have been determined for the specified scope, and have been enhanced through a spatio-temporal quantification. The synthesis of the three research objectives aids the establishment of optimal waste management infrastructure for EoL WTB. It has been illustrated that substantial environmental and economic benefits can theoretically be achieved, especially under implementation of higher circular strategies, provided that measures or incentives are introduced to support this. Seeing as numerous circular wind hubs will need to be developed throughout Europe, or even globally, this research offers guidance in the considerations to make. Furthermore, the results from this research shed additional light on the RL component of WTB which is oftentimes left outside of consideration in analyses of this sector.

	Port of Amsterdam	Port of Rotterdam	Port of Den Helder	Groningen Seaports	North Sea Port
Port suitability					
Total	4.9	3.4	5.4	4.6	4.0
Port willingness	1	0.5	1	1	0.75
Available space	0.75	0.25	1	1	0.75
Companies, infrastructure & activities	1	1	1	1	1
Accessibility	1	1	1	1	1
Circular strategies	0.29	0.04	0.36	0.04	0.13
Centrality	0.85	0.58	1.00	0.59	0.37
Application of circular strategies					
Reuse					
Viable volume [kt]	263	234	278	234	194
Economic benefits [M€]	113	108	113	100	90
Energy savings from EoL [PJ]	16	14	17	14	12
Repurpose					
Viable volume [kt]	31	27	21	24	21
Economic benefits [M€]	2	2	1	2	1
Energy savings from EoL [PJ]	0.9	0.8	0.6	0.7	0.6
Recycle					
Viable volume [kt]	60	63	62	53	56
Economic benefits [M€]	6	6	5	5	5
Energy savings from EoL [PJ]	0.8	0.9	0.9	0.7	0.8

Table 5.1: Overview of final results per port. Note that the port suitability scores are in normalised form, i.e. with values between $0 - 1$, hence the total score for this aspect can be a maximum of 6. The results of the application of circular strategies represent the cumulative amounts over time until 2050, shown only for the mid transport cost scenario

5.2 DISCUSSION

The discussion first covers the contribution of this research to academic literature. Next, the research limitations resultant from the choices made in modelling assumptions and system demarcation are reviewed.

5.2.1 Contribution to academic literature

In the literature, EoL WTB have long remained a blind spot. The EoL component is oftentimes not taken up in LCA, or only to a limited extent. In any case, the question of RL for EoL WTB requires more focus. This research has responded to this by analysis of the potential of a circular wind hub in the Netherlands, to better fit the expected return volumes of EoL WTB inside a CE.

The idea of a circular wind hub is a relatively new idea and will, in a short amount of time, become more and more pressing due to rapidly increasing return volumes of EoL WTB. The development of a framework for the comparison of ports for the development of a circular wind hub aids decision-making on which port is most feasible, or which ones could collaborate.

While a number of studies have already been performed on quantifying the return volumes of WTB, this study offers a more in-depth analysis by including not only the magnitude of this material flow, but also the geographical origins of it. Such a geographical explicit quantification whereby the locations of the WTB are included aids future LCA and studies of RL of EoL WTB. It furthermore helps to determine which ports are optimally located with regard to the expected return volumes. By placing the results in the context of different circular strategies, light is shed on how much material a circular wind hub could actually treat. In this way, the research makes the challenge of EoL WTB more concrete and maps out the magnitude of this challenge in light of different circular strategies. As such, it aids the optimal establishment of a waste management infrastructure for EoL WTB. This can assist other countries with similar considerations.

5.2.2 Discussion on modelling assumptions

The lifetime of the wind farms is approached as a Normally distributed variable with a mean lifetime that increases over time. Different developments in wind farm decommissioning are observed: on the one hand, permits for wind farms are extended to prolong the lifetimes; on the other hand, sites are decommissioned sooner as new turbines are available that make it economically interesting to dismantle the current turbines prematurely and install new ones. There is little experience with the long-term development of wind farms in an offshore environment, which makes it difficult to draw conclusions with regard to quality and technical development of these turbines. Thus, there are a wide number of variables at play that influence at which time a wind farm will be dismantled. To accommodate all these variables, it is assumed that a Normally distributed lifetime is the preferred way to approach this. Since the results generated by the dMFA are in line with other published results, it may be concluded that the choice of lifetime is indeed valid. With more experience in decommissioning - especially offshore -, this could be improved and refined.

Another important concept is the transport distance and associated transport costs. The transport distance is determined with the straight-line distance from the wind farms to the ports. This therefore disregards potential travel restrictions such as protected nature areas or military areas offshore, and does not consider road- and waterways onshore. Therefore the transport distance is likely underestimated. This could be addressed by either modelling this component in more detail or by introducing a scaling factor to the determined distances. However, as this is underestimated in a similar way for each port and wind farm, this is not assumed to be a significant issue.

Furthermore, the future locations of onshore wind farms were approached with a proxy, namely the central location of each province. Examination of the distance between the centroid in the largest province in the Netherlands and its borders gives a range of around 60 km. However as it is the central location of the province, inaccuracies with regard to the actual location could be either underestimated or overestimated. It is assumed that this cancels each other out well enough to remain as is. When more information becomes available in terms of onshore wind plans, this aspect could be reviewed.

In the current analysis, the material composition of a blade and the material use of different manufacturers is approached in a generic fashion. In light of recent developments such as the launch of a fully recyclable blade by SGRE, more careful analysis of material composition of different blades would enhance the research.

From the sensitivity analyses in Sections 4.2.2 and Section 4.3.4, it has become clear that the model outcomes are sensitive to a change in average lifespan, transport costs and economic value. It is therefore important to be aware of the modeling choices for these parameters as these have a significant impact on the outcomes.

5.2.3 Discussion on system demarcation

In terms of system demarcation, there are a number of relevant aspects to the research that ask for consideration.

First of all, the economic analysis deserves mentioning here. The sensitivity analysis has shown that the model outcomes are sensitive to changes in both the transport costs and the economic value of the secondary material. Despite this, the main conclusions generally still hold. It proved difficult to define both economic factors to begin with, and no developments were incorporated in terms of potential changes in these values up to 2050. The economic value is determined on the basis that a market for the material exists, which is not generally the case yet. Furthermore, it is in any case a limited economic analysis, since it disregards other costs associated with decommissioning and treatment at EoL. The strong sensitivity in the model to these parameters indicates that they are important ones to address in the development of policy measures. Moreover, interpretation of the results and conclusions must be done in light of this sensitivity.

The system demarcation is currently drawn around the first application of different circular strategies. The delayed material flow that results from this secondary EoL material is therefore not considered. For reusing blades, for instance, it is assumed that 100% of the material may be reused, and that this has a second lifetime of another 10-15 years. While this concerns a significant amount of material that would re-enter the waste treatment stream, it is difficult to keep track of this material: reused WTB are often installed in Southern or Eastern Europe or Northern Africa, and repurposed or recycled WTB could end up in a wide range of industry sectors. It therefore seems unlikely that this material, while it might be of significant volume, is of interest to the ports at hand.

In terms of application of the circular strategies, the current research analyses each strategy separately and assumes the complete return volume is treated accordingly. There is no one-size-fits-all solution, and no market that can absorb all the material. Hence, a combination of the strategies is required. Therefore, the research results - while valuable for theoretical insight in the potential of each strategy - offer a limited conclusion with regard to actual implementation of a hub. For further steps in the development of the circular hub, analysis of scenarios for a mix of strategies could be valuable.

At present, the research is limited to wind farms that are currently installed and will be installed until 2030. A significant growth in wind installations is also expected post-2030: for instance, the Netherlands aims towards 11.5 GW of offshore wind by 2030, and this might reach 60 GW in 2050. Furthermore, these new WTB might also undergo redesign in their material composition. This is left out of the current analysis since it seems unlikely that redesign will play a significant role in turbines until 2030. However, near the end of this decade and especially also in the time hereafter, this will become more plausible. Redesign of blades may have as effect that certain recycling or treatment techniques become applicable to only a fraction of the blades, as is already seen in polyester versus epoxy treatment. Therefore, on the one hand the outflow of material until 2050 will likely be higher than this research predicts; on the other hand the fraction applicable to specific treatment options might be reduced.

It should be noted that the findings in this research are based on the presumption that all the offshore wind farms in the North Sea and English Channel will be available to be treated at one of the Dutch ports. However, there is no certainty that all of this material will be accessible to the Netherlands. This will be influenced by (local) legislation, as well as potentially similar hub developments elsewhere.

Another point to note is that the current research has incorporated a limited environmental analysis related to the question of EoL WTB. Including emissions resulting from transport and looking in more detail at the processing techniques of the different circular strategies, as well as looking at a more diverse selection of impact categories apart from energy use, would further complete the comparison of the circular strategies and shed further light on the question of RL.

Finally, sustainable development has been introduced as depending on three fundamental pillars: social, economic and environmental. The current analysis has touched upon the economic and environmental pillar. While it has been illustrated that these analyses could be further refined, it would also be of value to shed light on the social pillar. For instance with respect to labour opportunities that the hub could generate or its effect on the surrounding communities. Such an expansion of the research also corresponds with the holistic, system-wide approach that is key in IE.

5.3 RECOMMENDATIONS

This section offers recommendations based on the obtained results and the limitations of the research. Recommendations are offered for further research to refine and expand the analysis, as well as for industry partners and policy-makers.

5.3.1 Recommendations for further research

Further research could initially address the limitations mentioned in Section 5.2. First of all, updating the research with new findings on lifetime development, development of onshore wind installations, and wind capacity growth after 2030 is advised.

The most important aspects to approach more carefully and with more detail are the transport costs and the economic value of the material for which the model output is not robust. It is advised that more research be directed towards more accurate definitions of the transport costs for the different transport methods. Additionally, further research could assess what the economic value of the secondary material would need to be under each circular strategy to reach the desired increase in viable volumes; this would help in defining policy measures. In any case, more elaborate evaluation of this economic element would not be misplaced.

The research results have shown that without external support, the ultimate volume to be treated at the hub under each circular strategy is (very) limited. It is therefore advised that further research be directed towards the evaluation of potential policy measures to support this - to investigate how effective these could be in increasing the viable volume and to aid the general development of a circular wind hub. This could be done against the backdrop of the Shared Socioeconomic Pathways (Riahi et al., 2017), to investigate the effects of the circular strategies and a circular wind hub in various future scenarios.

It could additionally be of interest to expand the research scope. Further research could look into including other circular strategies to complete the circular ladder in the analysis. Furthermore, analysis could look at possible scenarios for the application of a mix of strategies. This could also include research into the minimum required throughput for each circular strategy, and the evaluation of the effects of redesign of the blades on the different available treatment options. Such analyses would aid the actual implementation and feasibility of a circular wind hub.

The current research is mainly focused on two of the three pillars of sustainability, namely economics and environment. This calls for further research to focus on the social pillar as well. This also corresponds to the holistic research approach of IE. For instance, the evaluation of port locations for the development of a circular wind hub could be expanded to include socio-economic considerations such as required growth of employment opportunities in the area and could consider potential symbiosis opportunities with other industries in proximity to the port in more detail.

Finally, incorporating composite flows from other industry sectors in the analysis may help to reach minimum required throughputs at earlier dates and as such, improve the potential desirability of a central hub for recycling. And besides the material flows, analysis of the management and organisation of EoL components in other composite-industries such as the aviation sector may offer inspiration to the wind sector. The material flows can furthermore be enhanced by including other WTB waste streams (manufacturing, service) and not only the EoL material flow.

5.3.2 Recommendations to industry and policy

From the findings in this research, a number of recommendations can be made to industry players and policy-makers. First of all, for the development of a circular wind hub, none of the ports is deemed unsuitable. Especially since it has been suggested by numerous ports that the hub be a larger entity rather than a single, clearly demarcated, physical area, it is recommended to the ports to work together on this initiative. With the PoA and PoDH as most centrally located ports with regard to WTB return volumes, and simultaneously as two of the ports with most clear and eager ideas about a circular wind hub, it would be advised that these parties take the lead in this. The main part of the hub could for instance be located at these ports, while further collaboration and cooperation takes place with the other ports.

The modelled material outflows indicate that a growing material stream is in upswing. For the development of a circular wind hub, it would be very interesting to combine the material outflows from other countries: this first analysis has shown that the minimum required throughput for for instance a recycling plant could - theoretically - already be reached next year.

Moreover, it is imperative to know what the actual material composition and design of the blades is. For development of the application of the circular strategies and their potential markets, more transparent documentation of WTB and monitoring of their quality throughout their operational life is critical. Increased transparency on the material composition and design of the blades is oftentimes diametrically opposed to the concept of intellectual property. This therefore asks for collaboration from both industry and policy.

With regard to economic value, it is recommended to policy-makers to look into instruments (financial or otherwise) to (a) stimulate market demand for the secondary material and (b) provide incentive for the treatment of these materials by arranging higher revenue margins. More financial stability in this regard would be a step towards providing industry parties with the increased certainty that they require for setting up treatment facilities. This would moreover help to increase the total viable volume to be treated at dedicated facilities, which the research results have shown to be significantly lower than the total material outflows in the region without intervention. Finally, the mismatch between the potential benefits from applying a circular strategy and their potential market size should be addressed.

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A BACKGROUND INFORMATION

This Appendix presents background information on some of the concepts introduced and used in this thesis. First, background information on two of the circular strategies, prevention and recycling, is offered, complementary to Chapter 2. Next, a full overview of sources for WTB material is presented.

A.1 PREVENTION

Prevention means decreasing the volume of waste and/or the (harmful) substances in it (Gharfalkar et al., 2015). There are a number of developments in this category, particularly regarding the replacement of the complex thermoset composites. These could be replaced by thermoplastics. In contrast to thermosets, thermoplastics can be molten and reshaped (PlasticsEurope, 2020), which would facilitate EoL treatment. The results have shown that the thermoplastic composites score higher than the thermosets regarding strength, environmental impact, and lifetime of the blades (Forsythe et al., 2014).

In this regard, the ZEBRA research consortium has launched in 2020, with the aim to produce fully recyclable, thermoplastic blades. Martijn Koelers from LM Wind Power has voiced the expectation to use the thermoplastic resin from ZEBRA in their blades within three to four years, where it can be applied to blades of all sizes. In contrast, Julie Teuwen from Delft University of Technology mentions the difficulty of using thermoplastics in the load-carrying structural parts of the blade as it has a higher risk of creep and fatigue; this means application for large turbines is still limited and if this resin would be applied by 2030, then most likely only for small turbines ($\leq$ 2 MW) onshore. Mishnaevsky (2021) agrees with this, stating that until now, thermoplastic resins have only been applied in demonstration projects of blades of 13 or 25 metres length; application in blades of larger sizes still faces challenges. According to Ierides and Reiland (2019), the use of thermoplastic resins in blades is currently at TRL 6. This research therefore assumes that thermoplastic blades will only be produced on a significant scale from 2030 onwards, and as such, will not be taken into account in the analysis.

A.2 RECYCLING AND RECOVERY

Recycling means using the waste material in a new application (Jensen and Skelton, 2018), thereby (partially) replacing virgin materials. There are currently three main recycling techniques (Beauson et al., 2014; Chen et al., 2019):

1. Mechanical: shredding, grinding
2. Thermal: pyrolysis, fluidised bed
3. Chemical: solvolysis

Jensen and Skelton (2018) group the thermal and chemical recycling techniques under recovery and not recycling. After Gharfalkar et al. (2015), recycling is defined as "any recovery operation by which waste materials are reprocessed into products, materials or substances", while recovery concerns processes "which produce energy [. . .] and materials from waste", which are to be applied as *fuels* (Gharfalkar et al., 2015, p. 307-308). From Chen et al. (2019), it can be concluded that thermal and chemical processes are able to recover fibres which can subsequently be reprocessed. From ETIPWind (2019), it becomes clear that the thermal and chemical recycling techniques have as output both recovered material and energy or other fuels. Therefore, it is chosen to remove the differentiation between recycling and recovery here, and merge these categories, since the techniques may be applicable to either category.

A.3 SOURCES FOR WIND TURBINE BLADE MATERIAL

Lifetime is not the sole relevant indicator for waste streams of WTB material. After Liu and Barlow (2017), there are three categories of waste streams, occurring throughout the entire life cycle of a blade:

- Manufacturing waste: waste from in-process, testing, defects
- Service waste: waste from transportation, operation, maintenance
- End-of-life waste: based on lifetime of the blade

The manufacturing waste stream consists of in-process waste from the production process, waste from testing blade materials and waste from defects. Estimates for the amount of production waste vary between 10% (Psomopoulos et al., 2019), a range between 12-30% with a median of 17% (Liu and Barlow, 2017), 30% (Lefeuvre et al., 2019) and a range between 20-35% (Liu and Barlow, 2015). Optimisation in the production process may be expected in the future (Psomopoulos et al., 2019) and is estimated at 10% per annum from 2026 onwards by Lefeuvre et al. (2019). Apart from production waste, manufacturing waste is generated by testing material and defects. After Liu and Barlow (2015, 2017), 0.1% of blade material is discarded due to testing and 0.1% of blade material is discarded due to defects per year. These waste streams are expected in the first year of operation (Liu and Barlow, 2017).

The service waste stream is made up of waste generated during transport, from operations and required maintenance, and from the upgrading of blades. The waste from transport and installation is of such low occurrence, that this is considered zero (Liu and Barlow, 2017). Waste due to required maintenance is more common. Due to failures and accidents or routine maintenance, blades may need to be replaced or repaired. The yearly replacement rates vary between 2% (Lichtenegger et al., 2020), 1.5-4.5% (Liu and Barlow, 2016, 2017), 2.2% (Tota-Maharaj and McMahon, 2020) and 3% (Zimmermann et al., 2013). These waste streams are expected in the sixth year of operation since most failures occur in the first five years (Liu and Barlow, 2017). The upgrading of blades, i.e. repowering, varies between 2%, 5% and 10% in different scenarios, and this is expected in the sixteenth year of operation (Liu and Barlow, 2017).

It should be noted here that the results of research by Liu and Barlow (2017) on waste streams from WTB are based on the analysis of 21 bills of materials of blade manufacturers, which are all of onshore turbines. Data on offshore turbines is much more scarce since the offshore wind sector is currently much younger and smaller than the onshore one. For offshore turbines, the previously determined values may differ, especially considering the fact that the offshore environment is harsher compared to onshore. Nevertheless, the above-mentioned values are considered a best estimate.

Whilst these streams are not unimportant, a demarcation needs to be made in the research scope since time and resources do not allow full consideration of all aspects. Thus, the manufacturing and service waste streams are left out of consideration for this research.

B SYSTEM DEMARCATION AND MODELLING ASSUMPTIONS

This Appendix gives an overview of the system demarcation and modelling assumptions applied in this research. The reasoning behind the chosen system boundaries and applied values can be found throughout the main report, in Chapters 1 and 4.

System demarcation:

- Countries included in analysis are the Netherlands, Germany, Denmark, England, France, Belgium;
- For the Netherlands, both on- and offshore turbines are analysed, for the other countries only offshore turbines are analysed;
- The geographical boundaries of the offshore region are shown in Figure 4.3;
- Planned installed wind capacity is included up to 2030;
- The research considers application of three circular strategies for EoL WTB: reuse, repurpose and recycling (mechanical grinding).

Modelling assumptions:

- Concerning the dMFA:
  - Material composition and manufacturer share are assumed to remain the same until 2030;
  - The lifetime of wind farms is approached as a Normal distribution with an increasing varying mean over time. Two scenarios are introduced whereby the mean is increased or decreased by 20% (see Table 4.18);
  - The average turbine size is expected to increase annually according to the trend line shown in Figure 4.4;
  - The future installed capacity for offshore wind is based on existing tenders and published plans. Future installed capacity for onshore wind is based on 7 GW installed capacity by 2030;
  - For future locations for onshore wind, the centroid of each province in the Netherlands is used as a proxy.
- Concerning the effect of circular strategies:
  - Each wind farm is assigned a decommissioning date based on the Normal distribution from the default-lifetime scenario;
  - Transport costs for EoL WTB are approached as fixed values in three scenarios (low, mid, high cost), summarised in Section 4.3.3.3;
  - The monetary value of secondary blade material under the different circular strategies is approached as a fixed value and summarised in Table 4.28. For this, it is assumed that there is a market for the material;
  - The environmental impact is approached as energy savings;
  - It is assumed that the *entire* viable return volume is processed in each of the three circular strategies;
  - For determining for which wind farms it is economically viable to transport them to the ports, only the transport costs and the proceeds of the different circular strategies are considered.

C DATA CLEANSING AND RESEARCH APPROACH

This Appendix offers information regarding data cleansing and the filling in of missing data for the quantitative analyses in the research. These are summarised separately for each quantitative research method.

Concerning the dMFA

The dataset from *The Wind Power* with historic data was loaded into QGIS to select only those wind farms that fall within the scope of this research: offshore wind farms in the North Sea and the English Channel, and onshore wind farms in the Netherlands. This selection rendered a few errors in distinguishing between onshore and offshore turbines: 16 wind farms had been categorised as offshore but were in fact onshore, for instance on dikes or at the coast. Five of these were outside of the Netherlands and were thus removed from the analysis. The remaining eleven were moved to the onshore dataset.

As described in Chapter 3 and Section 4.2.1.1, the future offshore wind capacity is based on existing tenders and plans. This information was not always complete.

Regarding the commissioning year: if only the year when the tender was accepted or the plan was approved was provided and not when the wind park would *actually* be commissioned, the commissioning date was set 5 years after the tender date (Freeman et al., 2019). If there was no official tender yet, only the plan that a wind farm would be operational by 2030 without further concrete plans, the commissioning date was set at 2030. For wind farms categorised as currently being under construction, the commissioning date was set for 2021.

Regarding the size of the wind farm or the number of turbines: if the wind farm was provided with a possible range of installed capacity or number of turbines, the average of this range was taken. If the output generated by this was unrealistic, then the minimum or maximum of the range was taken to generate a more realistic result.

As described in Chapter 3, the dMFA works with inflows, stocks and outflows. At present, most of the data is in the form of individual wind farms, their size and commissioning date - which is an inflow in the dMFA. This is the case for historic onshore and offshore wind capacity, as well as for future offshore wind capacity. The only exception is future onshore wind: this is given as a stock, namely: 7 GW installed capacity by 2030. For the dMFA, all the data must be in the same format.

To do so, a number of steps have to be undertaken. First, the 7 GW installed capacity by 2030 is interpolated linearly back from 2030 to 2020 to determine how much capacity must be installed each year, starting from the 4.2 GW installed capacity in 2020.

Next, the historic inflows are grouped per year, and with the determined lifetime from Section 4.2.1.7[1], these go into an inflow-driven DSM as developed by Pauliuk (nd). This yields the annual stocks. However, the historic onshore wind dataset was not complete: an amount of 452 MW was missing when compared to the reported onshore wind capacity in 2020 of 4,177 MW - a 12% difference. Therefore, there is also a discrepancy between the newly calculated stocks and the known stock of 4.2

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[1] Only the default scenario for average lifetime is used

GW in 2020. As it is assumed that this missing capacity is resultant from missing data over time from small and individual wind turbines that were not taken up by a central database, all years are scaled by the percentage difference to fill this data discrepancy.

Subsequently, the newly calculated and scaled historic stocks are merged with the determined future stocks. This gives a total overview of all onshore wind capacity stocks up to and including 2030. This data is fed into a stock-driven DSM as developed by Pauliuk (nd), which yields the required data: a complete overview of all annual onshore wind inflows up to and including 2030.

Now, all the required input data is in the same format and the inflow-driven dMFA for EoL WTB can be performed.

Concerning the GIS analysis and the effect of circular strategies

Due to the lack of information on future onshore wind, the centroid of each province in the Netherlands is taken as a proxy for the location. Subsequently, every wind farm is assigned a sample of the Normal distribution for its lifetime. This gives a prediction for wind farm decommissioning over time. This is done with a fixed random seed so that each wind farm is assigned the same lifetime each time the model is run.

While this is not correct for individual wind farms, on average over all wind farms, it does approach a correct prediction. In this way, a 93% overlap between the GIS and dMFA outflows is achieved. It is not 100% due to the discrepancy from assigning individual predictions. However, this gives a good enough indication.

This does result in a much more jumpy trend in annual outflows, whereas the outflows from the dMFA analysis are smoothened out. Per year there can therefore be quite a discrepancy, but overall it yields similar results. With these assigned decommissioning dates, one arrives at a more realistic representation of how the outflows will develop: in batches rather than a continuous outflow, with some years much more and some years much less material.

D CURRENT INSTALLED CAPACITY

This Appendix elaborates on on the current installed wind capacity by analysing the data retrieved by *The Wind Power* database and country-specific data. This acts as both a validation of the data from *The Wind Power* database and helps to fill data gaps where required. The current installed wind power in each country is described in the sections below.

D.1 NETHERLANDS

Onshore capacity

The current installed capacity of onshore wind in the Netherlands is regionally distributed throughout the twelve different provinces as shown in Table D.1. Comparing the regional distribution in 2019 to 2020 shows a fairly similar trend in distribution. By the end of 2020, the total onshore capacity had grown to over 4 GW (RVO, 2021b). Installed onshore wind capacity is currently 4,177 MW (RVO, 2021a).

Province	Percentage in 2019 [%]	Percentage in 2020 [%]
Groningen	13	16
Friesland	6	5
Drenthe	1	1
Overijssel	1	2
Flevoland	32	27
Gelderland	2	4
Utrecht	1	1
North Holland	9	15
South Holland	13	11
Zeeland	14	13
North Brabant	7	6
Limburg	0	1

Table D.1: Regional distribution of onshore wind in the Netherlands in 2019 and 2020 (CBS, 2020; RVO, 2021a)

An overview of the regional distribution of onshore wind can be seen in Figure D.1. The light blue triangles depict current wind capacity, while the circles display plans either under construction or in a planning phase.

The onshore wind capacity from the Netherlands included in the dataset from *The Wind Power* totals to 3,725 MW. Hence, 452 MW is missing from the dataset, i.e. 12%. It is assumed that this missing capacity is resultant from missing data over time from small and individual wind turbines that were not taken up by a central database. Therefore, all known onshore wind farms are scaled by the percentage difference to bridge this gap in installed capacity.

Two wind farms in the dataset do not have a commissioning date defined; these are only 0.6 MW and 0.85 MW in size and are therefore removed from the analysis.

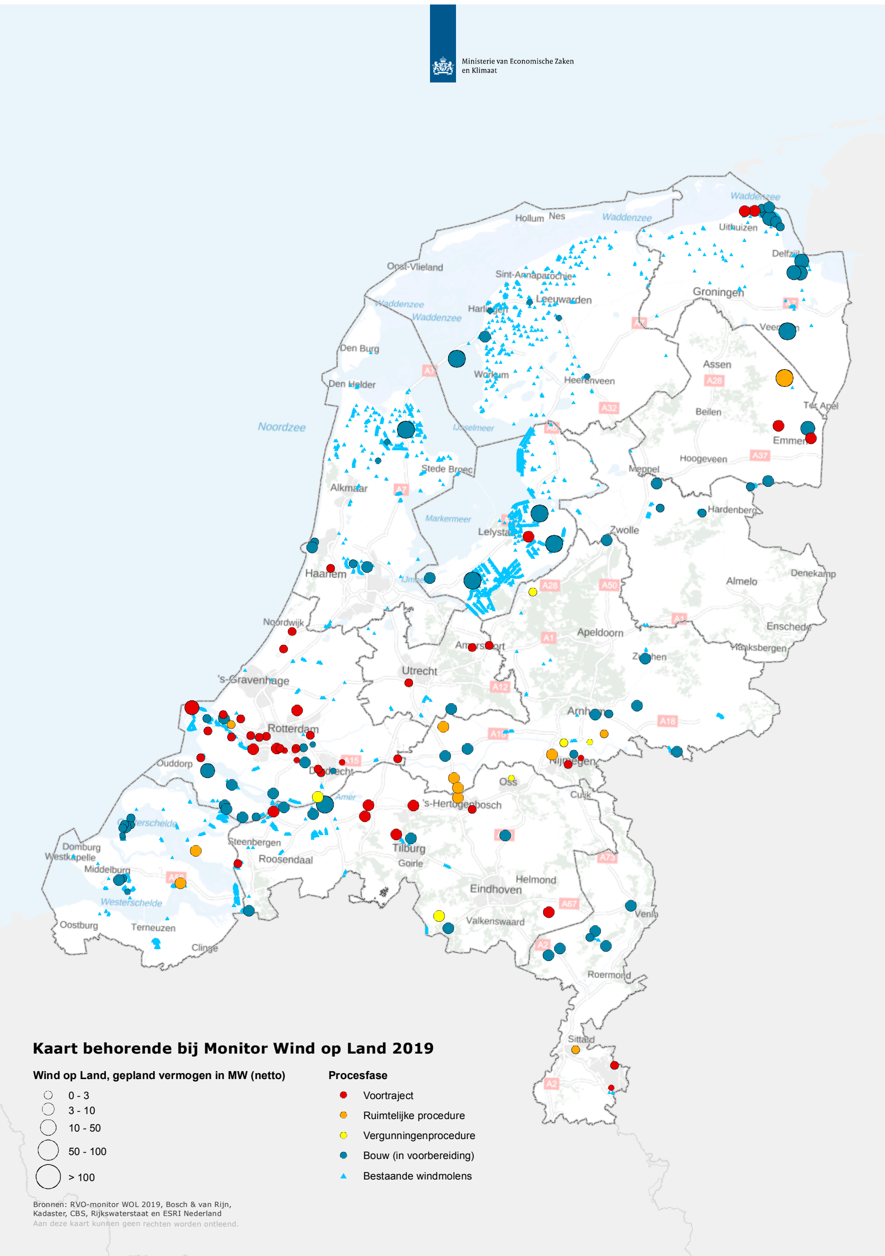

Figure D.1: Onshore wind in the Netherlands in 2019 (RVO, 2019)

Offshore capacity
The current installed capacity of offshore wind in the Netherlands is shown in Table D.2, based on data from 2021.

Wind farm	In use since	Installed capacity [MW]	Nr of turbines	Type	Distance to shore [km]
Borselle V	2021	19.00	2	V164-9.5 MW	22
Borselle III and IV	2020	731.50	77	V164–9.5 MW	24
Borselle I and II	2020	752.00	94	SG 8.0 MW-167DD	24
Gemini	2016	600.00	150	SG SWT-4.0-130	60
Westermeerdijk	2016	144.00	48		
Luchterduinen	2015	129.00	43	V112	23
Prinses Amalia	2008	120.00	60	V80	23
Egmond aan Zee	2007	108.00	36	V90	11
Total		2,603.50			

Table D.2: Offshore wind in the Netherlands in 2021, from database and RVO (2021c)

D.2 GERMANY

In 2020, the offshore wind capacity in Germany totalled 7,770 MW. Of this, 6,698 MW was installed in the North Sea and 1,072 MW in the Baltic Sea (Deutsche Windguard, 2020). An overview of offshore wind is shown in Figure D.2. The turquoise circles depict installed wind capacity, red circles wind capacity awaiting a final investment decision, and grey circles wind farms that will be commissioned between 2022-2025. More information on these wind farms can be found in Appendix E.2. Table D.3 summarises the currently installed offshore wind farms in the North Sea. The total capacity shown in Table D.3 is not 100% identical to the 6,698 MW mentioned earlier; this is due to rounding errors.

Figure D.2: Offshore wind in Germany in 2020 (Deutsche Windguard, 2020, p. 5)

Wind farm(s)	Installed capacity [MW]	In use since
EnBW Hohe See, Global Tech I	900.00	2019
Borkum Riffgrund 2, Merkur Offshore	900.00	2018
Nordergründe	111.00	2017
Gode Wind 1, Gode Wind 2, Nordsee One	916.00	2016
Deutsche Bucht, EnBW Albatros, Veja Mate	800.00	2015
Butendiek, DanTysk, Sandbank	864.00	2015
Amrumbank West	302.00	2015
Meerwind Süd — Ost, Nordsee Ost	576.00	2015
Borkum Riffgrund 1, Trianel Windpark Borkum, Trianel Windpark Borkum II	800.00	2015
Riffgat	113.00	2014
BARD Offshore 1	400.00	2010
Alpha Ventus	62.00	2009
Emden Offshore	4.50	2004
Otto-Heinrich Voigt	0.40	1993
Total	6,748.90	

Table D.3: Offshore wind in Germany in 2020, from database and Deutsche Windguard (2020)

D.3 DENMARK

Denmark is a pioneer in wind energy, with the first offshore wind farm Vindeby installed already in 1991. Currently, the offshore wind capacity in Denmark's Western coast totals 804 MW. The current installed offshore wind farms are summarised in Table D.4.

Wind farm	In use since	Installed capacity [MW]	Nr of turbines	Type	Distance to shore [km]
Horns Rev 3	2019	406.70	49	V164-8.0 MW	20
EcoSwing	2019	3.60	1		
Nissum Bredning	2018	28.00	4	SWT-7.0-154	2.5
Horns Rev 2	2009	209.30	91	SWT-2.3-93	31.7
R/onland	2003	17.20	4		
Horns Rev 1	2002	160.00	80	V80-2.0MW	17.9
Made	2001	1.50	2		
Total		826.30			

Table D.4: Offshore wind in Denmark in 2021, from database and 4COffshore (2021)

D.4 UNITED KINGDOM

The current installed offshore capacity in the UK totals 10,428 MW (Komusanac et al., 2021); this capacity is spread over 35 offshore wind farms and some 2,000 turbines (NesFircroft, 2019). It should be noted that these figures are based on the entire UK, whilst this analysis is limited to the North Sea region. Within the geographical scope of this research, the UK has 7,510 MW installed.

Wind farm(s)	Installed capacity [MW]	In use since
East Anglia One	714.0	2020
Beatrice	588.0	2019
Hornsea Project One	1,218.0	2019
Rampion	400.2	2018
Blyth Offshore	41.5	2018
EOWDC	93.2	2018
Galloper	353.0	2018
Race Bank	573.3	2018
Dudgeon	402.0	2017
Hywind Scotland Pilot Park	30.0	2017
Humber Gateway	219.0	2015
Kentish Flats 2	49.5	2015
Westermost Rough	210.0	2015
Fife Energy Park	7.0	2013
Gunfleet Sands 3 Demonstration	12.0	2013
Lincs	270.0	2013
London Array	630.0	2013
Teesside	62.1	2013
Greater Gabbard	504.0	2012
Sheringham Shoal	316.8	2012
Gunfleet Sands	172.8	2010
Thanet	300.0	2010
Lynn and Inner Dowsing	194.4	2009
Kentish Flats	90.0	2005
Scroby Sands	60.0	2004
Total	7,510.8	

Table D.5: Offshore wind in the UK in 2020, from database, RenewableUK (2021) and 4COffshore (2021)

D.5 FRANCE

France currently has 2 MW (Komusanac et al., 2021) of offshore wind, i.e. a negligible amount.

D.6 BELGIUM

The total installed offshore wind capacity in 2020 is 2,262 MW. An overview of currently installed offshore wind farms in Belgium is shown in Table D.6.

Wind farm(s)	Installed capacity [MW]	In use since
Mermaid	235	2020
Northwester 2	219	2020
Seastar	252	2020
Norther	370	2019
Rentel	309	2018
Nobelwind	165	2017
Northwind	216	2014
Belwind	171	2010
C-power	325	2009
Total	2,262	

Table D.6: Offshore wind in Belgium in 2020, from database and Belgian Offshore Platform (nd)

E FUTURE INSTALLED CAPACITY

This Appendix elaborates on country-specific data on the planned installed capacity up to and including 2030. The planned installed wind power in each country is described in the sections below. For all countries, 4COffshore (2021) and country-specific databases and websites were used to identify future wind farms.

E.1 NETHERLANDS

While the Netherlands have clear plans and tenders for offshore wind development, there is little certainty regarding plans for onshore wind. From the *Monitor Wind op Land 2020* - the onshore wind monitor of 2020 - the current installed capacity per province is shown (Table D.1). The implementation of the onshore energy transition in the Netherlands is organised in such a way that the country is divided into 30 'regional energy strategy'-zones. These zones each decide individually on the locations for the development of renewable energy technologies such as wind, however these plans are not yet definitive. Therefore, the scenario for 7 GW installed capacity for onshore wind in the Netherlands in 2030 is apportioned among the provinces according to the current regional distribution in 2020 from Table D.1. The current capacity is assumed to grow linearly towards the 2030 figures posted in the low, middle and high scenarios for onshore wind development. More information on this can be found in Appendix C.

In terms of offshore development, there are more concrete plans available. Table E.1 shows the planned wind farms in the North Sea. The Netherlands aims for 11.5 GW of offshore wind power in 2030 (RVO, 2021c). Missing coordinates of the wind farms were found via RVO (nd). More information on the filling of missing data (such as commissioning date) can be found in Appendix C.

Wind farm(s)	Installed capacity [MW]	Commissioning date
Hollandse Kust Zuid, I and II	760.00	2022
Hollandse Kust Zuid, III and IV	760.00	2022
Hollandse Kust Noord, V	700.00	2023
Hollandse Kust West, VI and VII	1,400.00	2025-26
Ten Noorden van de Waddeneilanden, I	700.00	2027
IJmuiden Ver, I, II, III and IV	4,000.00	2028-9
IJmuiden Ver, V	1,350	2030
Total	9,670.00	

Table E.1: Offshore wind plans in the Netherlands (RVO, 2021c)

There are also two offshore wind farms being developed in inland water basins: Windpark Fryslân with 382.70 MW and Windplanblauw with 112 MW. These will be commissioned in 2021 and 2023, respectively. This brings the total capacity of planned offshore wind projects to 10,364 MW.

E.2 GERMANY

Initially, Germany had aimed for 15 GW offshore capacity by 2030 (IRENA, 2019); this has recently been increased to 20 GW (Reve, 2020). The 20 GW target is also taken up in the offshore development plans published by the Deutsche Windguard (Deutsche Windguard, 2020). Tenders from up to 2018 will add 2384 MW offshore capacity until 2025 to reach 10.8 GW by 2025; tenders from 2021-2025 will add another 9388 MW until 2030 (Deutsche Windguard, 2020). An overview of planned installations is shown in Table E.2. Missing coordinates were found via Bundesamt für Seeschiffahrt und Hydrographie (nd).

Wind farm(s)	Installed capacity [MW]	Commissioning date
Kaskasi	342.00	2022
Gode Wind	241.75	2024
AquaPrimus	28.00	2025
Borkum Riffgrund 3	900.00	2025
EnBW He Dreiht	900.00	2025
N-3.7	225.00	2026
N-3.8	433.00	2026
N-7.2	930.00	2027
N-3.5	420.00	2028
N-3.6	480.00	2028
N-6.6	630.00	2029
N-6.7	270.00	2029
N-9.1	1,000.00	2029
N-9.2	1,000.00	2029
N-10.1	1,000.00	2030
N-10.2	1,000.00	2030
N-9.3	1,000.00	2030
N-9.4	1,000.00	2030
Total	11799.75	

Table E.2: Offshore wind plans in Germany (Deutsche Windguard, 2020)

E.3 DENMARK

The offshore plans for Denmark are mostly concerned with the development of two energy islands by 2030. One of these will be placed in the Baltic Sea and is therefore outside of the scope of this research; the other island will be placed in the North Sea. The plan is that these islands are operational by 2030. The North Sea island will initially have a capacity of 3 GW, which can be expanded to 10 GW in the future. While the exact location of this island is still to be determined, it will be around 60-80 km off the coast of Thorsminde. The tenders for the island will be opened in 2022. (Danish Energy Agency, nda; Durakovic, 2020a). The island may contain up to 600 turbines (Broom, 2021). The development of this North Sea island will involve the construction of an artificial island; doubts have been expressed whether it is realistic that this will be operational by 2030 (BBC, 2021). This research assumes so.

Apart from the island, there are three other developments in the Danish North Sea. These are shown in Table E.3. The fourth entry is the energy island, in the area labelled Nordsøen I.

Wind farm(s)	Installed capacity [MW]	Commissioning date
Vesterhav Syd	168.00	2021
Vesterhav Nord	176.00	2021
Thor	1,000.00	2027
Nordsøen I	3,000.00	2030
Total	4,344.00	

Table E.3: Offshore wind plans in Denmark (Danish Energy Agency, ndb)

E.4 UNITED KINGDOM

Initially, the UK had aimed for 30 GW offshore capacity by 2030 (IRENA, 2019); this has recently been increased to 40 GW (Reve, 2019). It should be noted that this is based on the entire UK, whilst the analysis in this research is limited to the North Sea and English Channel.

The current tenders and approved plans for offshore wind are summarised in Table E.4. Not all commissioning dates are already known. Where these were not specified, an assumption was made based on the date when the plans for the offshore wind farm were approved. More information on this can be found in Appendix C. Additional information was retrieved from Ambrose (2020); NesFircroft (2019); CrownEstate (nd); RenewableUK (2020).

E.5 FRANCE

The offshore wind sector in France is quite limited. In total, an extra 2.4 GW of wind should be installed by 2023 and another 5.2-6.2 GW by 2028 (ENCP, 2020). There is a 1 GW tender for an offshore wind farm near St-Vaast-la-Hougue (Buljan, 2020) and for 600 MW near Dunkirk (ENCP, 2020). Some 3 GW of wind will be installed around the coastlines of Normandy, Brittany and Pays de la Loire (ENCP, 2020); of these areas, only Normandy and parts of Brittany are relevant for this research. In 2021, a tender for a 250 MW floating wind farm around Brittany will be released (Durakovic, 2020b). Other designated areas include the Mediterranean and South Atlantic, or there is no defined area yet (Durakovic, 2020b). However, it is said that between 2024-28, France will tender 1 GW of wind each year (Durakovic, 2020b). The relevant wind farms that will be developed by 2030 are shown in Table E.5. Additional information was retrieved from Ministère de la Transition Écologique (2021).

E.6 BELGIUM

Belgium aims to have 4 GW of offshore wind capacity by 2030. For this, a region of 281 km^2 in the North Sea has been designated (Economy, nd). The wind farms will be commissioned around 2026-28 (Platform, 2019) and are summarised in Table E.6. Additional information was retrieved from Federal Public Service of Health and Environment (2020) and Platform (2019). The areas for the future wind farms can be seen in Figure E.1.

Wind farm(s)	Installed capacity [MW]	Commissioning date
Kincardine 1 & 2	50.00	2021
Triton Knoll	857.00	2021
Moray East	950.00	2022
Neart na Gaoithe	448.00	2022
Hornsea 2	1,386.00	2023
Seagreen	1,140.00	2023
Moray West	875.00	2024
Blyth phase 2	58.40	2025
Dogger Bank A	1,235.00	2025
Dolphyn	10.00	2026
Dogger Bank B	1,235.00	2026
East Anglia One North	800.00	2026
East Anglia Two	900.00	2026
Inch Cape	1,000.00	2026
Seagreen 1A	360.00	2026
Sofia	1,400.00	2026
Berwick Bank	1,850.00	2027
Dogger Bank C	1,330.00	2027
East Anglia Three	1,400.00	2027
Hornsea 3	2,400.00	2027
Marr Bank	1,375.00	2027
Dudgeon Extension	402.00	2028
Hornsea 4	1,000.00	2028
Norfolk Vanguard	1,800.00	2028
Sheringham Shoal Extension	317.00	2028
Norfolk Boreas	1,800.00	2029
Rampion 2	1,200.00	2029
ForthWind 1 & 2	65.00	2030
Five Estuaries	353.00	2030
North Falls	504.00	2030
Round 4 - Area 1	1,500.00	2030
Round 4 - Area 2	1,500.00	2030
Round 4 - Area 3	1,500.00	2030
Total	33,000.40	

Table E.4: Offshore wind plans in the UK (NesFircroft, 2019; 4COffshore, 2021; RenewableUK, 2021)

Wind farm(s)	Installed capacity [MW]	Commissioning date
Baie de Saint-Brieuc	496.00	2023
Fécamp	498.00	2023
Calvados	450.00	2024
Dieppe-Le Tréport	496.00	2024
Dunkerque	598.00	2027
Normandie	1,000.00	2028
Guernsey	30.00	2030
Total	3,568.00	

Table E.5: Offshore wind plans in France

Wind farm(s)	Installed capacity [MW]	Commissioning date
Noordhinder Noord	700.00	2026
Noordhinder Zuid	1,400.00	2028
Total	2,100.00	

Table E.6: Offshore wind plans in Belgium

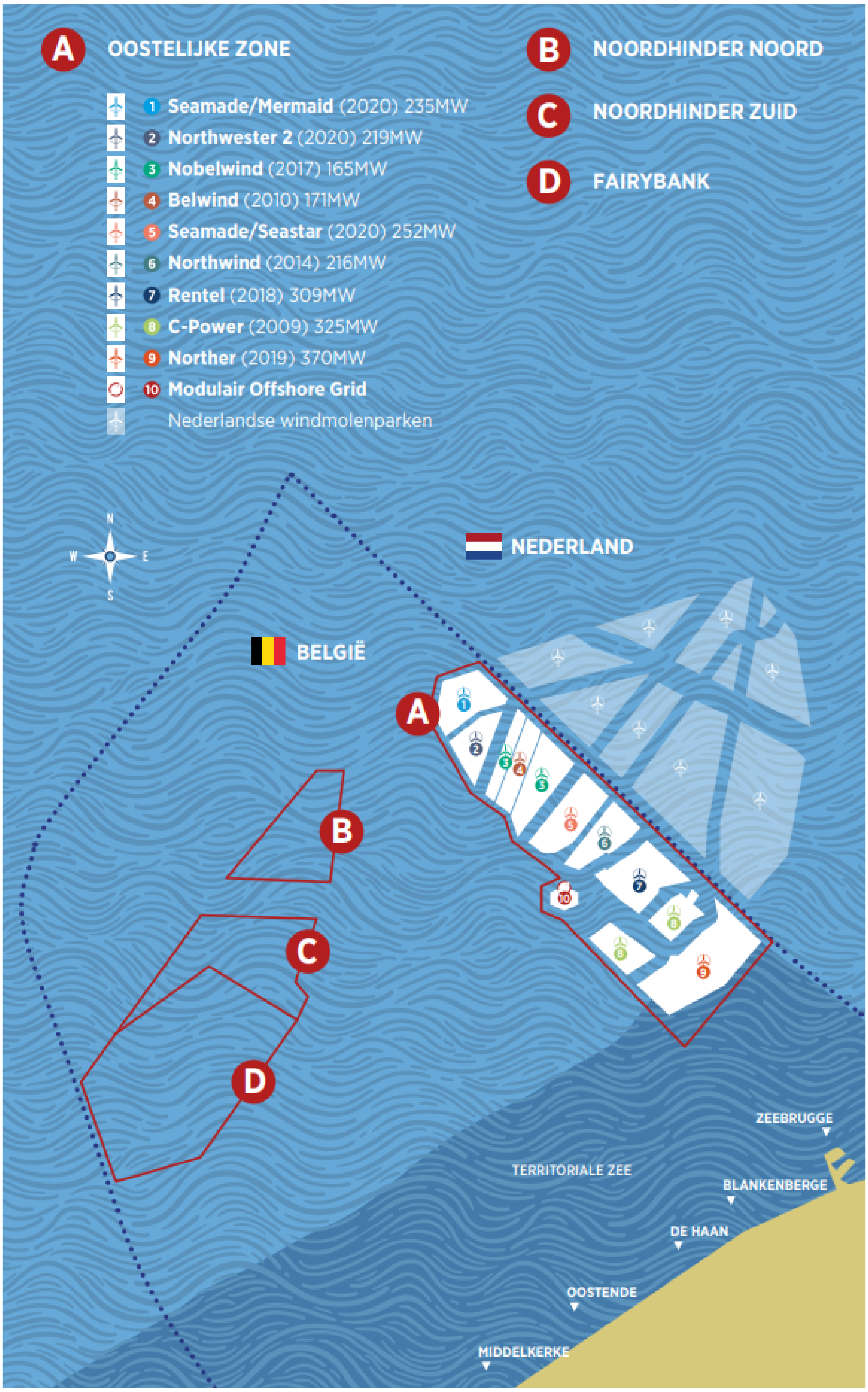

Figure E.1: Offshore wind in Belgium (Platform, 2019)

F VOLUME OF END-OF-LIFE WIND TURBINE BLADES TO BE TREATED AT EACH PORT

This Appendix offers for each port, under each transport cost scenario, and for each circular strategy, the total viable volume to be treated at the hub. First, an overview is given whereby the viable volumes are divided into their onshore and offshore constituents which helps to explain why the volumes are the magnitude that they are. Second, the development of the viable volumes over time, in kilotonnes per annum, is illustrated. Finally, these viable volumes under application of the recycling strategy are compared with the 4 kt/a minimum required throughput for a recycling facility.

F.1 CUMULATIVE VIABLE VOLUME DIVIDED INTO ONSHORE AND OFFSHORE WIND TURBINE BLADES

Table F.1 shows for each port, under each transport cost scenario, and under application of each circular strategy, the cumulative viable volume of EoL WTB that may be treated at the hub until 2050, in kilotonnes. In each case, the viable volume is divided into its onshore and offshore constituents.

F.2 ANNUAL VIABLE VOLUME OVER TIME

This section shows for each port, under each transport cost scenario, and under application of each circular strategy, the annual viable volume of EoL WTB that may be treated at the hub until 2050, in kilotonnes per annum. The overviews can be seen in Figures F.1, F.2, F.3, F.4 and F.5.

F.3 ANNUAL VIABLE VOLUME OVER TIME UNDER APPLICATION OF THE RECYCLING STRATEGY

This section shows for all ports combined, under each transport cost scenario, and under application of the recycling strategy, the annual viable volume of EoL WTB that may be treated at the hub until 2050, in kilotonnes per annum. This is enhanced with the 4 kt/a minimum required throughput for a recycling facility. The overview can be seen in Figure F.6. It can be seen how, in the low cost transport scenario, the minimum threshold is only reached around 2040, while in the mid and high transport costs, it is not reached at all (or at least not sufficiently).

		Reuse [kt]	Repurpose [kt]	Recycle [kt]
Low transport cost scenario				
PoA	Offshore	454	196	82
	Onshore	58	25	94
	Total	512	220	177
PoR	Offshore	443	168	79
	Onshore	57	29	90
	Total	500	198	169
PoDH	Offshore	483	208	67
	Onshore	57	17	93
	Total	540	225	160
GSP	Offshore	454	186	70
	Onshore	44	22	87
	Total	498	208	157
NSP	Offshore	442	137	67
	Onshore	46	20	67
	Total	488	157	134
Mid transport cost scenario				
PoA	Offshore	236	24	0
	Onshore	27	7	60
	Total	263	31	60
PoR	Offshore	202	17	0
	Onshore	32	10	63
	Total	234	27	63
PoDH	Offshore	260	14	0
	Onshore	18	7	62
	Total	278	21	62
GSP	Offshore	210	17	0
	Onshore	24	6	53
	Total	234	24	53
NSP	Offshore	171	18	0
	Onshore	22	3	56
	Total	194	21	56
High transport cost scenario				
PoA	Offshore	37	0	0
	Onshore	8	3	38
	Total	45	3	38
PoR	Offshore	29	0	0
	Onshore	16	5	42
	Total	44	5	42
PoDH	Offshore	20	0	0
	Onshore	8	1	28
	Total	28	1	28
GSP	Offshore	29	0	0
	Onshore	11	4	26
	Total	40	4	26
NSP	Offshore	33	0	0
	Onshore	5	1	30
	Total	38	1	30

Table F.1: Cumulative viable volumes up to 2050 under each circular strategy, split between onshore and offshore constituents

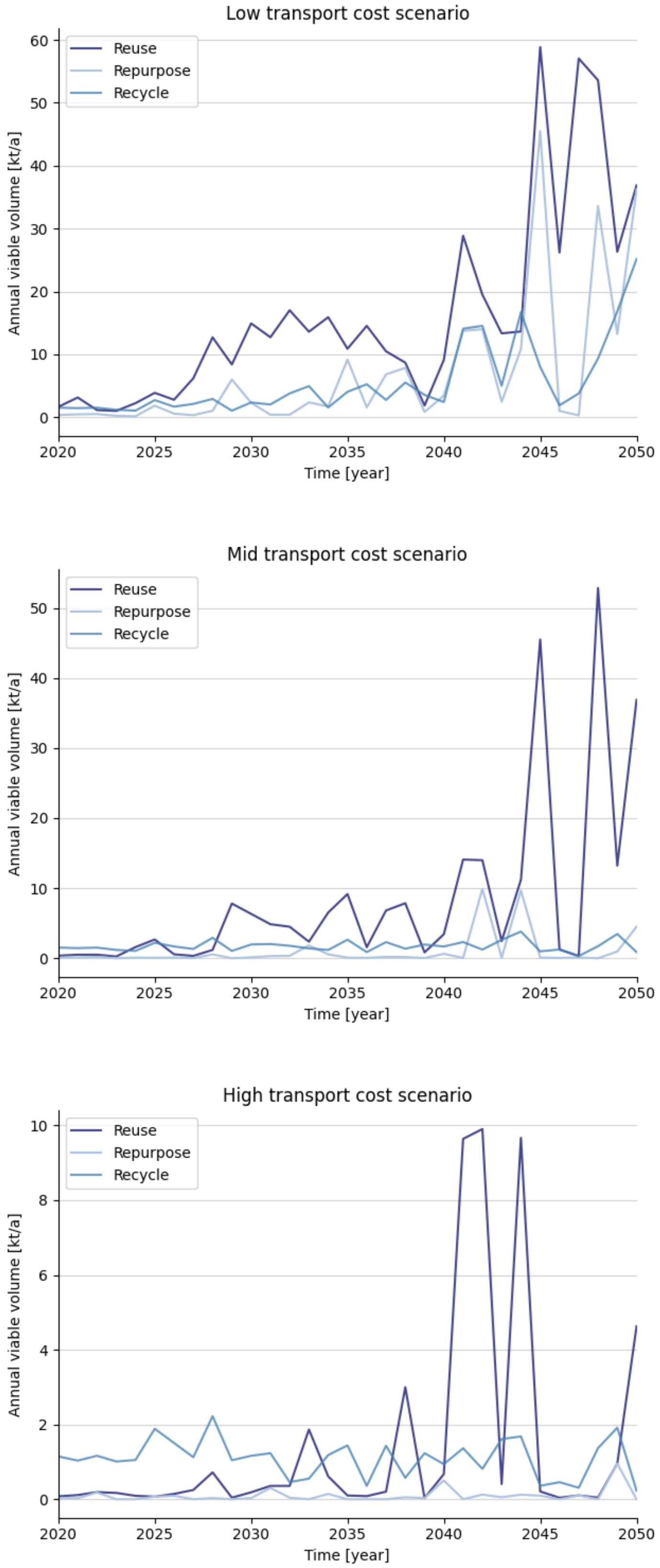

Figure F.1: Viable volume to be treated at PoA in the low, mid and high transport cost scenario

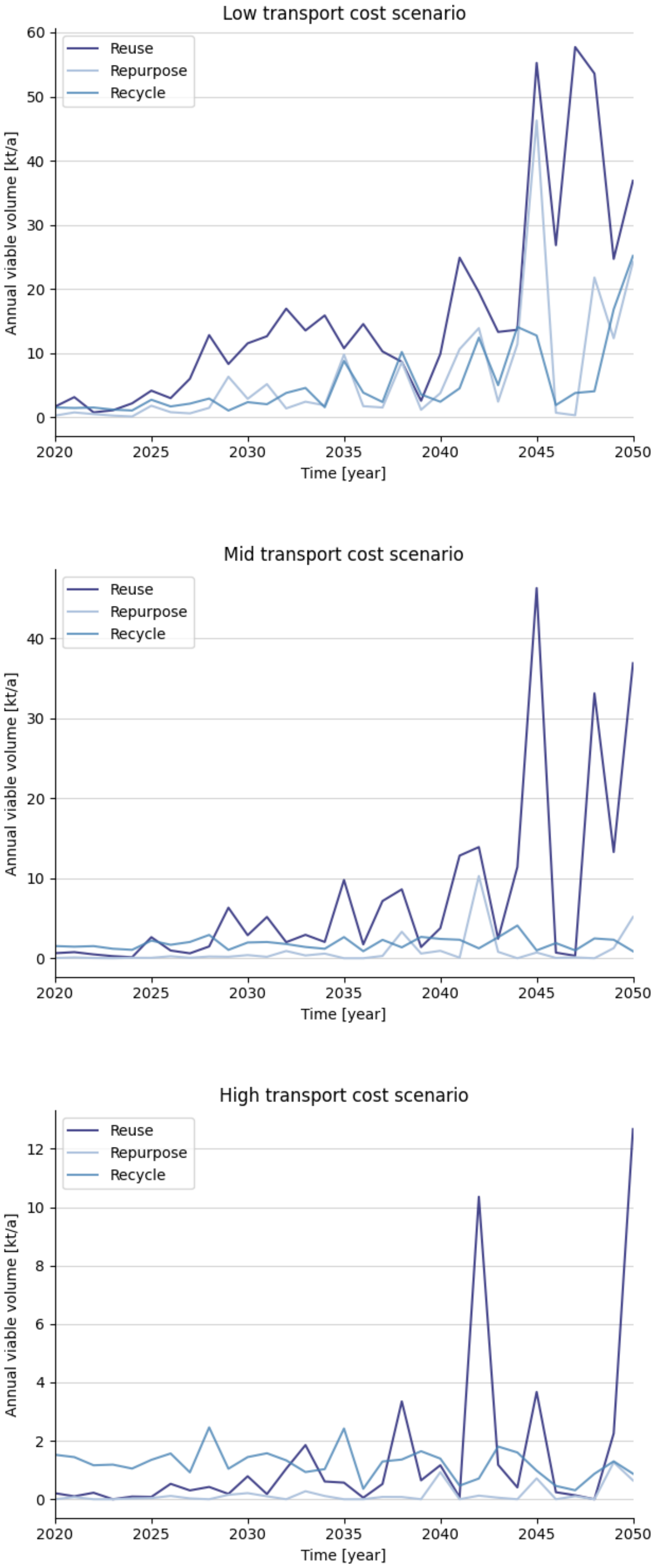

Figure F.2: Viable volume to be treated at PoR in the low, mid and high transport cost scenario

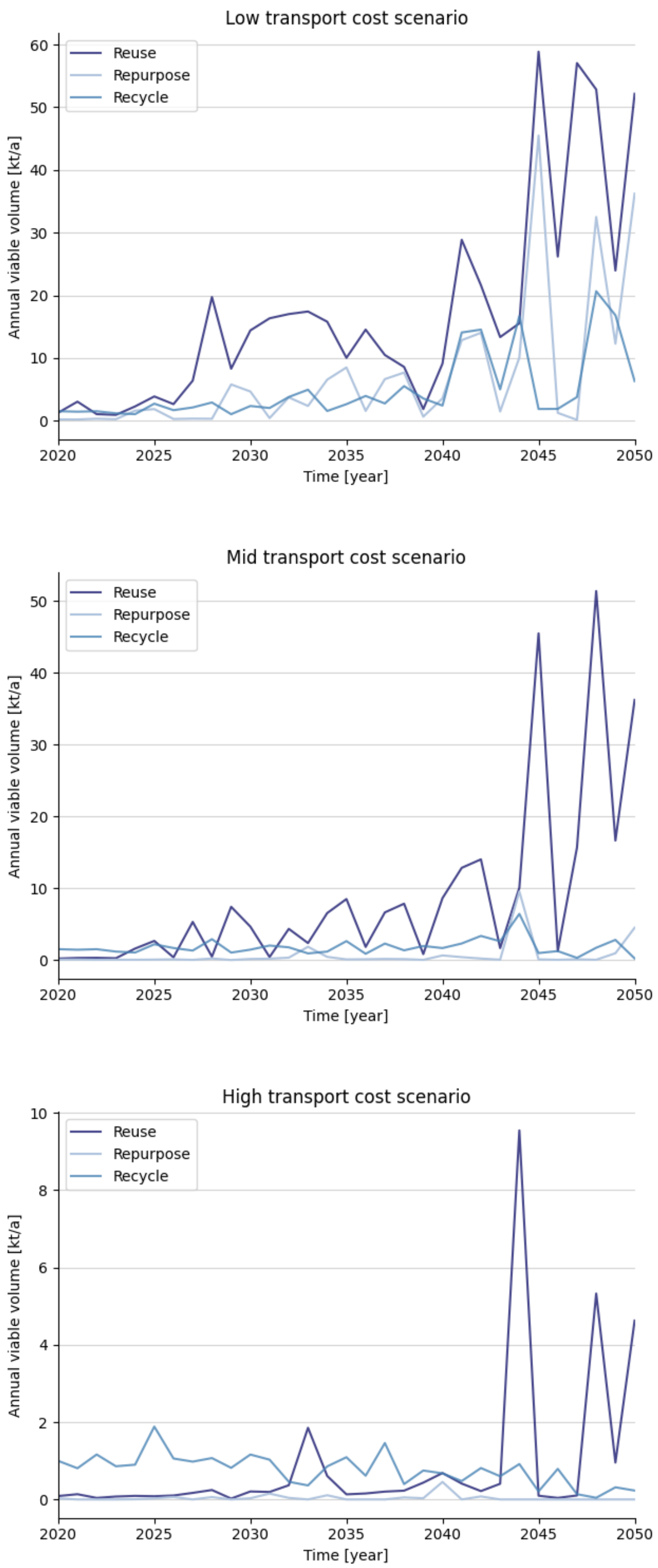

Figure F.3: Viable volume to be treated at PoDH in the low, mid and high transport cost scenario

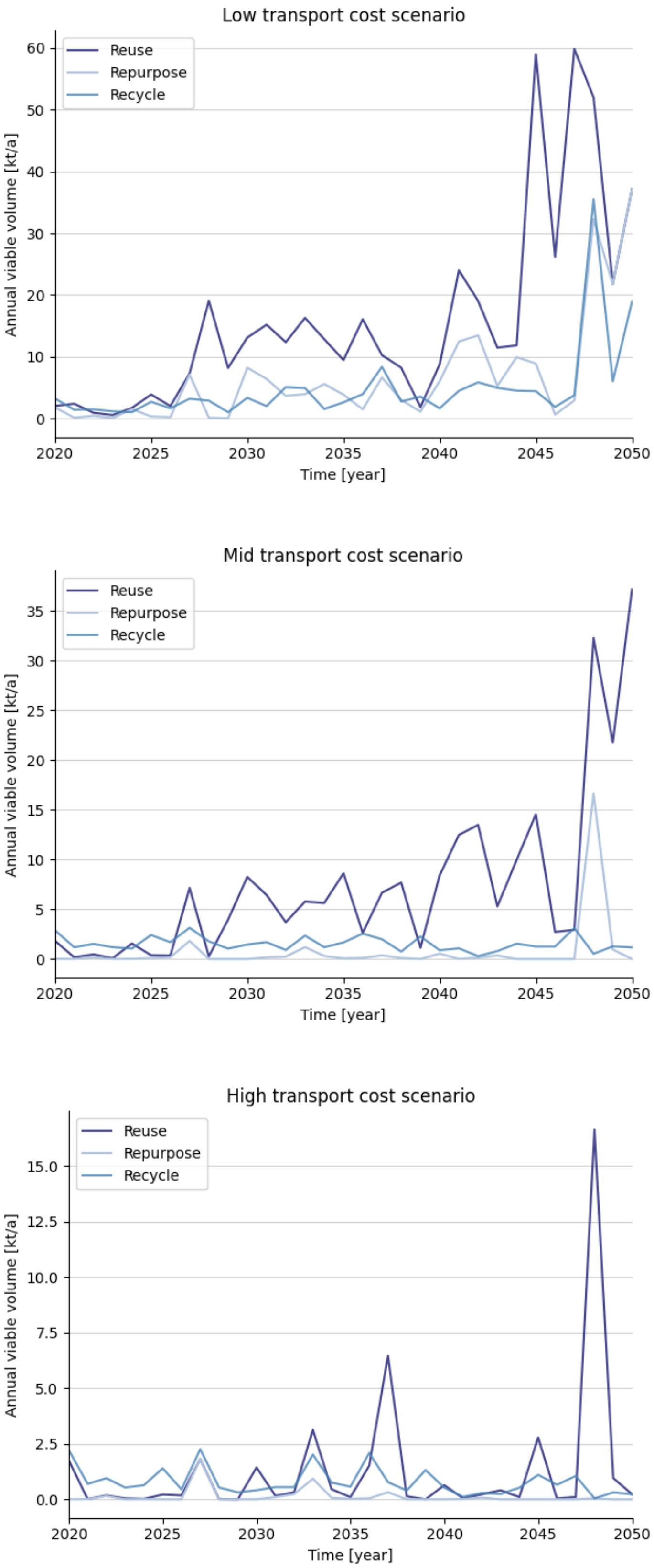

Figure F.4: Viable volume to be treated at GSP in the low, mid and high transport cost scenario

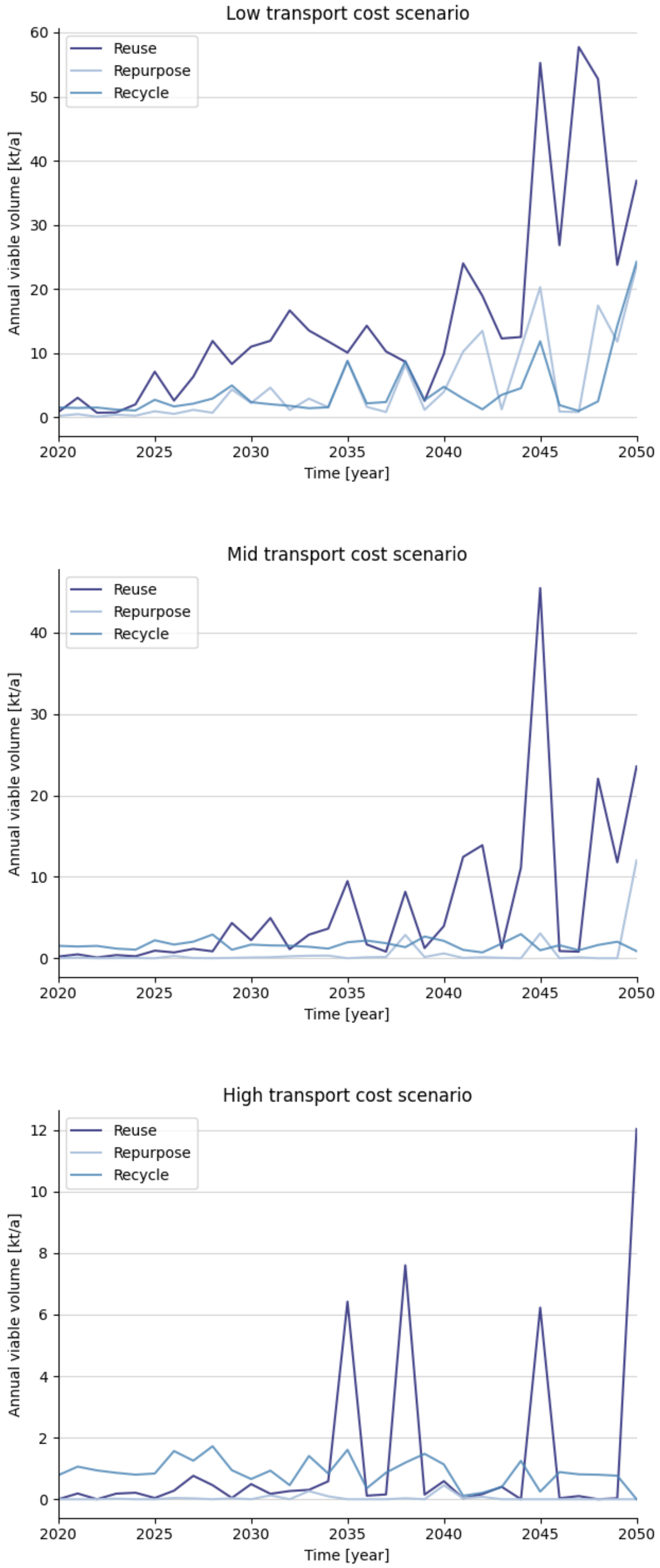

Figure F.5: Viable volume to be treated at NSP in the low, mid and high transport cost scenario

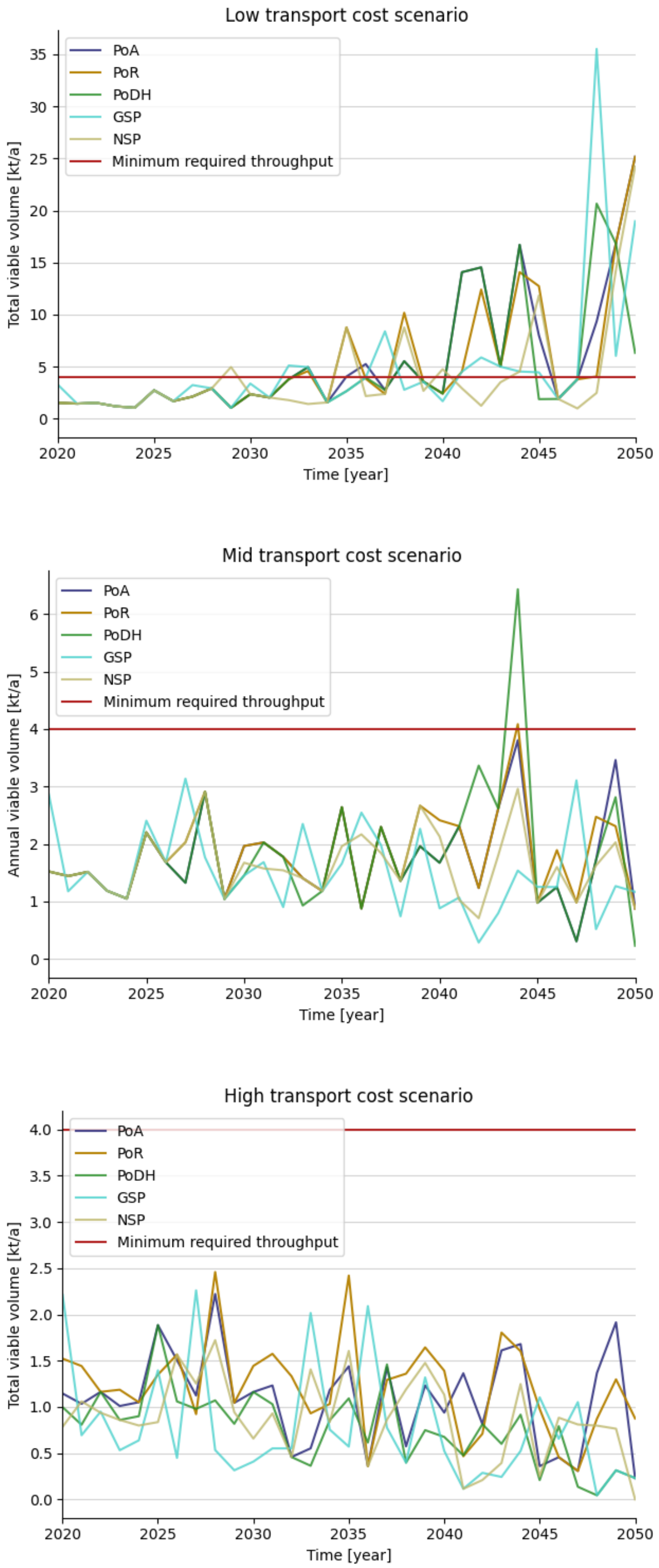

Figure F.6: Viable volume of all ports under recycling vs. the 4 kt/a minimum required throughput for a recycling facility in the low, mid and high transport cost scenario

G SENSITIVITY ANALYSIS

This Appendix contains overviews of the performed sensitivity analyses on the model results. First of all, the sensitivity analysis of average lifetime is shown, first on the annual blade mass outflows and second on the cumulative blade mass outflows from the dMFA. The second and third sections show the results of the sensitivity analysis of transport costs and economic value, respectively, on the total viable volume to be treated at each port, for each circular strategy.

G.1 SENSITIVITY ANALYSIS OF AVERAGE LIFETIME

Table G.1 shows the results of the sensitivity analysis of a ±10% change in average lifetime on the annual blade mass outflows of the dMFA. This is done for the default lifetime scenario. Table G.2 shows the same, but for the cumulative blade mass outflows. Tables G.3 and G.4 show the sensitivity analysis results for cumulative blade mass outflows for the low and high average lifetime scenarios, respectively. As the numbers are rounded to two decimal places, the percentages do not always seem to correspond exactly to the numbers presented in the table.

Year	Default	-10%	% change	+10%	% change
1989	0.00	0.00	0%	0.00	0%
1990	0.00	0.00	178%	0.00	-68%
1991	0.00	0.00	161%	0.00	-66%
1992	0.00	0.00	145%	0.00	-64%
1993	0.00	0.00	130%	0.00	-61%
1994	0.00	0.00	119%	0.00	-59%
1995	0.00	0.00	107%	0.00	-57%
1996	0.00	0.00	142%	0.00	-62%
1997	0.00	0.00	144%	0.00	-62%
1998	0.00	0.00	137%	0.00	-61%
1999	0.00	0.01	131%	0.00	-60%
2000	0.00	0.01	122%	0.00	-59%
2001	0.01	0.01	112%	0.00	-57%
2002	0.01	0.02	102%	0.00	-55%
2003	0.02	0.03	102%	0.01	-54%
2004	0.03	0.05	98%	0.01	-53%
2005	0.04	0.07	92%	0.02	-52%
2006	0.06	0.11	87%	0.03	-50%
2007	0.08	0.15	82%	0.04	-49%
2008	0.12	0.21	76%	0.06	-47%
2009	0.17	0.29	72%	0.09	-45%
2010	0.23	0.39	69%	0.13	-44%
2011	0.32	0.52	65%	0.18	-42%
2012	0.42	0.67	60%	0.25	-41%
2013	0.55	0.87	56%	0.34	-39%
2014	0.73	1.12	54%	0.45	-38%
2015	0.94	1.41	51%	0.59	-37%
2016	1.20	1.79	49%	0.77	-35%

Table G.1: Sensitivity analysis of average lifetime in the default lifetime scenario: total annual blade mass outflows until 2050 in kt/a

2017	1.50	2.20	46%	0.99	-34%
2018	1.88	2.72	44%	1.26	-33%
2019	2.33	3.33	43%	1.59	-32%
2020	2.88	4.07	42%	1.98	-31%
2021	3.50	4.89	40%	2.44	-30%
2022	4.23	5.83	38%	2.99	-29%
2023	5.07	6.88	36%	3.64	-28%
2024	6.03	8.04	33%	4.39	-27%
2025	7.10	9.28	31%	5.25	-26%
2026	8.28	10.58	28%	6.23	-25%
2027	9.53	11.89	25%	7.33	-23%
2028	10.83	13.16	21%	8.52	-21%
2029	12.13	14.35	18%	9.79	-19%
2030	13.37	15.44	15%	11.09	-17%
2031	14.51	16.42	13%	12.37	-15%
2032	15.52	17.32	12%	13.58	-13%
2033	16.40	18.23	11%	14.66	-11%
2034	17.18	19.24	12%	15.60	-9%
2035	17.94	20.45	14%	16.37	-9%
2036	18.78	21.96	17%	17.03	-9%
2037	19.82	23.78	20%	17.65	-11%
2038	21.15	25.91	23%	18.33	-13%
2039	22.81	28.29	24%	19.20	-16%
2040	24.78	30.85	24%	20.37	-18%
2041	27.00	33.56	24%	21.88	-19%
2042	29.37	36.48	24%	23.72	-19%
2043	31.85	39.75	25%	25.81	-19%
2044	34.44	43.51	26%	28.04	-19%
2045	37.29	47.84	28%	30.33	-19%
2046	40.57	52.63	30%	32.66	-19%
2047	44.46	57.51	29%	35.14	-21%
2048	48.97	61.84	26%	37.97	-22%
2049	53.87	64.84	20%	41.37	-23%
2050	58.65	65.77	12%	45.48	-22%

Table G.1: Sensitivity analysis of average lifetime in the default lifetime scenario: total annual blade mass outflows until 2050 in kt/a

Year	Default	-10%	% change	+10%	% change
1989	0.00	0.00	0%	0.00	0%
1990	0.00	0.00	178%	0.00	-68%
1991	0.00	0.00	167%	0.00	-67%
1992	0.00	0.00	156%	0.00	-65%
1993	0.00	0.00	144%	0.00	-63%
1994	0.00	0.00	133%	0.00	-61%
1995	0.00	0.00	122%	0.00	-59%
1996	0.00	0.00	134%	0.00	-61%
1997	0.00	0.00	139%	0.00	-62%
1998	0.00	0.01	138%	0.00	-61%
1999	0.00	0.01	134%	0.00	-61%
2000	0.01	0.02	129%	0.00	-60%
2001	0.01	0.03	122%	0.01	-59%
2002	0.02	0.05	114%	0.01	-57%
2003	0.04	0.08	109%	0.02	-56%
2004	0.07	0.13	105%	0.03	-55%
2005	0.10	0.21	100%	0.05	-54%

Table G.2: Sensitivity analysis of average lifetime in the default lifetime scenario: cumulative blade mass outflows until 2050 in kt

2006	0.16	0.32	95%	0.08	-52%
2007	0.25	0.47	91%	0.12	-51%
2008	0.36	0.68	86%	0.18	-50%
2009	0.53	0.96	82%	0.27	-48%
2010	0.76	1.35	78%	0.40	-47%
2011	1.08	1.87	74%	0.59	-46%
2012	1.50	2.55	70%	0.83	-44%
2013	2.05	3.41	66%	1.17	-43%
2014	2.78	4.54	63%	1.62	-42%
2015	3.72	5.95	60%	2.22	-40%
2016	4.92	7.73	57%	2.99	-39%
2017	6.42	9.93	55%	3.98	-38%
2018	8.30	12.65	52%	5.24	-37%
2019	10.64	15.98	50%	6.83	-36%
2020	13.51	20.05	48%	8.81	-35%
2021	17.01	24.94	47%	11.26	-34%
2022	21.24	30.77	45%	14.25	-33%
2023	26.31	37.65	43%	17.89	-32%
2024	32.33	45.68	41%	22.27	-31%
2025	39.44	54.96	39%	27.52	-30%
2026	47.71	65.54	37%	33.76	-29%
2027	57.25	77.43	35%	41.08	-28%
2028	68.08	90.59	33%	49.61	-27%
2029	80.21	104.94	31%	59.39	-26%
2030	93.58	120.38	29%	70.48	-25%
2031	108.09	136.79	27%	82.85	-23%
2032	123.61	154.12	25%	96.42	-22%
2033	140.01	172.35	23%	111.09	-21%
2034	157.19	191.58	22%	126.69	-19%
2035	175.12	212.04	21%	143.06	-18%
2036	193.91	233.99	21%	160.09	-17%
2037	213.72	257.78	21%	177.74	-17%
2038	234.87	283.69	21%	196.07	-17%
2039	257.68	311.98	21%	215.27	-16%
2040	282.46	342.83	21%	235.64	-17%
2041	309.46	376.38	22%	257.51	-17%
2042	338.84	412.87	22%	281.23	-17%
2043	370.68	452.61	22%	307.04	-17%
2044	405.13	496.12	22%	335.08	-17%
2045	442.42	543.96	23%	365.41	-17%
2046	482.99	596.59	24%	398.08	-18%
2047	527.45	654.10	24%	433.22	-18%
2048	576.42	715.93	24%	471.19	-18%
2049	630.30	780.77	24%	512.55	-19%
2050	688.94	846.54	23%	558.03	-19%

Table G.2: Sensitivity analysis of average lifetime in the default lifetime scenario: cumulative blade mass outflows until 2050 in kt

Year	Default	-10%	% change	+10%	% change
1989	0.00	0.00		0.00	
1990	0.00	0.00	84%	0.00	-49%
1991	0.00	0.00	78%	0.00	-48%
1992	0.00	0.00	73%	0.00	-46%
1993	0.00	0.00	67%	0.00	-44%
1994	0.00	0.00	62%	0.00	-42%
1995	0.00	0.00	57%	0.00	-40%
1996	0.00	0.00	67%	0.00	-43%
1997	0.01	0.01	70%	0.00	-44%
1998	0.01	0.02	69%	0.01	-44%
1999	0.03	0.05	66%	0.02	-43%
2000	0.05	0.08	63%	0.03	-42%
2001	0.08	0.12	60%	0.04	-41%
2002	0.12	0.18	55%	0.07	-39%
2003	0.18	0.28	54%	0.11	-38%
2004	0.29	0.44	52%	0.18	-38%
2005	0.44	0.66	51%	0.28	-37%
2006	0.65	0.96	49%	0.42	-36%
2007	0.94	1.38	47%	0.61	-35%
2008	1.32	1.91	45%	0.87	-34%
2009	1.83	2.61	43%	1.23	-33%
2010	2.52	3.55	41%	1.71	-32%
2011	3.40	4.74	39%	2.35	-31%
2012	4.51	6.19	37%	3.17	-30%
2013	5.91	8.00	35%	4.21	-29%
2014	7.69	10.31	34%	5.55	-28%
2015	9.88	13.11	33%	7.22	-27%
2016	12.64	16.65	32%	9.32	-26%
2017	15.96	20.84	31%	11.89	-26%
2018	20.05	25.99	30%	15.06	-25%
2019	25.00	32.22	29%	18.93	-24%
2020	31.03	39.77	28%	23.65	-24%
2021	38.13	48.54	27%	29.28	-23%
2022	46.41	58.60	26%	35.93	-23%
2023	55.94	69.96	25%	43.73	-22%
2024	66.77	82.61	24%	52.75	-21%
2025	78.90	96.50	22%	63.06	-20%
2026	92.27	111.52	21%	74.66	-19%
2027	106.78	127.55	19%	87.52	-18%
2028	122.30	144.52	18%	101.55	-17%
2029	138.70	162.39	17%	116.61	-16%
2030	155.88	181.23	16%	132.53	-15%
2031	173.83	201.22	16%	149.18	-14%
2032	192.64	222.65	16%	166.46	-14%
2033	212.51	245.90	16%	184.38	-13%
2034	233.78	271.39	16%	203.06	-13%
2035	256.85	299.53	17%	222.75	-13%
2036	282.13	330.73	17%	243.81	-14%
2037	310.03	365.40	18%	266.65	-14%
2038	340.92	403.96	18%	291.71	-14%
2039	375.18	446.87	19%	319.36	-15%
2040	413.20	494.60	20%	349.95	-15%
2041	455.44	547.50	20%	383.81	-16%
2042	502.38	605.63	21%	421.30	-16%

Table G.3: Sensitivity analysis of average lifetime in the low lifetime scenario: cumulative blade mass outflows until 2050 in kt

2043	554.41	668.51	21%	462.89	-17%
2044	611.64	734.99	20%	509.06	-17%
2045	673.65	803.18	19%	560.25	-17%
2046	739.32	870.63	18%	616.62	-17%
2047	806.82	934.66	16%	677.79	-16%
2048	873.69	992.76	14%	742.71	-15%
2049	937.27	1.043.01	11%	809.54	-14%
2050	995.03	1.084.34	9%	875.88	-12%

Table G.3: Sensitivity analysis of average lifetime in the low lifetime scenario: cumulative blade mass outflows until 2050 in kt

Year	Default	-10%	% change	+10%	% change
1989	0.00	0.00	0%	0.00	0%
1990	0.00	0.00	370%	0.00	-82%
1991	0.00	0.00	346%	0.00	-81%
1992	0.00	0.00	321%	0.00	-80%
1993	0.00	0.00	295%	0.00	-79%
1994	0.00	0.00	271%	0.00	-77%
1995	0.00	0.00	248%	0.00	-76%
1996	0.00	0.00	256%	0.00	-76%
1997	0.00	0.00	261%	0.00	-76%
1998	0.00	0.00	257%	0.00	-75%
1999	0.00	0.00	251%	0.00	-75%
2000	0.00	0.00	241%	0.00	-74%
2001	0.00	0.01	229%	0.00	-73%
2002	0.00	0.01	215%	0.00	-72%
2003	0.01	0.02	205%	0.00	-71%
2004	0.01	0.03	194%	0.00	-70%
2005	0.02	0.05	183%	0.01	-68%
2006	0.03	0.08	173%	0.01	-67%
2007	0.05	0.12	163%	0.02	-66%
2008	0.07	0.18	153%	0.03	-64%
2009	0.11	0.27	144%	0.04	-63%
2010	0.17	0.40	135%	0.07	-61%
2011	0.26	0.59	127%	0.10	-60%
2012	0.38	0.83	120%	0.16	-58%
2013	0.55	1.17	113%	0.24	-57%
2014	0.79	1.62	106%	0.35	-55%
2015	1.11	2.22	100%	0.51	-54%
2016	1.53	2.99	95%	0.74	-52%
2017	2.10	3.98	90%	1.04	-51%
2018	2.84	5.24	85%	1.44	-49%
2019	3.78	6.83	81%	1.98	-48%
2020	4.99	8.81	77%	2.68	-46%
2021	6.52	11.26	73%	3.58	-45%
2022	8.41	14.25	69%	4.73	-44%
2023	10.76	17.89	66%	6.19	-42%
2024	13.63	22.27	63%	8.01	-41%
2025	17.13	27.52	61%	10.25	-40%
2026	21.36	33.76	58%	13.02	-39%
2027	26.43	41.09	55%	16.38	-38%
2028	32.46	49.61	53%	20.46	-37%
2029	39.56	59.41	50%	25.35	-36%
2030	47.83	70.51	47%	31.17	-35%
2031	57.37	82.91	45%	38.05	-34%

Table G.4: Sensitivity analysis of average lifetime in the high lifetime scenario: cumulative blade mass outflows until 2050 in kt

2032	68.20	96.56	42%	46.08	-32%
2033	80.33	111.36	39%	55.36	-31%
2034	93.70	127.20	36%	65.93	-30%
2035	108.21	143.98	33%	77.79	-28%
2036	123.73	161.66	31%	90.89	-27%
2037	140.13	180.27	29%	105.14	-25%
2038	157.31	199.94	27%	120.38	-23%
2039	175.24	220.91	26%	136.46	-22%
2040	194.01	243.45	25%	153.24	-21%
2041	213.81	267.83	25%	170.64	-20%
2042	234.90	294.23	25%	188.67	-20%
2043	257.58	322.75	25%	207.49	-19%
2044	282.11	353.32	25%	227.32	-19%
2045	308.61	385.90	25%	248.48	-19%
2046	337.09	420.48	25%	271.28	-20%
2047	367.42	457.27	24%	295.94	-19%
2048	399.45	496.77	24%	322.51	-19%
2049	433.16	539.72	25%	350.91	-19%
2050	468.78	586.90	25%	380.92	-19%

Table G.4: Sensitivity analysis of average lifetime in the high lifetime scenario: cumulative blade mass outflows until 2050 in kt

G.2 SENSITIVITY ANALYSIS OF TRANSPORT COSTS

This section presents the results of the sensitivity analysis of a ±10% change in transport costs on the cumulative viable volume to be treated at each port, under application of each circular strategy. These are summarised in Table G.5.

	% change in cumulative viable volume					
	Reuse		Repurpose		Recycle	
	+10%	-10%	+10%	-10%	+10%	-10%
Low transport cost scenario						
PoA	-2.9%	5.0%	-9.5%	6.3%	-10.2%	0.0%
PoR	-0.6%	3.1%	-19.8%	9.6%	-11.1%	14.2%
PoDH	-5.3%	1.6%	-8.7%	3.5%	-13.3%	18.4%
GSP	-5.9%	4.2%	-15.5%	6.4%	-17.5%	7.2%
NSP	-8.2%	2.7%	-1.5%	17.6%	-0.5%	15.3%
Mid transport cost scenario						
PoA	-12.3%	13.1%	-3.2%	11.2%	0.0%	0.0%
PoR	-8.0%	15.2%	-14.5%	41.9%	-4.1%	5.7%
PoDH	-17.1%	8.5%	-25.8%	4.8%	-3.9%	4.5%
GSP	-7.8%	5.0%	-53.2%	10.7%	-2.1%	5.3%
NSP	-7.2%	13.7%	-18.0%	52.8%	-2.7%	4.5%
High transport cost scenario						
PoA	-22.5%	50.8%	-13.0%	6.1%	-5.7%	6.5%
PoR	-15.4%	85.1%	-28.0%	11.2%	-6.8%	3.2%
PoDH	-20.7%	95.6%	-6.4%	0.9%	-9.3%	10.7%
GSP	-29.1%	39.3%	0.0%	2.9%	-19.1%	24.7%
NSP	-14.5%	63.4%	-8.2%	11.3%	-7.1%	4.8%

Table G.5: Sensitivity analysis of transport costs: cumulative viable volume at each port until 2050 in kt

G.3 SENSITIVITY ANALYSIS OF ECONOMIC VALUE

This section presents the results of the sensitivity analysis of a ±10% change in economic value on the cumulative viable volume to be treated at each port, under application of each circular strategy. These are summarised in Table G.6. It can be seen how the results are very similar to the sensitivity analysis of transport costs shown in Appendix G.2, just mirrored for +10% and -10%.

	% change in cumulative viable volume					
	Reuse		Repurpose		Recycle	
	+10%	-10%	+10%	-10%	+10%	-10%
Low transport cost scenario						
PoA	4.3%	-2.9%	6.0%	-9.7%	0.0%	-13.2%
PoR	3.1%	-0.7%	9.5%	-19.9%	14.2%	-11.1%
PoDH	1.4%	-5.4%	3.4%	-8.8%	11.3%	-13.3%
GSP	4.2%	-6.0%	5.2%	-18.0%	6.9%	-21.9%
NSP	2.7%	-8.2%	16.3%	-4.4%	14.7%	-8.0%
Mid transport cost scenario						
PoA	13.1%	-12.6%	11.2%	-3.3%	0.0%	-0.7%
PoR	14.1%	-8.1%	30.6%	-14.5%	5.0%	-5.4%
PoDH	8.3%	-17.1%	4.6%	-26.0%	3.8%	-3.9%
GSP	4.9%	-8.0%	10.7%	-53.2%	4.9%	-2.1%
NSP	13.7%	-7.2%	52.6%	-18.4%	4.5%	-2.7%
High transport cost scenario						
PoA	50.7%	-22.8%	6.1%	-46.3%	5.9%	-5.7%
PoR	58.2%	-16.3%	11.2%	-28.9%	1.9%	-6.8%
PoDH	93.3%	-20.8%	0.9%	-6.4%	8.2%	-9.3%
GSP	38.8%	-29.5%	1.6%	0.0%	24.3%	-19.6%
NSP	62.1%	-14.5%	11.3%	-8.2%	4.8%	-8.8%

Table G.6: Sensitivity analysis of economic value: cumulative viable volume at each port until 2050 in kt

COLOPHON

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