LEUPHANA
UNIVERSITÄT LÜNEBURG

Circular Supply Chain Development for the Wind Industry –
Conceptional framework, exploration and quantification of second lifecycle pathways

By the School of Management and Technology
of the Leuphana University Lüneburg for the award of the degree

Doctor of Engineering / Doktor der Ingenieurwissenschaften
– Dr.-Ing. –

approved dissertation by Kathrin Julia Kramer

born on 11th April 1991 in Düsseldorf, Germany

Submitted on:	16.10.2024
Disputation on:	11.12.2024
First examiner and supervisor:	Prof. Dr.-Ing. habil. Matthias Schmidt, Leibniz University Hannover
Second examiner and supervisor:	Assoc. Prof. Ph.D. Anne P. M. Velenturf, University of Leeds
Third examiner:	Prof. Dr.-Ing. Noomane Ben Khalifa, Leuphana University Lüneburg

Submitted as dissertation under the title:

Circular Supply Chain Development for the Wind Industry – Conceptional framework, exploration and quantification of second lifecycle pathways

Author:

Kathrin Julia Kramer

DOI:

10.48548/pubdata-1733

“Change takes longer than you think –
and then it happens faster than you ever thought was possible.”

– Christiana Figueres –

Acknowledgement

First of all, I would like to thank my supervisors and examiners. Prof. Dr.-Ing. habil. Matthias Schmidt, thank you very much for your great support, the trust you have placed in me and the corresponding freedom. This was the cornerstone for the development of the thesis's objectives. Assoc. Prof. Ph.D. Anne Velenturf, thank you for your continued support and feedback, which has given me a lot of confidence along the journey. Prof. Dr.-Ing. Noomane Ben Khalifa, thank you for being the third examiner, which I really appreciate.

I would like to acknowledge that I was employed at the Institute for Production Technology and Systems (IPTS) at the Leuphana University Lüneburg and funded by the Lower Saxony Ministry of Science and Culture under grant number ZN3489 within the Lower Saxony "Vorab" of the Volkswagen Foundation. Thanks to my colleagues from the other research institutes, ZDIN, industry partners, and especially Jonas Kallisch.

A special thanks goes to my team at the Leuphana University, in particular to Dr. Alexander Rokoss, Thorben Green and Simon Hillnhagen. Moreover, thank you for the valuable feedback provided to the final draft, Alexander Rokoss and Jonah Schulz. Thanks to the colleagues at the IPTS, the working students, especially Patrick Jaenecke and Danial Mousavi, and the various students for their great collaboration during the supervision of their bachelor's and master's theses.

My gratitude goes to the department of Wind and Energy Systems from the Technical University of Denmark. Thank you for the given opportunity of a six months-stay to derive an understanding of the overall wind energy system. Special thanks to Justine Beauson and Asger Bech Abrahamsen – thanks for all the inspiring discussions and the great collaboration.

Thanks to the many industry experts from suppliers, OEMs, operators, service companies, decommissioners, refurbishment companies, recyclers, advisors and industry associations, who supported me throughout my thesis. Thanks to the researchers in the field, who created a sense of belonging and a very collaborative environment.

My deepest gratitude goes to my incredible friends and family – you don't know how happy I am to have you in my life. Anna, Kate, Susanne, Kathi, Henning, Sarah, Dennis, Christian, you believed in me, pushed me, challenged me and enjoyed life with me during the process of the thesis. There is not enough space to name everyone who contributed to this journey, but I am really grateful for having such true friends. My biggest thanks belong to my family for your support and love: My triplets Sven and Carolin, my older brother Christoph, Mom, Dad, Gilla and Wolfgang.

All in all, I am absolutely grateful to have met all these incredible people to help me find, shape and walk my path.

Hamburg, October 2024 Kathrin Kramer

Forward on the Thesis Format

This thesis follows the classical structure of a monographically dissertation typical at German universities. However, parts of the dissertation have already been published in advance in the form of peer-reviewed articles in a journal and conference proceedings. The early publication made it possible to ensure that the chosen research topic is relevant to research and practice. It also reinforced the dissertation's gradually developed research methodology. The usage of the following papers’ content will be highlighted throughout the thesis by providing appropriate references:

Kramer, Kathrin J., Bach Abrahamsen, Asger, Beauson, Justine, Hansen, Ulrich E., Clausen, Niels-Erik, Velenturf, Anne P. M., Schmidt, Matthias (2024): Quantifying circular economy pathways of decommissioned onshore wind turbines in Denmark and Germany. Journal of Sustainable Production and Consumption, 49, 179-192. DOI: 10.1016/j.spc.2024.06.022.

Kramer, Kathrin J., Beauson, Justine (2023): Review existing strategies to improve circularity, sustainability and resilience of wind turbine blades – A comparison of research and industrial initiatives in Europe. In: 43rd Risø International Symposium on Materials Science, IOP Conf. Series: Materials Science and Engineering 2023, 1293(1):12039. DOI: 10.1088/1757-899X/1293/1/012039.

Kramer, Kathrin J., Schmidt, Matthias (2023): Circular Supply Chain Management in the Wind Energy Industry – A Systematic Literature Review. In: 18th Global Conference on Sustainable Manufacturing. DOI: 10.1007/978-3-031-28839-5_10.

Kramer, Kathrin J., Schmidt, Matthias (2022): Circular Supply Chain Management for the Wind Energy Industry – Conceptional ideas towards more circularity. In: Digitization of the work environment for sustainable production. DOI: 10.30844/WGAB_2022_4.

Abstract

A rapid scaling from 1 TW to more than 10 TW of wind capacity is necessary until 2050 for the transformation of the energy system. As the installation of the required wind turbines will demand a significant input of materials and resources, the transition to a circular economy is seen as a promising approach to contribute to a sustainable and resilient scaling of supply chains in the wind industry. Despite, this recognition, research on circular supply chain management (CSCM) for the wind industry is rare, particularly for second lifecycle pathways of decommissioned wind turbines. In addition, understanding the circular economy pathways for rotor blades is critical to helping the industry build the recycling infrastructure for composites, which has yet to be established on an industrial scale.

The study takes a first step towards understanding CSCM and circular supply chains for second lifecycle pathways through the implementation of a mixed methods research design and by exploring the mature onshore wind markets Denmark and Germany from a multi-stakeholder perspective. A systemic and multi-level conceptual framework for CSCM in the wind industry is developed that details the circular flows of wind turbines, components and materials. Furthermore, interviews are conducted with industry experts and the results of the analysis reveal that a second lifecycle for decommissioned onshore wind turbines is common in Denmark and Germany. Additional insights are provided into the complex decision-making processes of the decision to decommission an onshore wind turbine and the choice of the subsequent circular economy pathway. To support capacity planning of supply chain actors and investment decisions in new infrastructure (e.g. blade recycling facility), new turbine, component and material flow models are developed and applied to the installed onshore wind turbine fleet in Denmark and Germany. Based on the newly derived empirical findings and comprehensive market data, annual estimates of decommissioning, second-lifecycle and recycling quantities are provided. It is therefore the first study to introduce annual second-lifecycle flows and to systematically include it into the estimation of recycling flows. The results reveal that the thresholds for a new blade recycling facility of 5,000-15,000 tonnes per year are not met in any of the scenarios provided for Denmark. For Germany, however, it is estimated that the minimum tonnage requirement will be exceeded within the next five years, provided that at least 30 % of the decommissioned onshore wind turbines are retained for recycling.

In conclusion, the findings of this study offer valuable insights which can inform the planning of circular supply chains in the wind industry. The study contributes to improving the decision-making basis for policy makers and companies to achieve sustainable resource use along the entire circular value chain.

Key words: Circular economy, circular supply chain management, wind industry, second lifecycle, component and material flow forecasts, sustainability

Kurzfassung

Für die Transformation des Energiesystems ist bis 2050 eine schnelle Skalierung von 1 TW auf mehr als 10 TW Windkapazität erforderlich. Da der Ausbau einen erheblichen Material- und Ressourceneinsatz erfordert, wird der Übergang zu einer Kreislaufwirtschaft als vielversprechender Ansatz angesehen, um zu einer nachhaltigen und resilienten Skalierung der Lieferketten in der Windindustrie beizutragen. Trotz dieser Erkenntnis gibt es nur wenige Forschungsarbeiten zum Circular Supply Chain Management (CSCM) für die Windindustrie, insbesondere für die zweite Lebenszyklusphase rückgebauter Windkraftanlagen. Um zudem die Industrie beim Aufbau der Recyclinginfrastruktur für Verbundwerkstoffe im industriellen Maßstab zu unterstützen, ist ein Verständnis über die zirkulären Materialflüsse für Rotorblätter von Bedeutung.

Die Studie leistet einen Beitrag zum Verständnis von CSCM und zirkulären Lieferketten für den zweiten Lebenszyklus durch die Untersuchung der etablierten Onshore-Windmärkte in Dänemark und Deutschland aus der Perspektive verschiedener Akteure. Es wird ein konzeptioneller Rahmen für CSCM in der Windindustrie entwickelt, der die zirkulären Ströme von Windturbinen, Komponenten und Materialien detailliert aufzeigt. Zudem erfolgt eine empirische Untersuchung auf Basis von Experteninterviews, dessen Analyse zeigt, dass ein zweiter Lebenszyklus für rückgebaute Onshore-Windkraftanlagen in Dänemark und Deutschland üblich ist. Es werden Einflussfaktoren der komplexen Entscheidungsprozesse in Bezug auf die Stilllegung einer Onshore-Windkraftanlage und die Wahl des anschließenden Kreislaufwirtschaftspfads aufgezeigt und untersucht. Um darauf aufbauend die Kapazitätsplanung der Akteure in der Lieferkette und Investitionsentscheidungen in neue Infrastruktur (z. B. Recyclinganlagen für Rotorblätter) zu unterstützen, werden Modelle für die Komponenten- und Materialströme entwickelt und auf die installierte Onshore-Windkraftanlagenflotte in Dänemark und Deutschland angewendet. Es ist die erste Studie, die den zweiten Lebenszyklus systematisch integriert und demnach jährliche Prognosen der Rückbau-, Zweitlebenszyklus- und Recyclingmengen aufzeigt. Die Ergebnisse zeigen, dass die Schwellenwerte für eine neue Recyclinganlage für Rotorblätter von 5.000-15.000 Tonnen pro Jahr in keinem Prognoseszenario für Dänemark erreicht werden. Für Deutschland wird erwartet, dass die 5.000 Tonnen pro Jahr bereits innerhalb der nächsten fünf Jahren überschritten werden, sofern mindestens 30 % des erwarteten Rückbaus für das Recycling bestimmt sind.

Die in der vorliegenden Studie gewonnenen Erkenntnisse können folglich in die Planung von zirkulären Lieferketten in der Windindustrie einfließen. Die Studie kann somit einen Beitrag dazu leisten, die Entscheidungsgrundlage für die Politik und Industrie zu verbessern, um eine nachhaltige Ressourcennutzung entlang der gesamten zirkulären Wertschöpfungskette zu erreichen.

Schlüsselbegriffe: Kreislaufwirtschaft, Circular Supply Chain Management, Windindustrie, zweiter Lebenszyklus, Komponenten- und Materialflussprognosen, Nachhaltigkeit

Overview of Chapters

Table of Content

Abbreviations

Abbreviation	Description
°C	*Degree Celsius*
CAPEX	*Capital expenditures*
CFRP	*Carbon-fibre reinforced plastics*
CE	*Circular economy*
CSC	*Circular supply chain*
CSCM	*Circular supply chain management*
DEA	*Danish Energy Agency*
DFIG	*Doubly-fed induction generators*
DNK	*Denmark*
EU	*European Union*
EEG	*Erneuerbare-Energien-Gesetz*
EoL	*End-of-life*
FSIG	*Fixed speed induction generator*
GER	*Germany*
GFRP	*Glass-fibre reinforced plastics*
GW	*Gigawatt*
GWEC	*Global Wind Energy Council*
IEC	*International Electrotechnical Commission*
ISO	*International Organisation for Standardisation*
LCA	*Life cycle assessment*
LCOE	*Levelized cost of energy*
m	*Meter*
MAE	*Mean absolute error*
MaStR	*Marktstammdatenregister/market master data register*
MRO	*Maintenance, repair and overhaul*
MW	*Megawatt*
OEM	*Original Equipment Manufacturer*
PMSG	*Permanent magnet synchronous generator*
RQ	*Research question*
SCM	*Supply chain management*

Abbreviation	**Description**
SDG	*Sustainable Development Goals*
SLR	*Systematic literature review*
TRL	*Technical readiness level*
TW	*Terawatt*
UK	*United Kingdom*
USA	*United States of America*
VDMA	*Verband Deutscher Maschinen- und Anlagenbau e.V.*
Vestas	*Vestas Wind Systems A/S*

List of Figures

List of Tables

List of Formulas

1 Introduction

1.1 Problem definition

In the light of the current triple planetary crises – biodiversity loss, climate change, pollution – caused mainly by the immense extraction and processing of material resources by humans, there is an urgent need to return to planetary boundaries (Richardson et al., 2023, pp. 1; United Nations Environment Programme [UNEP], 2024, pp. 2). The three planetary crises are closely interlinked, and one of the global and legally binding targets is to keep the increase in the global average temperature to ideally 1.5 degree Celsius (°C) above pre-industrial levels (UNEP, 2024, pp. 3; Paris Agreement, 2015, p. 5). This target is globally-wide endorsed across different stakeholder groups (e.g. Andre et al., 2024, pp. 2; Paris Agreement, 2015, p. 5) and has led, for instance, in the European Union (EU) to the legal-binding target of climate neutrality by 2050 (European Climate Law, 2021, p. 2). To remain the average temperature trendline within a 1.5 °C increase, a rapid transformation of all operating systems (e.g. energy, mobility, housing) is therefore required (International Energy Agency [IEA], 2023b, pp. 42). In this context, the transition of the energy system is especially time critical as the transition of other systems (e.g. mobility) rely on the electrification with renewable energy (The European Green Deal, 2019, pp. 6; IEA, 2023b, p. 102). This means phasing out fossil-based energy and instead deploying renewable energy and energy efficiency measurements (IEA, 2023b, pp. 26, 47; International Renewable Energy Agency [IRENA], 2023, pp. 21-26).

Consequently, an immense deployment of renewable energy technologies is required until 2050, in particular of onshore wind, offshore wind and photovoltaic, as those technologies are mature, cost-efficient and scalable (IEA, 2024a, pp. 7-9; Roser, 2020). In total, the annual average investment in power generation capacity over the period 2023-2050 will need to be 1.38 trillion per year (IRENA, 2023, p. 148). By 2050, ~7.82 terawatts (TW) of onshore wind capacity, ~2.5 TW of offshore wind capacity and ~18.2 TW of photovoltaic capacity are required to meet the 1.5 °C target (IRENA, 2023, p. 78). In the EU, the target for 2030 is an increase to 500 gigawatts (GW) of installed onshore and offshore wind capacity and around 600 GW of photovoltaic capacity (REPowerEU Plan, 2022, p. 6; European Wind Power Action Plan, 2023, p. 1).

Thanks to the fact that renewable energy technologies are the cheapest available energy technologies in most countries globally, exponential growth of renewable technologies has been already materialised in some countries (e.g. Denmark) and is expected to continue (IEA, 2023b, pp. 75, 2024a, p. 7; Lenton et al., 2022, p. 5). However, the realisation of the deployment targets will lead to a large extraction and consumption of virgin materials, in absolute terms particularly for onshore wind energy and photovoltaic (Carrara et al., 2020, p. 3; Energy Transitions Commission [ETC], 2023, pp. 9-10). This thesis focuses on onshore wind energy as it has a large material footprint of ~640 tonnes of material per megawatt (MW) (Global Wind Energy Council [GWEC], 2022, p. 38). The expected high absolute quantities of materials required and the required speed of the scale-up underline the importance of ensuring sustainable production and consumption of resources in the wind industry. This is further emphasised as follows:

- Levelized cost of energy (LCOE): The majority of the LCOE lies in the capital expenditures (CAPEX) and is hence sensitive to changes in material prices, financing costs and inflation (GWEC, 2023c, pp. 18-21; IEA, 2023b, pp. 60).
- Environmental footprint: The already shallow environmental footprint needs to be further reduced in alignment with zero greenhouse gas emissions (United Nations Economic Commission for Europe, 2021, p. 7). Approximately 78.5 % of the emissions during an onshore wind turbine's life are linked to the material extraction and processing (Bonou et al., 2016, p. 333).
- Dependencies in sourcing and supply chain bottlenecks: For Europe there are heavy dependencies for some materials (e.g. rare earth materials, copper) and components (e.g. gearbox, blades) on just a few countries (e.g. China) (Carrara et al., 2020, pp. 26-30; GWEC & Boston Consulting Group [BCG], 2023, pp. 27-35; Rystad Energy, 2023, pp. 27, 44). Moreover, production bottlenecks are foreseen for the manufacturing of wind turbines and their components from 2026 onwards in Europe (GWEC, 2023c, p. 26; Rystad Energy, 2023, pp. 6).
- Emerging decommissioning: In the near-term high absolute volumes of decommissioning from wind turbines are expected, in particular in Europe, as countries like Denmark and Germany were early movers in installing onshore wind capacity (GWEC, 2023b; Schaffarczyk, 2023, p. 49). This leads to the need to establish supply chains for the handling of decommissioned wind turbines, including blade composite, for which there is currently no economically viable and sustainable recycling solution (Andersen et al., 2016, p. 10; Beauson et al., 2022, pp. 4; Deeney et al., 2021, p. 2; Graulich et al., 2021, pp. 49).

Accordingly, a sustainable production and consumption of resources could facilitate a reduction in costs, emissions and supply chain dependencies, given that a significant proportion of these factors is related to the utilisation of resources. It is therefore essential to decouple the wind energy system from resource use, initially relatively and in the long term absolutely (UNEP, 2024, p. 8). This could be achieved through a transition from a linear economy to a circular economy, that researchers, practitioners and policy makers widely acknowledge across the wind industry, other industries and regions (Barrie et al., 2024, p. 11; ETIPWind, 2023, p. 6; IRENA, 2023, p. 62; UNEP, 2024, p. 7). In a linear economy, the resource flows end after a first use phase with waste disposal (Kara et al., 2022, p. 505). In contrast, a circular economy aims for a system-wide change that decouples from virgin material use and reduces waste to a minimum by narrowing, slowing and closing resource flows for sustainable development (Bocken et al., 2016, p. 309; Schröder et al., 2019, p. 89; A. P. Velenturf & Purnell, 2021, pp. 1444). In this light, circular supply chains (CSC) enable the cascading flow of the product, its components and its materials along the entire value chain (Kara et al., 2022, pp. 512).

Despite the recognition of the potential benefits of a circular economy, implementation is still marginal, with only 7.2 % of all materials currently being reused globally, as the Circular Gap Report 2024 reveals for 2023 (Fraser et al., 2024, p. 8). This emphasises that circular supply chains still need to be developed and further scaled. Progress in the EU is also lagging behind, despite a slightly higher rate of 11.5 % in 2022 (Eurostat, 2024). Evidence-based decision-making and empirical investigations are required to gather practical and industry-specific knowledge and to overcome that the concept is known across sustainability professionals, but not fully recognised in the mainstream discourse yet (Ayati et al., 2022, p. 16; Kirchherr et al., 2018, pp. 270; Kramer & Schmidt, 2023, p. 90; UNEP, 2024, p. 9). More empirical research has been particularly called by researchers in regard to circular strategies that foresee to slowdown the resource use of products, e.g. lifetime extension and reuse (Bakker et al., 2021, p. 6; Bals et al., 2022, pp. 183-184).

Moreover, for the development and scaling of circular supply chains, reliable information on actual and expected component and material flows along the value chain are crucial (Mathur et al., 2023, p. 4). Also, for the wind industry, the development of circular supply chains has only been rarely researched and it is widely unknown how sustainable and resilient circular supply chains are developed along the entire lifecycle of wind turbines (ETIPWind, 2023, pp. 6, 9; Kramer & Schmidt, 2023, p. 90). In particular circular strategies that foresee to retain the structural value of wind turbines and their components have received little attention by researchers to date (e.g. Graulich et al., 2021, p. 50). Therefore, the motivation of this thesis is to contribute to closing this knowledge gap.

1.2 Motivation

The thesis has the overarching aim to contribute to an understanding of how sustainable and resilient circular supply chains can be developed along the entire lifecycle of an onshore wind turbine by fulfilling the following three research objectives.

To overcome a lack of implementation of circular strategies in supply chain management (SCM), researchers have called for more industry-specific and systemic research (Farooque et al., 2019, p. 895). However, a systemic conceptual understanding of circular supply chains in the wind industry is still missing (research gap 1, see 2.4.1). Therefore, the first research objective (RO1) of the thesis is to provide a conceptual understanding of circular supply chain management (CSCM) in the wind industry.

RO1 Contribute to the emerging theoretical understanding of circular supply chain management in the wind industry.

Moreover, empirical investigations are crucial to promote the practical implementation of a circular economy (Ayati et al., 2022, p. 16), that is highlighted to be in particular lacking for strategies in regard to retaining the structural value (Bakker et al., 2021, p. 6; Bals et al., 2022, pp. 183-184). The strategies associated to the slowdown of resource flows are applied after an initial use phase and involve the planning and management of supply chain processes (e.g. logistics, refurbish, reinstallation) that enable circular resource flows (e.g. direct reuse, reuse after refurbishment) (Batista et al., 2018, p. 441; Farooque et al., 2019, p. 885). Also, in the wind industry a second lifecycle of the onshore wind turbine and their components (e.g. rotor blades) has only rarely been researched (research gap 2, see 2.4.2). The significance of this subject is further reinforced by the growing number of onshore wind turbines that are approaching the end of their first operational phase (see 2.2 and 6.2.1).

For the development and operation of circular supply chains, it is crucial to understand the necessary processes of the different actors in the supply chains and how they are interconnected, as it outlines the possible directions of resource flows. Building on this, to make informed decisions regarding capacity planning and investments in new facilities, it is therefore essential for supply chain actors to have sufficient data on circular resource flows (Bressanelli et al., 2019, p. 7405; Kirchherr et al., 2018, p. 267; Schmitt et al., 2023, pp. 42-44). An empirical understanding and data about the flow of wind turbines, their components and their materials after their initial operating phase are however widely missing (see 2.4.2). It is unclear what pathways were taken after the decommissioning of onshore wind turbines and whether a second lifecycle is common.

This leads to the second research objective (RO2) of the thesis and hence the objective to empirically explore second lifecycle pathways in the wind industry from the perspective of multiple stakeholders.

RO2 Explore second lifecycle pathways in the wind industry from a multi-stakeholder perspective.

The aforementioned research gaps have led to uncertainties of the expected turbine, component and material quantities for the supply chains after decommissioning wind turbines, as current forecasts are usually based on static assumptions (e.g. time of decommissioning after 20 years, neglect a second lifecycle). Therefore, there is a lack of reliable component and material flow forecasts along the circular value chain (see 6.1.1, research gap 3). The newly derived conceptual and empirical understanding, along with the accompanying data on circular resource flows of decommissioned onshore wind turbines (RO1 & RO2), can be used to address this research gap. Accordingly, the third research objective (RO3) of the thesis is to quantify the expected inflows for decommissioning companies, actors within second-lifecycle supply chains, and the recycling chain.

RO3 Quantify expected turbine, component and material flows to establish circular supply chains for further lifecycles (e.g. refurbishment) and end-of-life pathways (e.g. recycling).

All in all, with fulfilling the three research objectives, this thesis strives for the introduction of a systemic perspective on the design, establishment and scaling of circular supply chains in the wind industry, grounded in a theoretical conceptualisation and multi-stakeholder investigations of existing circular supply chains. Consequently, a comprehensive understanding of circular flows from decommissioned onshore wind turbines is established, a central basis for the long-term capacity planning of various stakeholders and the planning of the geographical distribution of facilities (e.g. refurbishment, recycling). The provided foresights on expected resource flows from decommissioned onshore wind turbines, thus support the stakeholders to manage complexity and uncertainties in their supply chain effectively. In light of the above, the thesis contributes to the establishment of circular supply chains for the purpose of slowing and closing resource flows from decommissioned onshore wind turbines. This, in turn, supports the development and industrialisation of sustainable and resilient circular supply chains within the wind industry.

2 Scope of Research

This chapter explains the scope of research, i.e. circular supply chain management in the onshore wind industry. Onshore wind turbines are selected because they are more resource intensive than offshore wind turbines and a higher absolute number of onshore wind turbines will be required by 2050 (GWEC, 2022, p. 38, p. 111; IRENA, 2023, p. 78). In addition, the onshore wind industry has a long track record and therefore, in principle, empirical data is available along the entire value chain.

In order to provide deeper empirical insights into component and material flows, the scope of the research objectives RO2 and RO3 is further refined. Accordingly, the focus is set to the circular supply chains of decommissioned onshore wind turbines and their blades in the mature wind markets of Denmark (DNK) and Germany (GER). Blades are of particular interest as their continuous increase in size leads to complex logistics and moreover recycling supply chains for composites are yet to be established in Europe (Andersen et al., 2016, p. 10; Beauson et al., 2022, pp. 4; Deeney et al., 2021, p. 2; Graulich et al., 2021, pp. 49). Denmark and Germany are being analysed in more detail as they have a long and extensive track record of installing onshore wind turbines and are pioneers in the wind industry, hence, other countries could likely follow practices (Schaffarczyk, 2023, p. 49). In this regard, it is of interest to compare the practices of both countries.

The reasons for the chosen scope of the research are explained in more detail in the following subsections, together with a thorough description of the research topic (see Figure 1). In chapter 2.1, key characteristics of onshore wind turbines and their blades are introduced, followed by a description of the Danish and German wind markets in the European and global context (2.2). Thereafter, chapter 2.3 defines a circular economy and finally chapter 2.4 gives and overview of the ongoing research on CSCM in the wind industry.

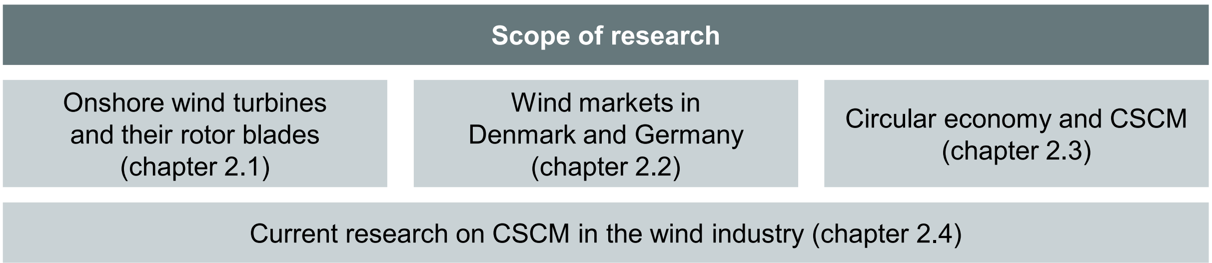


Figure 1. Scope of research in this thesis.

2.1 Design of onshore wind turbines and their blades

A horizontal-axis onshore wind turbine with three blades is illustrated in Figure 2 and is the most common installed wind turbine and the standard design in the industry (Hau, 2016, pp. 71). Alternative structures like vertical-axis onshore wind turbines, horizontal-axis turbines with one or two blades, floating offshore turbines, fixed-bottom offshore wind turbines and small-scale turbines are out of scope for this thesis (Manwell et al., 2009, pp. 4, 463, 520).

Overview of weights, costs and carbon emission of onshore wind turbines

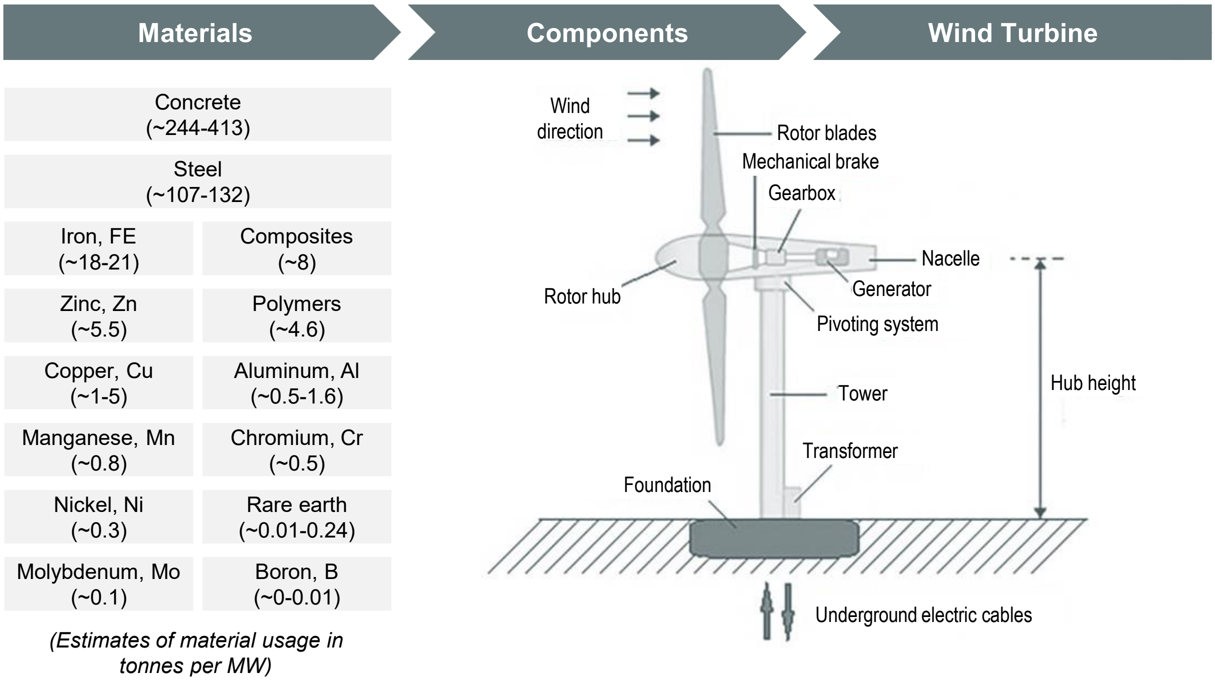
An onshore wind turbine with its foundation weights approx. 390-590 tonnes per MW and mostly comprises of concrete (~62-70 %) and steel (~22-27 %), followed by iron (~3.5-4.6 %) and composite materials (~1.4-2 %), as illustrated in Figure 2 (Carrara et al., 2020, p. 21). Most of the mass is accounted to the foundation (~75 %), followed by the turbine (~23 %) and site cables (~2 %). The weight of the turbine is spread across the tower (~59 %), the nacelle (~22 %) and the rotor blades (19 %). Moreover, ~55.4 % of total CAPEX are associated with the turbine costs and ~41 % when looking at the LCOE, based on utility-scale projects (Stehly et al., 2023). Most capital intensive are the nacelle with its several systems (~24.2 %), the rotor (~17.1 %) and the tower (~14 %). The shallow lifecycle greenhouse gas emissions of wind energy show a similar distribution, ~78.5 % are associated with the material extraction and processing for the onshore turbine, in particular for the tower (~24.9 %), foundation (~18 %), nacelle (~12.25 %) and the blades (~11.7 %) (Bonou et al., 2016).

Technical lifetime of onshore wind turbines

The design lifetime of an onshore wind turbine equals to a minimum of 20 years (International Electrotechnical Commission [IEC], 2019), although newer turbines begin to be designed with longer lifetimes such as 25 years (Schaffarczyk, 2023, p. 291). Actual lifetimes vary and can go beyond 20 years. For instance, components are designed for loads according to wind conditions defined in three classes (I, II, III) and class S for special cases (IEC, 2019; Manwell et al., 2009, p. 328). Hence, if the actual load is lower than the planned load, it can result in a longer lifetime. On this note, the maintenance efforts also play an important role, that correlate with failure rates: The electronics, control system, blades, hub and pitch system tend to fail most often and the gearbox, generator, blade and hub incline to be the failure with the longest downtime (Dao et al., 2019, pp. 1861). Moreover, a trend towards an increasing failure frequency for larger wind turbines is mentioned in literature (Dao et al., 2019, p. 1862; Ribrant & Bertling, 2007, pp. 167).

Design of onshore wind turbines

An onshore wind turbine commonly consists of a foundation, a tower, a rotor hub and three areo-dynamic designed blades that are attached to a nacelle (see Figure 2) (Manwell et al., 2009, pp. 3). Inside of a nacelle, a drive train system (typically a gearbox and generator), a control system and a braking system are located. The pivoting system, also called yaw system, is situated between the tower and the nacelle and has the function to rotate the turbine into the wind. The transformer commonly located at the base of the tower, transforms the electrical output to the required voltage level of the electrical grid.



Concrete (~244-413)	
Steel (~107-132)	
Iron, FE (~18-21)	Composites (~8)
Zinc, Zn (~5.5)	Polymers (~4.6)
Copper, Cu (~1-5)	Aluminum, Al (~0.5-1.6)
Manganese, Mn (~0.8)	Chromium, Cr (~0.5)
Nickel, Ni (~0.3)	Rare earth (~0.01-0.24)
Molybdenum, Mo (~0.1)	Boron, B (~0-0.01)

(Estimates of material usage in tonnes per MW)

Figure 2. Horizontal-axis onshore wind turbine with its main components and materials, based on Năstase (2017), Carrara et al. (2020).

Over time the hub height of the turbine and blade length have increased significantly, from ~100 kW installed capacity and 20 meter of rotor diameter of an onshore wind turbine in 1985 (Burton et al., 2011, p. 368) to 7.2 MW installed capacity, 172 meter of rotor diameter and up to 199 m hub height, announced in 2022 (Vestas Wind Systems A/S [Vestas], 2022). Furthermore, different designs of components occurred over time across original equipment manufacturers (OEM). Table 1 summarises common design concepts of key components.

For the foundation, depending on the site conditions and the height of the turbine, either shallow or deep foundations with a steel structure and concrete are used (Schaffarczyk, 2023, pp. 309). A criterion for differentiating design concepts of a tower is, next to the height, the main used materials that are either concrete, steel, a hybrid form (steel & concrete), other materials such as wood (Hau, 2016, pp. 516) or glass fibre reinforced plastic (Schaffarczyk, 2023, p. 307). Modular steel towers are most common, particularly for hub heights of up to 100 m (Schaffarczyk, 2023, pp. 305). With hub heights beyond 100 m, hybrid structures with concrete elements below and steel above are becoming the standard.

Table 1. Design concepts of key components of horizontal-axis onshore wind turbines, based on Marwell et al. (2009), Schaffarczyk (2023), Hau (2016), Burton et al. (2011).

<table>
<tr><th>Component</th><th colspan="60">Different designs</th></tr>
<tr><td>Foundation</td><td colspan="30">Shallow</td><td colspan="30">Deep</td></tr>
<tr><td>Tower</td><td colspan="15">Concrete</td><td colspan="15">Concrete & Steel</td><td colspan="15">Steel</td><td colspan="15">Other materials</td></tr>
<tr><td rowspan="2">Drive train system</td><td colspan="15"><i>Constant speed</i></td><td colspan="45"><i>Variable speed</i></td></tr>
<tr><td colspan="15">Synchronous generator with gearbox</td><td colspan="15">Doubly-fed induction generators, commonly with gearbox</td><td colspan="15">Permanent magnet synchronous generator, with or without gearbox</td><td colspan="15">Direct drive generators without gearbox</td></tr>
<tr><td>Control system</td><td colspan="12">Passive stall</td><td colspan="12">Active stall</td><td colspan="12">Passive pitch</td><td colspan="12">Active pitch</td><td colspan="12">Yaw</td></tr>
<tr><td>Blades</td><td colspan="20">Non-composite materials</td><td colspan="20">GFRP</td><td colspan="20">GFRP/CFRP</td></tr>
</table>

The drive train system is responsible to transform the wind to electrical energy through the mechanical system, the transmission system, and the electrical system, hence the generator (Burton et al., 2011, pp. 367; Hau, 2016, pp. 337; Manwell et al., 2009, pp. 5, 221, 235). A distinction can be made between constant and variable speed operation. For constant wind speed, synchronous generators with a gearbox are commonly used, e.g. a fixed speed induction generator (FSIG) with a gearbox. For variable speed operation, doubly-fed induction generators (DFIG), permanent magnet synchronous generator (PMSG), and a direct drive generator (without a gearbox) are standard designs. FSIG have been used in wind turbine designs around 1985-1995 for turbines until 1.5 MW, but have problems in meeting grid code requirements for large wind farms (Burton et al., 2011, p. 368). DFIG became common around 2000 and PMNG and direct drive generators started to be introduced. In total, a conventional drive system with a gearbox is mostly used as the global market share of ~64 % as of 2022 indicates (GWEC, 2023a, p. 31). Moreover, for a control system five designs exist: passive stall control, active stall control, passive pitch control, active pitch control, and yaw control system (Burton et al., 2011, pp. 475). Nowadays, most commonly an active pitch system and yaw system are jointly used to optimise the energy capture (Hau, 2016, pp. 117, 166). In contrast, for example a passive stall control system cannot react to varying wind conditions during operation, making it less suitable for variable wind speeds and to feed into electricity grids with high penetration of variable energy sources (Burton et al., 2011, pp. 425; Hau, 2016, pp. 166). Rotor blades that differ in their areodynamic and structural optimised designs (Schaffarczyk, 2023, pp. 181, 197), also vary regarding the use of materials (Mishnaevsky et al., 2017; Schaffarczyk, 2023, pp. 193). The cross-section of a rotor blade and the common used materials are illustrated in Figure 3.

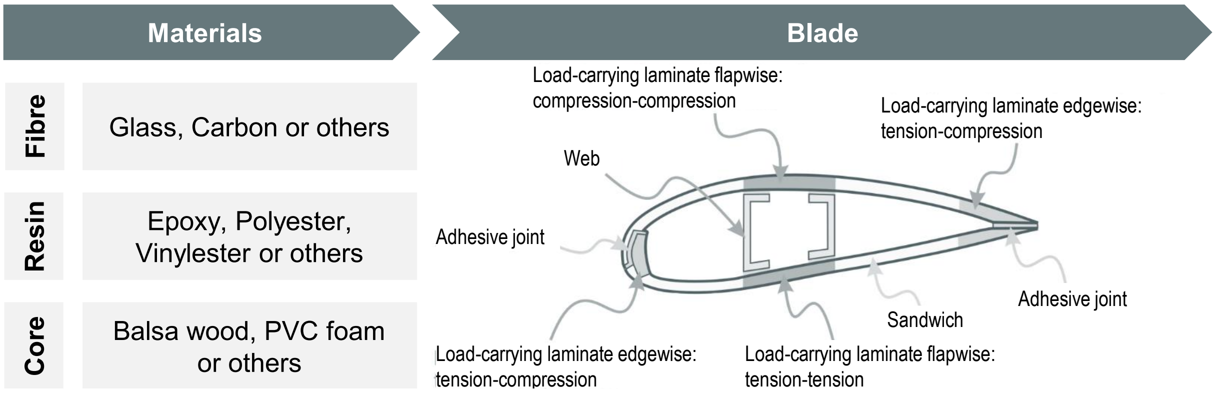


Figure 3. Wind turbine blade and possible material compositions, based on Mishnaevsky et al. (2017), Mølholt Jensen & Branner (2013, p. 6).

The figure shows that blades are usually build with a sandwich structure, consisting of two layers of composites (made with fibre and resin), that surround the core material, e.g. balsa wood, PVC or PET (Mishnaevsky, 2021; Schaffarczyk, 2023, p. 193). Commonly the composites are made with glass fibre and epoxy resin (Schaffarczyk, 2023, p. 188). These materials are also expected to be primary decommissioned in the next 10 years, for instance in Germany (Volk et al., 2021). However, to reinforce some parts, carbon fibre is more increasingly being used (Schaffarczyk, 2023, p. 188). In addition, to overcome the challenges of recycling composites in existing turbines, new composites are being developed and tested for new-to-be installed wind turbines and new recycling technologies are developed (Beauson et al., 2022; Mishnaevsky, 2021).

Summary

In summary, a horizontal-axis onshore wind turbine with three rotor blades and a technical design life of 20-25 years is the common wind turbine design, while the actual lifetime of a wind turbine may differ from the design life. The high proportion of costs and emissions associated with the turbine, underlines the potential for increasing ecological and economic sustainability and supply chain resilience when decoupling from virgin materials. It should be noted that the overall material composition, costs and associated emissions vary across turbine types and corresponding design choices.

2.2 Onshore wind markets in Denmark and Germany

To ease the transferability of the research to other markets, the historical development of wind turbine installations in Denmark and Germany are described and put in a European and global context.

The Danish and German wind turbine fleet in a European and global context

Denmark and Germany are both part of the European electricity market, but differ in regards to their energy mix: In 2022, the majority of Denmark's electricity generation came from wind (54.0 %), biofuels (17.9 %) and coal (12.7 %) (IEA, 2024b). In Germany, it is coal (32.8 %), wind (21.3 %), natural gas (15.6 %) and solar (10.3 %) (IEA, 2024b). In the same year, Denmark's electricity generation came largely from renewables (81.1 %) and in Germany that share accounted to 43.0 % (IEA, 2022). Going forward, Denmark has set the target to quadruple current levels of onshore wind and solar capacity by 2030, however without quantifying the share of onshore wind (IEA, 2023a, p. 10). Moreover, offshore wind is targeted to increase from 2.3 GW to 18 GW by 2030 and 35 GW by 2050. Germany has defined a legal binding target of 115 GW onshore wind capacity by 2030, 160 GW until 2040 and the continuation of this installed capacity after 2040 (EEG 2023, 2014/2023, § 4). The target for offshore wind capacity is set to 30 GW by 2030 and 70 GW by 2045 (Windenergie-auf-See-Gesetz (WindSeeG), 2017/2023, § 1). The EU' target equals to 500 GW onshore and offshore wind capacity by 2030 (European Wind Power Action Plan, 2023, p. 1) and the global onshore wind target amounts to ~3.04 TW by 2030 according to IRENA's 1.5° scenario (IRENA, 2023, p. 78).

Denmark and Germany have pioneered the wind industry with long-established domestic wind markets and an industry of global players, e.g. Vestas, LM Wind, Ørsted in Denmark and Enercon, Nordex, SGRE, RWE in Germany (Schaffarczyk, 2023, p. 49). Roughly ~33,000 jobs in Denmark (as of 2020) and ~124,000 jobs in Germany (as of 2022) are associated to the wind industry (Bundesministerium für Wirtschaft und Klimaschutz [BMWK], 2023, p. 1; Damvad Analytics A/S & Wind Denmark, 2021, p. 3).

To put Denmark's and Germany's historical installations of wind turbines in a global perspective, Figure 4 shows on the left side the cumulative installed capacity of onshore wind turbines per country and moreover, on the right side the decommissioned capacity from 2006-2022 (GWEC, 2023b). The left side of Figure 4 outlines that various countries have installed onshore wind turbines with a total capacity of ~841.9 GW, of which 26.7 % was installed in Europe. The red-marked countries installed more than 15 GW with the largest deployment in China (334.0 GW), the USA (144.2 GW) and Germany (58.9 GW). The share of Denmark's and Germany's markets equals to 7.6 % of the global and 28.4 % of the European wind market.

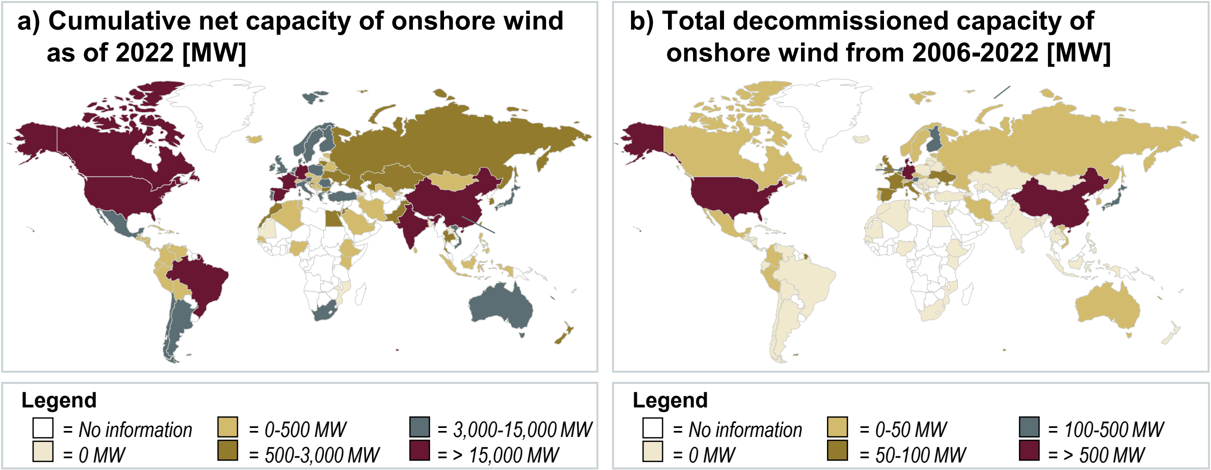


Figure 4. Overview of onshore wind energy per country by (a) cumulative installed capacity in MW as of 2022, and (b) total decommissioned capacity in MW between 2006-2022, based on data from GWEC (2023b).

Furthermore, some wind turbines have already been decommissioned, as displayed on the right side of Figure 4. From 2006 to 2022, wind capacity of ~8.7 GW was world-wide decommissioned from predominately onshore wind turbines (~99.2 %). The majority of this took place in Germany (~3.3 GW), the USA (~1.9 GW), China (~1.1 GW) and Denmark (~0.7 GW). China's decommissioning is fully accounted to the year 2022. Denmark's and Germany's share of global decommissioning accounts to 45.5 % and to 73.6 % in Europe; however, it should be noted that Germany and Denmark have decommissioned prior to 2006 and as such the share is likely larger.

The onshore wind turbine fleet in Denmark and Germany

The following details the development of the onshore wind turbine fleet in Denmark and Germany. The analysis bases on publicly available market data: For Denmark as of 31/01/2022 (Danish Energy Agency [DEA], 2022) and for Germany as of 30/06/2023 (Bundesnetzagentur, 2023). Further details about the selection, assessment and preparation of the market data are provided in chapter 6.1.2 and Kramer et al. (2024).

Figure 5 illustrates the annually installed onshore wind turbine fleet in Denmark (red bars) and in the geographically larger Germany (grey bars), on the left in terms of the number of turbines and on the right in the form of the installed capacity in MW.

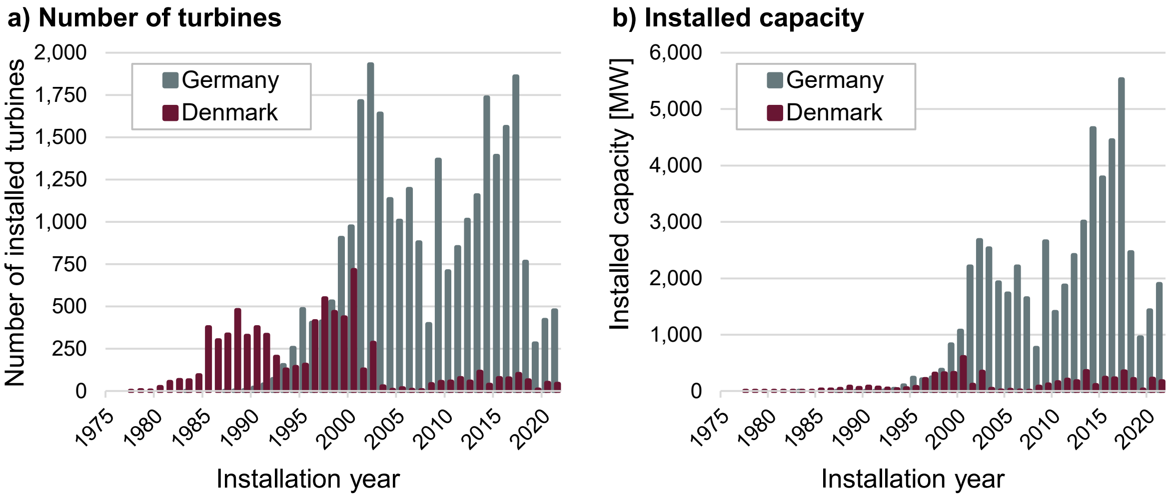


Figure 5. Development of annual installation rates of onshore wind turbines in Denmark and Germany by a) number of turbines and b) installed capacity. Based on data from DEA (2022), Bundesnetzagentur (2023).

As of 31/01/2022 (DEA, 2022), Denmark installed 7,381 turbines over the last decades, of which 4,186 onshore wind turbines with an installed capacity of 4,711.9 MW are in operation. As Figure 5 shows, the number of turbines installed and capacity per installation year fluctuates considerably, rising steadily for the most part until 2000, plumping one year later and forming a plateau until 2007. The highest installation rate was achieved in 2002 with around 700 turbines (600 MW), from which around 650 turbines (545 MW) are in operation according to the market register. In contrast, the lowest level of installations is recorded in 2004 (7 turbines) and 2007 (6 turbines). Since 2008, the installation rates have unveiled a gradual increase, albeit at levels that are lower than previously observed. However, when examining the installed capacity, it becomes evident that similar levels have been achieved, given the steady increase in the size of turbines over time (see chapter 2.1). It should be noted that Denmark has already decommissioned 3,195 onshore turbines (826.4 MW) since 1998 (based on data of DEA, 2022). However, 85.1 % of the overall installed capacity is still in operation with an average age of 20.9 years. Noticeable is that 73.5 % of the turbines – or 39.7 % when based on installed capacity – are being operated with an age of 20 years or beyond and hence surpass the 20-year design lifetime (IEC, 2019).

Also shown in Figure 5, as of 30/06/2023 (Bundesnetzagentur, 2023), Germany is operating an onshore wind turbine fleet of 28,611 turbines with an installed capacity of 59,231.0 MW. This is significantly larger than the Danish onshore fleet. Also, in Germany annual rates per installation year vary strongly with one turbine in 1983 and 1987 to around 1,900 turbines in 2002 and 2017. When comparing the development of the annual number of turbines (left side of Figure 5) to the annual installed capacity (right side of Figure 5), it also becomes evident that turbines have increased in size over the years. For instance, in comparison to the year 2002, almost the same number of turbines in 2017 corresponds to twice as much installed capacity. Furthermore, decommissioning totals around 4,500 turbines with an installed capacity of ~3,600 MW

(Deutsche WindGuard, 2023) since around 2000, when assuming 0.8 MW per turbine. As such, still a significant fraction of the overall installed onshore wind turbines is in operation with an average of 14.5 years. However, a large fraction has already surpassed an age of 20 years: 29.4 % and 14.8 % based on the number of turbines and installed capacity respectively. Compared to the Danish onshore fleet, the German fleet is still younger in average thanks to high installation rates in the last 10-15 years.

Summary

In summary, Denmark and Germany pioneered in onshore wind with a long history of installing onshore wind turbines and an increasingly aging fleet. The annual installation rates have significantly fluctuated in the past and as such also the age of the current operating fleet varies greatly. At the time of decommissioning, the currently 32,797 operational onshore turbines with 63.9 GW of installed capacity will require handling. This provides the rationale for the prioritisation of this thesis on circular supply chain processes for decommissioned onshore wind turbines from Denmark and Germany.

2.3 Circular economy

Definition of a circular economy

A circular economy has been defined in various different ways (Alhawari et al., 2021, pp. 1-2; Kirchherr et al., 2017, p. 221; Kirchherr et al., 2023, p. 7). In the following, an overview of common definitions are given, hence the definitions by Kirchherr et al. (2017; 2023), Ellen MacArthur Foundation (2019), and the European Parliament (2023) are introduced. Moreover, the understanding by Bocken et al. (2016) and Velenturf & Purnell (2021) as well as the newly published ISO-norm are presented (International Organization for Standardization [ISO], 2024).

Kirchherr et al. (2017, pp. 224-225) aim at establishing a complete definition through analysing 114 different definitions and propose the following: “*A circular economy describes an economic system that is based on business models which replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations*”. In 2023, they published an update of their original paper, providing an analysis of 221 definitions, but this did not lead to a revision of their definition (Kirchherr et al., 2023, p. 2). Instead, they highlight that most scholars acknowledge the need for a systemic shift and that a circular economy is not an end in itself, but foresees a contribution to sustainable development.

The definition by the Ellen MacArthur Foundation is also commonly used and according to Kramer and Schmidt (2022, p. 62) reflects some of the mentioned aspects of Kirchherr et al. (2017). They define a circular economy as "[…] *a systems-level approach to economic development designed to benefit businesses, society, and the environment. A circular economy aims to decouple economic growth from the consumption of finite resources and build economic, natural, and social capital. […] It is built on three principles: Design out waste and pollution, keep products and materials in use, regenerate natural systems*" (Ellen MacArthur Foundation, 2019, p. 19).

A further definition is the one from the European Parliament (2023), which reads as follows: "*The circular economy* is *a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended. In practice, it implies reducing waste to a minimum. When a product reaches the end of its life, its materials are kept within the economy wherever possible thanks to recycling".*

Bocken et al. (2016, pp. 308-309, 316) do not provide a short definition, but outline that a circular economy aims for a shift from a linear model to a circular one and emphasise the need for circular business models and a circular product design that narrow, slow and close resource flows.

Velenturf & Purnell (2021) underpin the need to have a circular economy that is not understood as an end to itself and instead is clearly linked to sustainable development. In this context, they provide 10 principles that guide the system transition from a linear economy to a sustainable circular economy, amongst others an open, multi-dimensional, whole system approach, reduction and decoupling of resource use, and design for circularity. Moreover, they highlight that circular strategies in their cascading nature can be used to guide a whole system approach and mention that it can help to derive "*the best option for a supply chain in a given context*" (A. P. Velenturf & Purnell, 2021, p. 1449).

The ISO norm 59004:2024 aims to harmonize the various understandings of a circular economy by defining vocabulary and principles as well as by providing guidance for its implementation (ISO, 2024). Accordingly, the term 'circular economy' is defined as an "*economic system […] that uses a systemic approach to maintain a circular flow of resources […], by recovering, retaining or adding to their value […], while contributing to sustainable development […]*". It is further noted that resources "*can be considered concerning both stocks and flows*" and that the "*inflow of virgin resources […] is kept as low as possible, and the circular flow of resources is kept as closed as possible to minimize waste […], losses […] and releases […] from the economic system*" (ISO, 2024).

In summary, as Kirchherr et al. (2017, pp. 224-225) acknowledge with their definition, a systemic shift, the cascading order of narrowing, slowing and closing resource flows, the multiple levels of a system and the necessary contribution to a sustainable development, this definition is considered in this study. Their definition emphasises the need for circular business models, but does not simultaneously stress the need for a circular product design and circular supply chains. Despite, the understanding used in this thesis is based on the premise that the design and implementation of circular business models, circular products and circular supply chains and their interconnection is considered a crucial aspect of a circular economy and is hence following Velenturf & Purnell (2021, p. 1447). Moreover, in line with the just named authors, this thesis recognises that there is not one circular economy, but multiple approaches are possible for the implementation, depending on the context (e.g. locally different possibilities of industrial symbiosis exist).

Overview of R-principles

The following paragraph further zooms into the various circular strategies, also called R-principles. Kirchherr et al. (2017), Ellen MacArthur Foundation (2019), Velenturf & Purnell (2021, p. 1449), Bocken et al. (2016, p. 309), and the European Parliament (2023) mention the cascading nature of circular strategies in their definitions and conceptual understanding. The cascading order of R-principles is organised in models such as the 4R-model, 6R-model and 9R-model (Directive 2008/98/EC, 2008; Jawahir & Bradley, 2016, p. 105; Potting et al., 2017, p. 15). For instance, Kirchherr et al. (2017, pp. 224-225) refer to Reduce, Reuse, Recycle and Recover (4R-model). Also, the EU Waste Framework Directive has implemented the cascading management of the waste by first prevention, followed by reuse, recycling, recovery, and as a last resort disposal (Directive 2008/98/EC, 2008). Furthermore, the 9R-model proposed by Potting et al. (2017, p. 15) is frequently referenced in literature and is used in this thesis. The 9R-model is considered as it offers a more comprehensive overview of potential circular strategies than the 4R-model or the 6R-model. Table 2 summarises the ten strategies, ranking the R-principle with the highest priority at the top (R0) and the one with the lowest priority at the bottom of the table (R9), also referred to as the ‘R-ladder’ (Potting et al., 2017, p. 15). The strategies that are in the scope of this thesis are highlighted in grey, namely R3-R9, as those are associated to slowing and closing resource flows after a first lifecycle of an onshore wind turbine (Kramer et al., 2024, p. 81).

Table 2. Overview of the 9R-model by Potting et al. with outline of definitions for R0-R2 from Potting et al. (2017, p. 15) and R3-R9 according to Kramer et al. (2024, p. 81).

R-principle	Definitions
R0-Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product (Potting et al., 2017, p. 15).
R1-Rethink	Make product use more intensive (e.g. through sharing products, or by putting multi-functional products on the market) (Potting et al., 2017, p. 15).
R2-Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials (Potting et al., 2017, p. 15).
R3-Reuse	Direct reuse of products for the same function (Directive 2008/98/EC, 2008, p. 5). This may include inspecting, cleaning and repairing parts to enable reuse (Defra, 2011, p. 3), but it does not foresee overall refurbishment or remanufacturing.

R-principle	Definitions
R4-Repair	Extend lifetime of products (Reike et al., 2018, p. 255) by restoring them after decay or damage to a usable state (Bocken et al., 2016, p. 311).
R5-Refurbish	A multi-component product is updated by replacing or repairing some components (Potting et al., 2017, p. 15; Reike et al., 2018, pp. 255-256).
R6-Remanufacture	Through a fully documented standard industrial process, the product's function is brought up to at least the originally manufactured quality (International Resource Panel [IRP], 2018, p. 46). This includes disassembly, checking, cleaning and, if required, replacing or repairing parts and providing a product warranty (DIN SPEC 91472, 2023, pp. 7-8; Reike et al., 2018, p. 256).
R7-Repurpose	Structural reuse of products or components, but for a different function (A. P. M. Velenturf, 2021, p. 16).
R8-Recycle	Reprocessing waste "into products, materials or substances whether for the original or other purposes" (Directive 2008/98/EC, 2008, p. 5).
R9-Recover	"energy recovery and the reprocessing into materials that are to be used as fuels or other means to generate energy" (Directive 2008/98/EC, 2008, p. 5).

Definition of circular supply chain management

This thesis focuses on circular supply chains as a crucial part of a fundamental systemic change to a circular economy, as also other scholars increasingly acknowledge (Kirchherr et al., 2023, p. 2). Similar to the diverse understanding of a circular economy, also various definitions exist for CSCM (Alhawari et al., 2021; Corvellec et al., 2021; Kirchherr et al., 2017; Lengyel et al., 2021). Farooque et al. (2019, p. 88) argue that a comprehensive definition was lacking and therefore propose the following: "*Circular supply chain management is the integration of circular thinking into the management of the supply chain and its surrounding industrial and natural ecosystems. It systematically restores technical materials and regenerates biological materials toward a zero-waste vision through system-wide innovation in business models and supply chain functions from product/service design to end-of-life and waste management, involving all stakeholder in a product/service lifecycle including parts/product manufacturers, service providers, consumers, and users*". In short, a CSCM is understood in this thesis as a "*multi-level and multi-objective system that embeds circular thinking in SCM*" (Kramer & Schmidt, 2022, p. 63); whereby SCM encompasses the design, management and execution of material, information and financial flows along the value chain network (The Supply Chain Council, 2017, pp. 4-5, 16). Further elaborations are outlined in Part A of the thesis.

Summary

To summarise, in this thesis the holistic definition of a circular economy by Kirchherr et al. (2017, pp. 224-225) and the principles for a sustainable circular economy by Velenturf and Purnell (2021, p. 1447) are considered. Moreover, the 9R-model by Potting et al. (2017, p. 15) is used when referring to circular strategies. CSCM is understood in accordance to the definition by Farooque et al. (2019, p. 88).

2.4 Current research on CSCM in wind turbine supply chains

In this chapter, an overview of ongoing research on CSCM in the wind industry is presented to provide a better understanding of the research topic and associated research gaps. The scope of the thesis lies at the intersection of SCM, circular economy and wind energy, and therefore a literature review of existing research in each discipline and at the interfaces is conducted to provide an overview. Accordingly, Figure 6 shows the results of a Scopus search for each discipline and at the intersections in a Venn diagram (as of 21/04/2022, analysis published in Kramer & Schmidt, 2022).

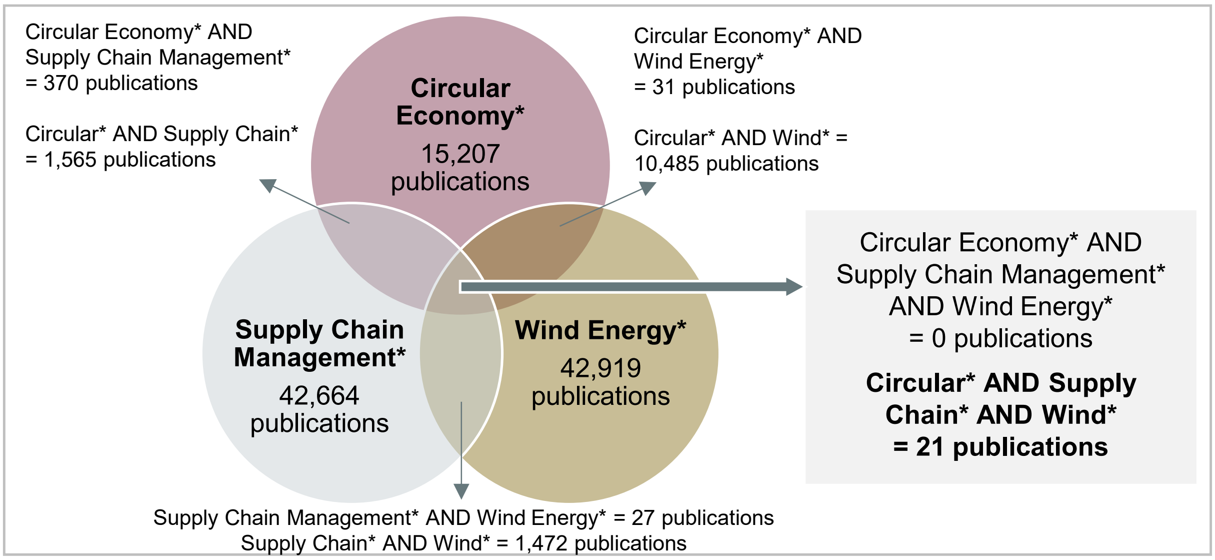


Figure 6. Publications from Scopus on SCM, circular economy and wind energy and their intersections. Based on Kramer & Schmidt (2022).

At the intersection of the disciplines SCM, circular economy and wind energy only 21 publications are identified. Consequently, despite the importance of the topic (see chapter 1), it seems that wind energy has rarely been researched from a CSCM perspective. In addition, it can be noted that wind energy (42,919 publications), SCM (42,664 publications), and circular economy (15,207 publications) are well researched disciplines. When looking at the development over time, Kramer & Schmidt (2022, p. 64) outline that circular economy has received a lot attention recently, and SCM and wind energy are long-established areas of research.

In the following subsections, the current research is described in more detail in relation to the research objectives of this thesis. Thus, the state of the art on (circular) SCM in the wind industry (2.4.1) and on circular strategies for decommissioned onshore wind turbines and their blades (2.4.2) is presented.

2.4.1 CSCM for wind turbines and their blades

Systematic CSCM overview in the wind industry

To further understand the current research in regard to the RO1 and thus the theoretical understanding of CSCM in the wind industry, Table 3 provides an overview of identified publications that present a more holistic overview (Kramer & Schmidt, 2023).

Table 3. Classification of existing research. Based on Kramer & Schmidt (2023).

Source	SCM	CE	Onshore wind	Offshore wind	SLR
Beauson et al. (2022)	(x)	(x)	(x)	(x)	(x)
Franco et al. (2021)	x	x			x
Jensen et al. (2019)		x	x	x	
Jensen et al. (2020)		x		x	
Koumoulos et al. (2019)	(x)	x	(x)	(x)	
Lapko et al. (2019)	(x)	(x)	(x)	(x)	
Mendoza et al. (2022)		x	(x)	(x)	
Nagle et al. (2022)	(x)	(x)	(x)		
Rentizelas et al. (2022)	(x)	(x)	(x)		
Velenturf (2021)		x	(x)	x	x

Beauson et al. (2022), Koumoulos et al. (2019), Nagle et al. (2022), and Rentizelas et al. (2022) have in common that they address circular economy and supply chain aspects, but focus on wind turbine blades. Beauson et al. (2022) give an overview of the process chain that takes place after the decommissioning of wind turbines and discuss economic, technical, legal and environmental aspects in this context. Koumoulos et al. (2019) focus on supply chains for composites and draw a strategic roadmap. Nagle et al. (2022) provide an overview of repurposing possibilities for blades from onshore wind turbines in Ireland. Rentizelas et al. (2022) outline a potential network design of recycling facilities of decommissioned wind turbine blades in Europe. Lapko et al. (2019) focus on the material level and outline influencing factors that enable the closing of the supply chain for critical materials from photovoltaic panels and wind turbines. Franco et al. (2021) is the only study that provides a systematic literature review (SLR) on circular supply chains, but instead of covering wind turbines, they look at the photovoltaic industry. The remaining four publications in Table 3, are placed at the intersection of wind energy and circular economy. Jensen et al. (2019) focus on remanufacturing (R-principle R6) and present three case studies of which one is from a wind turbine manufacturer. Jensen et al. (2020) highlight the need for embedding circular thinking in clean energy infrastructure by using the example of offshore wind in the United Kingdom (UK). Mendoza et al. (2022) present circular economy business models and technology management strategies in the wind industry based on a literature review. Finally, Velenturf (2021) developed a conceptual framework on a sustainable circular economy for the offshore wind energy industry and mentions that this could eventually be transferred to the onshore wind industry.

In summary, none of these publications provide a systemic overview on wind turbine supply chains that embeds circular thinking. Consequently, a systematic overview of existing research in relation to (circular) SCM is provided in the following.

SCM in wind turbine supply chains

For a comprehensive understanding of the current (circular) SCM research for wind turbines and their blades, the supply chain (i.e. turbine, components, materials) and the corresponding supply chain processes and circular strategies are presented.

The SLR process bases on Tranfield et al. (2003) and was carried out from 21/03/2022 to 12/05/2022 in Scopus and Web of Science (Martín-Martín et al., 2018). The majority of the results and methodology is published in Kramer & Schmidt (2023). The search string reads as follows and was applied to titles, abstracts and keywords of scientific literature in German and English: ("supply chain*" OR "value chain*") AND ("wind") AND NOT ("pv" OR "solar" OR "photovoltaic*" OR "biomass" OR "biofuel" OR "biogas" OR "hydro"). The string uses the approach of Franco et al. (2021, p. 5), but instead for photovoltaics for wind. By broadening the scope to the term ‘supply chain’ and ‘value chain’, the risk of overseeing important publications is reduced, as the term circular economy seems not yet well embedded in the research field. This has led to 392 publications in Scopus and 838 publications in Web of Science. After checking if these papers focus on aspects of the wind turbine supply chain, only 148 publications in Scopus and 68 publications in Web of Science remained. After removing duplicates between the two databases, the final sample dealing with the supply or value chain in wind energy research amounts to 163 scientific papers.

As illustrated in Figure 7, the absolute number of identified articles makes it evident that the research topic is a niche, but papers have been published since 2007 with a steadily increase since 2014. Surprisingly, only 8.6 % of these papers address onshore wind specifically, 36.2 % offshore wind and the remainder (55.2 %) did not differentiate or deals with both (onshore and offshore wind).

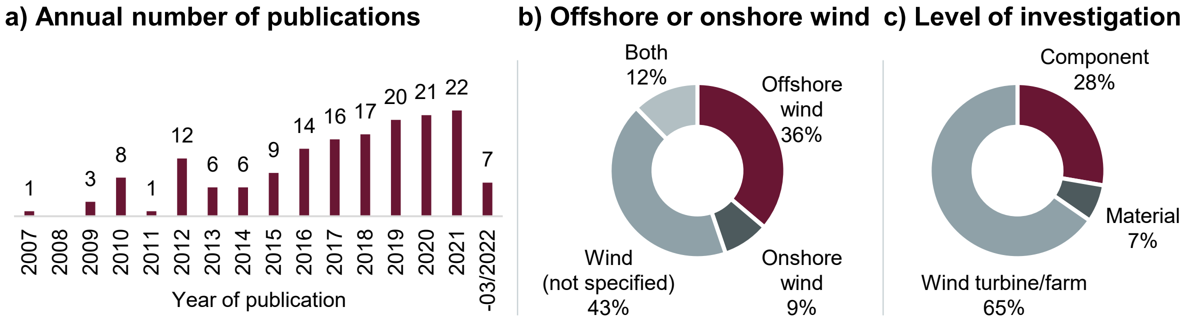

a) Annual number of publications **b) Offshore or onshore wind** **c) Level of investigation**

Figure 7. Scientific articles clustered by annual number of publications, type of wind technology and level of investigation. Based on Kramer & Schmidt (2023).

When further detailing the level of investigation, as shown on the right of Figure 7, it becomes apparent that 65.6 % focus on the wind turbine/farm level, 27.6 % on the component level, and 6.7 % on materials (Kramer & Schmidt, 2023, p. 89). The component which is mostly dealt with in the sample are the rotor blades, followed by the generator and foundation; the latter only in regards to offshore wind. Moreover, several papers have multiple components in their research scope, for example regarding spare parts management. The papers that were clustered to the material level deal with rare earth materials from permanent magnet generators.

Finally, to understand which parts of the circular supply chain are being addressed by research, it is useful to group the research identified into the main supply chain processes. Accordingly, the sample was analysed and clustered into the supply chain processes according to the adapted SCOR-model by Vegter et al. (2020). The results are shown in Figure 8 and display that the processes Plan (31.5%) and Enable (29.7%) were mostly covered (Kramer & Schmidt, 2023, p. 89). The remaining processes are less present in the sample, with Deliver (5.0 %), Recover (5.0 %) and Return (2.7 %) the least. Hence, in particular the planning and enabling processes within SCM receive attention, while supply chain processes such as delivery, return logistics, and recovery of wind turbines as well as their components and materials are only rarely addressed.

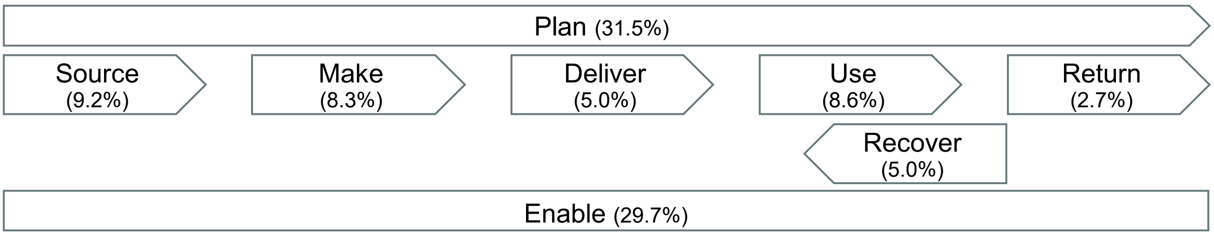


Figure 8. Final sample of scientific articles clustered by supply chain processes according to Vegter et al. (2020). Based on Kramer & Schmidt (2023).

When moreover, examining the titles of the sample on whether specific circular strategies, recovery processes, reverse logistics or similar aspects associated to a circular economy are addressed, only 14 publications are identified. As the following reveals, not all circular strategies are covered throughout the different supply chains along the turbine's value chain. In most cases, supply chain processes of remanufacturing and recycling are the focus of the papers.

Five studies are on remanufacturing (R6) of components and onshore wind turbines. Dahane et al. (2017, p. 1547) introduce a multi-agent model in order to assess how gearbox remanufacturing impacts the operation and maintenance performance of offshore wind turbines. They show that the use of a remanufactured gearbox is more attractive than the use of a new one; under the assumption that the remanufactured spare part is 10 % less in costs and in carbon emissions than the new gearbox. Dulman & Gupta (2018, pp. 147-148) show that the installation of sensors for condition monitoring of wind turbines can benefit the maintenance and remanufacturing strategy. Jensen et al. (2019, pp. 307, 311), as shown in Table 3, outline remanufacturing process chains of three cases and propose that for immobile products such as wind turbines, 'on-site' remanufacturing could be more suitable. Moreover, Ortegon et al. (2012, pp. 155-159) sketch economic and environmental benefits of remanufactured wind turbines, while also mentioning challenges in reverse logistics. This is followed by a more detailed overview and a discussion in comparison to recycling (R8), amongst others, an overview of the forward and reverse logistics is given (Ortegon et al., 2013, p. 197).

Further five studies address recycling (R8) of rare earth materials in permanent magnets (e.g. Bonfante et al., 2021; Cheramin et al., 2021) and one study explores the reverse supply chain design for recycling of blades (Rentizelas et al., 2022). Hence half of the CSCM papers deal with recycling. Also, repurposing (R7) of blades is covered by one study which provides a life cycle assessment (LCA) of three repurposing routes (R7) and one cement co-processing route (R9) after decommissioning an onshore turbine (e.g. including transport) in Ireland (Nagle et al., 2022, p. 8).

The remaining two studies address the reuse (R3) of packaging for large-scale components by exploring a reverse supply chain (Paul & Smyers, 2010) and the other study deals with decommissioning of an offshore wind farms. Devoy et al. (2018, pp. 7-8) provide a model suite for optimising logistics and financials during installation, operation and decommissioning. The decommissioning module allows for partial or full decommissioning with reflecting different destination ports, waste-handling facilities and the resale of components.

Conclusion

In summary, research within the scope of this thesis, CSCM for onshore wind turbines and their blades, is rare. No systemic overview of a (circular) value chain network in the wind industry exists to date. The SLR shows that wind industry-specific SCM research represents a research niche, particularly for onshore wind turbine supply chains and the supply chain processes after the initial use phase of turbines, components and materials. The researchers who address circular supply chains in more depth have focused on the recycling supply chain for permanent magnets and blades. Research on the development of supply chains for the second lifecycle of wind turbines and their blades is widely missing; with Ortegon et al. (2012, 2013) being the only relevant research, however they predominantly address the United States of America (USA). In summary, the literature review emphasises that the research area of the dissertation represents a research gap, and that the fulfilment of the research objectives therefore contributes to closing this gap.

2.4.2 Circular strategies for decommissioned onshore wind turbines and their blades

This section outlines existing research on circular strategies of decommissioned onshore wind turbines by distinguishing the research according to their focus on either the turbine, blade or blade materials. Hence, the following further details existing literature on second-lifecycle strategies for wind turbines and their blades as well as recycling options for blade materials, especially of composites.

Second-lifecycle strategies of wind turbines

The review of current research reveals that only a limited number of studies have been conducted that address circular strategies designed to retain the structural value of the entire turbine (R3-R6), thereby slowing down the resource flows.

Velenturf (2021, pp. 15-20) outlines that the repair (R4) and maintenance of components is commonly applied and leads to a longer lifetime of the wind turbine. Further second-lifecycle strategies are mentioned for the component level, where it is outlined that research is still emerging and only a few studies were identified on component reuse (R3), refurbishment (R5), remanufacturing (R6) and repurposing (R7) of offshore components. She further expresses that the application of these strategies could result in a lifetime extension of the wind turbine beyond the design lifetime, while further details on a potential impact for a second lifecycle of an entire wind turbine are not mentioned. Also, Jensen et al. (2020, pp. 275-278) stress for offshore wind that circular strategies beyond recycling and energy recovery have not received sufficient attention in the strategic decommissioning planning by operators in the UK.

For onshore wind turbines, the scope of this thesis, Woo and Whale (2022, pp. 1734-1735) outline that reuse of the entire decommissioned turbine exists and that it obtains the highest value of the decommissioned wind farm. However, they state that most decommissioning would enter the waste stream, despite also expressing that they expect an increase of second-lifecycle practices for components as spare parts. Martinez-Marquez et al. (2022, p. 16) explore circular strategies for wind turbine blades, but still acknowledge the possibility of refurbishment and remanufacturing of the entire decommissioned turbine. Ortegon et al. (2012, 2013) focus on the potential of remanufacturing onshore wind turbines, as already outlined in the SLR in 2.4.1. Another study on remanufacturing by Ortegon et al. (2014) apply system dynamics and reveals that functional and technological obsolescence could increase remanufacturing costs and hence would result in a less attractive business case for remanufacturing turbines. They note that functional obsolescence might be reduced through predictive maintenance and technological obsolescence is triggered by technological change.

Finally, studies on future waste volumes state that explorations on second-lifecycle strategies regarding the turbines and components are necessary to understand potential implications for recycling flows (e.g. Andersen et al., 2016, p. 14; Kühne et al., 2022, p. 122; Pehlken et al., 2017, p. 259).

In summary, the literature review reveals that, besides the studies by Ortegon et al. on remanufacturing, no comprehensive explorations dedicated to second-lifecycle strategies for the wind turbine in its entirely exists.

Second-lifecycle strategies of blades

For retaining the structural value of wind turbine blades, only 27 studies are identified by Kramer & Beauson (2023, pp. 7-8), which mostly address repurposing (R7). The following is an outline of the identified research on blades and the application of second-lifecycle strategies, where blades remain with the same function (R3-R6) and with a different function (R7).

In a search by Kramer & Beauson (2023, pp. 7-8), 27 papers are found on second-lifecycle strategies for wind turbine blades, which the paper's authors label to reuse (20 papers), repurpose (10 papers), and remanufacturing (4 papers). After analysing their content, it however appears that 23 papers address repurposing, two on modularisation, and two on volume predictions. The inconsistent use of the terms indicates that these strategies are not yet well embedded in the research field. Only Kaczmarek et al. (2016) address a potential second lifecycle of a blade or its modules by exploring possibilities for structural modularisation. In regard to the technical feasibility of a second lifecycle, Mishnaevsky (2021, p. 18) assumes a technical lifetime of up to 50 years for blades, but Beauson et al. (2022, p. 7) note that this might decrease, as OEMs aim at matching the blade design closer to the design lifetime, e.g. 20 years for onshore wind turbines (IEC, 2019). Both of them recognise the importance of reusing blades from a circular economy perspective, but Kwon et al. (2019, p. 1) neglect it due to safety concerns, which they do not further elaborate. Joustra et al. (2021, p. 1) also rule it out as unsuitable because, according to them, the blades cannot be easily reinstalled on another turbine and Martinez-Marquez et al. (2022, p. 16) outline that a further increase in size of the rotor blades will result in difficulties for reusing blades. Also, Beauson et al. (2022, p. 7) expect that larger blades will result in complex and high-cost intensive transportation that could hinder a second lifecycle and overall, conclude that further research is needed on the development of economics and quantities on the second-hand market. Besides, Mishnaevsky (2021, p. 18) hints at research on repair during the operation of a turbine to derive knowledge for repairing blades after decommissioning and concludes that repair and reuse has a technical readiness level (TRL) of 9. In this context, the review by Martinez-Marquez et al. (2022, p. 16) however finds that procedures for structural repair still require further developments. In regards to refurbishment/remanufacturing, they outline a TRL of 10 and also Ortegon et al. (2012, p. 2) outline the possibilities of remanufacturing a blade, but without further detailing it. In contrast, the definition in 2.3 states that remanufacturing involves the disassembly and inspection of each part of the product, but the disassembly of composite-based blades is technically difficult to carry out without effecting the structural properties and would require new blade designs (Beauson et al., 2022, p. 13). Due to the few available research papers and details in the available research papers as well as the different understanding of the terms in the respective research papers, the overview of the state of the art is still limited and cannot always be clearly assigned to one of the second-lifecycle strategies, R3-R6. On the subject of repurposing (R7), i.e. structural reuse with a different function, various examples such as playgrounds, bridges or bus shelters are cited in research (Kwon et al., 2019).

Recycling of blade materials

Following the cascading nature of a circular economy, if structural reuse (R3-R7) is not suitable anymore, circular strategies on the material level should be considered, namely recycling (R8), followed by energy recovery (R9).

In contrast to second-lifecycle strategies, Kramer & Beauson (2023, pp. 9-10) identified a higher research coverage on recycling materials from wind turbine blades, as 112 scientific papers appeared relevant. 77 % of these papers address the recycling of composites, some limited to materials of composites (e.g. resin or fibre) and only 3 publications each to PET and balsa wood. Also, comprehensive reviews were identified that provide an overview of the current state of the art on recycling (Beauson et al., 2022; Khalid et al., 2023; Mishnaevsky, 2021; Rathore & Panwar, 2023). The research can be divided into investigations on new materials and corresponding recycling technologies that are applicable to new blades and research on the development of recycling technologies for existing blades that are currently in operation. Alternative fibres and resins for new blades that are being researched are biocomposites, thermoplastic matrices, and modified epoxies (Beauson et al., 2022, pp. 6-7). Various recycling methods for existing and new blades are investigated and can be grouped into mechanical recycling (e.g. shredding), thermal recycling (e.g. pyrolysis), and chemical recycling (e.g. solvolysis) (Beauson et al., 2022, pp. 8-9; Mishnaevsky, 2021, p. 6). The high interest in recycling of composite material is justified by the fact that currently no high-quality recycling has yet been developed on an industrial scale, so that cement co-processing, a process for energy recovery, is currently the only existing solution that is economically viable (Beauson et al., 2022, p. 9). In this context, Nagle et al. (2020, p. 9) note that cement co-processing has a lower environmental impact than long-term landfilling of blades. Moreover, the European industry has called for a landfill ban in the EU, which would further promote the development of recycling and energy recovery strategies (WindEurope, 2020).

A further common research topic is the prediction of end-of-life waste volumes (e.g. Andersen et al., 2016; Sommer et al., 2020). Here, a wide-spread assumption is that blade recycling could occur directly after decommissioning and no further circular strategies that further slowdown the resource use, are considered (e.g. Kühne et al., 2022; Lichtenegger et al., 2020). However, this is not known, as actual data on the applied circular strategy after decommissioning are not yet existing, e.g. as outlined by Graulich et al. (2021, p. 52) for the EU.

Summary

In summary, research on circular strategies that keep the structural value of the turbine and their blades is rare and mostly conducted on the blade level with a focus on repurposing. As such, explorations of second-lifecycle turbines and blades are still a research gap. Among others, there is currently a lack of further studies on the technical and economic feasibility and, as a result, on the expected market developments. This could indicate why SCM-related research is currently limited. At the moment, research concentrates on the recycling of composites and aims at closing the resource flow through developing high-quality recycling solutions at industrial scale. In this light, it is unknown to which extend a second lifecycle of the turbine and its blades impacts the planning of recycling capacity.

Overall conclusion of chapter

Chapter 2.4 outlines that CSCM research for the wind industry is rare and a systemic view is lacking, thus justifying the first research objective of the thesis. Moreover, circular strategies for decommissioned onshore wind turbines and their blades have been addressed in research, however a second lifecycle of the turbines or their blades has not received sufficient attention. Therefore, proving the rationale for the scope of the research objectives 2 and 3. In this context, empirical investigations on the actual flows of decommissioned onshore wind turbines are currently not existing and are hence not reflected in expected flows of wind turbines, components and materials. This is however the key basis for capacity planning of various stakeholders in order to develop and scale circular supply chains. As such, it fulfils the demand of several researchers who are calling for further studies in this area (e.g. Beauson et al., 2022, p. 7; Kühne et al., 2022, p. 122).

2.5 Research questions and structure of the thesis

Following the outlined motivation for the scope of research and the identified research gaps, several research questions (RQ) are formulated to fulfil the overarching aim and the three research objectives. As illustrated in Figure 9, the three research objectives are linked to five research questions of the thesis.

Overarching aim of the thesis: Contribute to an understanding of how sustainable and resilient circular supply chains can be developed along the entire lifecycle of a wind turbine.

Research objectives	Research questions	Part
Objective 1: Contribute to the emerging theoretical understanding of circular supply chain management in the wind industry.	**RQ1:** How does a circular supply chain management framework in the wind industry look like?	A
	RQ2: What are the circular supply chain processes along the lifecycle of a wind turbine and its blades?	
Objective 2: Explore second lifecycle pathways in the wind industry from a multi-stakeholder perspective.	**RQ3:** Which paths are taken for onshore wind turbines and their blades after decommissioning in Denmark and Germany? Is a second lifecycle common or not?	B
	RQ4: What is influencing the development of second-lifecycle supply chains for onshore wind turbines from Denmark and Germany?	
Objective 3: Quantify expected turbine, component and material flows to establish circular supply chains for further lifecycles and end-of-life pathways.	**RQ5:** Which turbine, component and material flows are expected for decommissioning, second lifecycle pathways and domestic recycling in Denmark and Germany?	C

Figure 9. Research objectives and research questions of the thesis.

The first objective is addressed through RQ1 and RQ2. RQ1 “How does a circular supply chain management framework in the wind industry look like?” enables a theoretical understanding of the entire system. RQ2 zooms into the level of supply chain processes by asking “What are the circular supply chain processes along the lifecycle of a wind turbine and its blades?”. Therefore, providing a conceptual understanding of circular supply chain development for wind turbines and their blades by illustrating the product, component and material flows along the value chain.

For the reduction of the complexity of the subject under investigation, the subsequent research questions focus on onshore wind turbines and their blades, with an exemplary investigation of the mature markets of Denmark and Germany. The second objective foresees the exploration of second lifecycle pathways of onshore wind turbines from a multi-stakeholder perspective and is addressed through RQ3 and RQ4. RQ3 asks “Which paths are taken for onshore wind turbines and their blades after decommissioning in Denmark and Germany? Is a second lifecycle common or not?”. Accordingly, current circular supply processes are examined and compared to the conceptual understanding. After quantifying whether a second lifecycle is common or not, the existing circular economy pathways are qualitatively explored as reflected in RQ4 “What is influencing the development of second-lifecycle supply chains for onshore wind turbines from Denmark and Germany?”*.* Therefore, it offers insights into the factors that may have influenced the decision-making process regarding the choice between a second lifecycle pathway and an end-of-life pathway. Finally, the last objective, the quantification of expected turbine, component and material flows for multiple stakeholders is addressed by RQ5: “Which turbine, component and material flows are expected for decommissioning, second lifecycle pathways and domestic recycling in Denmark and Germany?”. This creates the basis for long-term capacity planning for the various actors and thus for the development of circular supply chains in the wind industry.

The thesis consists of nine chapters as displayed in Figure 10. The previous chapters have presented the problem definition, motivation and the scope of research. In chapter 3 the general research approach and chosen methodology is described. The methodology is step-wise evolving, hence reflecting findings from previous steps and is therefore detailed in the main parts of the thesis, Part A-C.

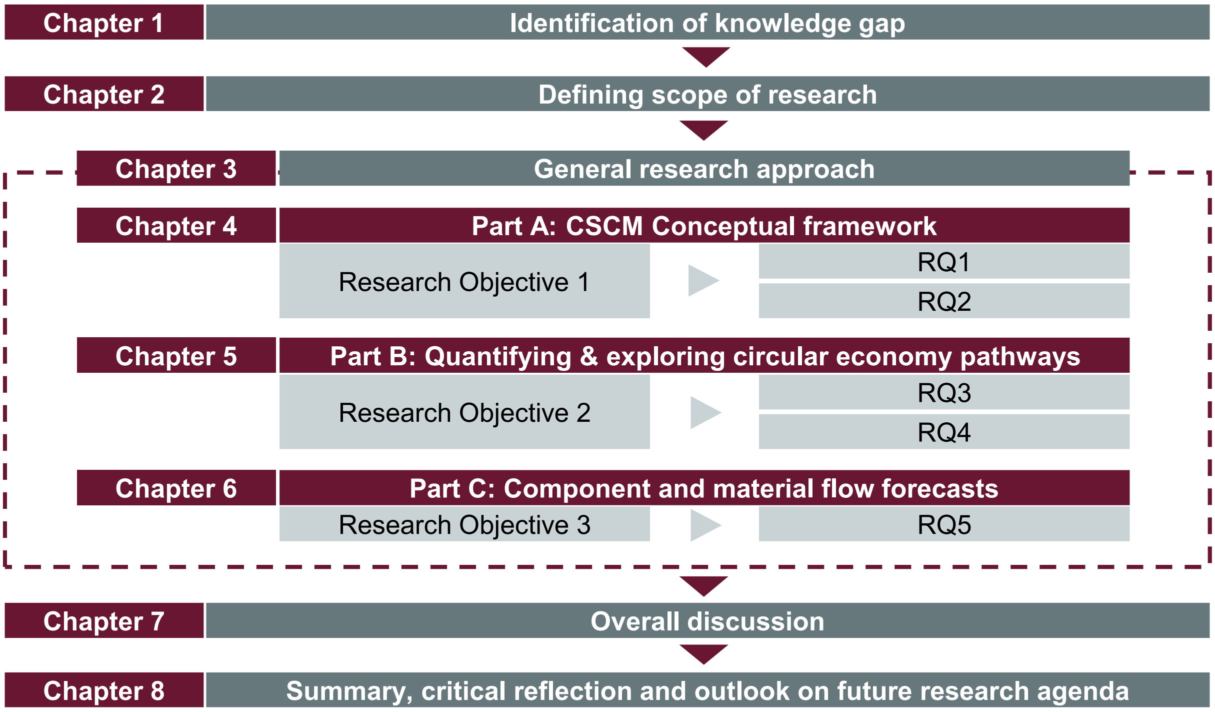


Figure 10. Structure of the thesis.

Part A, represented by chapter 4, deals with RQ1 and RQ2. Hence, it proposes a methodology for deriving a conceptual understanding (4.1) and presents the conceptual understanding for CSCM and its resulting circular economy pathways (4.2). The chapter ends with an interim conclusion (4.3) that summarizes the key findings.

Part B, represented by chapter 5, addresses RQ3 and RQ4. 5.1 outlines the methodology of the data collection and analysis, followed by 5.2 that presents the results. Finally, the results are discussed (5.3) and interim conclusions (5.4) are drawn.

Part C, represented by chapter 6, aims at answering RQ5. The related methodology (6.1) for turbine, component and material flow forecasts for multiple stakeholders of circular economy pathways is introduced. The results are presented (6.2) and discussed (6.3).

To put the contributions of the thesis into perspective, chapter 7 provides a comprehensive discussion of the results and research design in regard to the fulfilment of the overall research objective. Finally, chapter 8 summarises (8.1) and critically reflects the findings (8.2) and concludes with a future research agenda (8.3).

3 General Research Approach

Research methodology and methods

Supply chains and their interlinkages with the environment are in principle considered to be complex systems (Herrmann, 2010, pp. 1, 62; Werner, 2020, p. 34) that is also the case for the globally-spread supply chains in the wind industry: Different stakeholders are interacting to fulfil different processes (e.g. manufacture, transport, service, refurbish) for a product consisting of approx. 30,000 parts (Vestas, 2023, p. 4). This involves the complex flow of materials, information, and resources in the value chain network (The Supply Chain Council, 2017, pp. 4-5, 16). Complexity of the system is further increased by integrating the concept of a circular economy into SCM (F. R. Nilsson, 2019, p. 694).

Hence, to acknowledge the complexity and dynamic of the object under research, the research does not follow widely-spread assumptions of rationality, context-independent behaviour and objectivity in SCM (Nair & Reed-Tsochas, 2019, p. 80; F. Nilsson & Gammelgaard, 2012, p. 767). Instead, the system is viewed more through the lens of "*sense making of situations*" and recognises that uncertainties exist in the emergence of transition paths (F. Nilsson & Gammelgaard, 2012, p. 772; F. R. Nilsson, 2019, p. 685). To underpin, as defined in 2.3, the choice of circular economy pathways is not made uniform but need to reflect the specific context. In addition, in the process of generating knowledge, the researcher's "*basic set of beliefs*" guide action (Guba, 1990, p. 17).

As deduced from the previous chapters, the scope of the thesis is on circular supply chain development for onshore wind turbines and their blades in Denmark and Germany with an emphasize on second lifecycle pathways. The objectives are to contribute to the existing conceptual understanding (RO1), to explore second lifecycle pathways (RO2) and to quantify turbine, component and material flow forecasting for multiple stakeholders (RO3). The object of research is situated at the intersection of the disciplines of wind energy, SCM and circular economy and is defined as a relatively new and emerging research field with limited empirical investigations (see 1.2 and 2.4). The research is therefore of qualitative nature (Creswell & Poth, 2018, pp. 42; Golicic et al., 2005, p. 22) and focuses, within the cycle of empirical scientific inquiry – consisting of observation, induction, deduction, testing and evaluation – on the first two phases by exploring and developing a theory (Groot & J. A. A., 1969, pp. 27). It aims to observe and provide extensive insights of phenomena and to illustrate a range of possible future developments. Hence, the explorative research follows a bottom-up approach and uses inductive reasoning to step-wise develop a theory.

<u>Mixed methods approach</u>

In accordance with the above, the general research approach for the phenomena of the complex system under exploration is qualitative, interdisciplinary, exploratory and empirical. Taking this into account, a mixed methods approach is a suitable methodology (Golicic & Davis, 2012, pp. 726; Golicic et al., 2005, pp. 19). Golicic & Davis (2012) underpin for SCM that mixed methods research can enrich the understanding of phenomena in a dynamic business environment and increase the robustness of the explanations. In this light, it enables a wider exploration as different kind of research questions can be answered (Golicic & Davis, 2012, p. 727). Hence, it can support to grasp multiple aspects in CSCM in the wind industry and to extensively understand the circular supply chain process of decommissioned onshore wind turbines. In addition, the methodology can produce "*research that makes a higher-level contribution to managerial practice*" as it allows for bringing "*key stakeholders more directly into the research*" (Grant et al., 2023, p. 190). Therefore, it is supporting a multi-stakeholder perspective (see chapter 5.1.1). Consequently, a mixed methods approach in the core design of "*exploratory*" (Grant et al., 2023, p. 180), initiated with a "*qualitative path*" (Golicic & Davis, 2012, pp. 732) is chosen for this research.

As Figure 11 shows, the research purpose of the methodology is "*development*" (Golicic & Davis, 2012, pp. 734), hence the research methods are built in a sequence: the results of the previous step inform the method of the next step. It suits this research, a step-by-step and inductive development of theory, well. The methodology foresees to report results of each method separately (see Part A-C), "*followed by a general discussion that ties them together by comparing and contrasting findings*" (Golicic & Davis, 2012, p. 734).

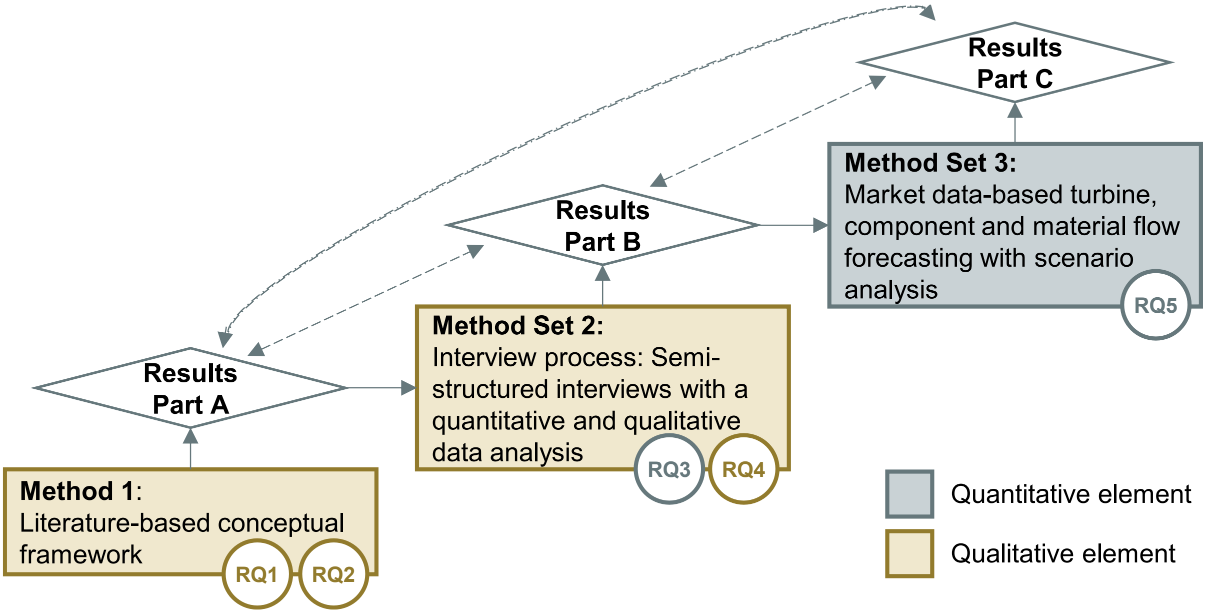


Figure 11. The research methodology of the thesis is a mixed methods approach, initiated with a qualitative path. Inspired by Golicic & Davis (2012).

Part A of the mixed methods approach

Part A uses a qualitative research approach and develops a literature-based conceptual framework to answer RQ1 and RQ2. This is argued in the widely agreed fact, that rigorous research foresees to review and reflect on existing research when developing a conceptual framework (Saunders et al., 2019, pp. 51-52; Seuring et al., 2005, p. 92). Further details on the methodology of Part A are given in chapter 4.1.

Part B of the mixed methods approach

With the derived conceptual understanding of circular supply chains in the wind industry from Part A, it is possible to systematically explore second lifecycle practices from a multi-stakeholder perspective in Part B. To explore and quantify the chosen pathways of decommissioned turbines and their blades in Germany and Denmark (refer to RQ3 and RQ4), the qualitative method of semi-structured interviews with industry experts is applied. The method is selected due to its particular suitability for an emerging field of research that is currently lacking in empirical studies (F. R. Nilsson, 2019, p. 687; Saunders et al., 2019, pp. 444). A semi-structured design guides the experts with the derived conceptual understanding from Part A, making the interviews more comparable between each other, but still allowing the emergence of new aspects (Döring & Bortz, 2016, pp. 372; Gläser & Laudel, 2010, pp. 37, 42; Saunders et al., 2019, pp. 437, 444). Disadvantages of this method could be that bias – interviewer, interviewee or participation bias – could occur and the number of interviews conducted could be small, which is argued to reduce transferability (Saunders et al., 2019, pp. 447). However, some of these potential shortcomings also apply to other qualitative research methods (e.g. observations, surveys, secondary data collection) and techniques have been developed to address them, which are considered in this thesis as detailed in chapter 5.1.1 (Döring & Bortz, 2016, pp. 321; Lincoln & Guba, 1985, pp. 289; Saunders et al., 2019, pp. 213). The collected data is quantitatively analysed to quantify which pathways have been chosen in Denmark and Germany and qualitatively analysed with a qualitative content analysis according to Mayring (2022). The method of Mayring allows to analyse large amounts of text data with a step-wise, structured and inductive approach to identify categories and patterns in the data (Mayring, 2010, pp. 603, 661; Seuring et al., 2005, pp. 94). It is therefore suitable for answering RQ4 as the method is used to identify categories and patterns, but it is not foreseen to quantify the frequencies of the derived codes. Hence, overcoming critique that the context is lost, in particular if text is reduced to frequencies of each derived category (Gläser & Laudel, 2010, pp. 198). The methods for data collection and data analysis are further detailed in chapter 5.1.

Part C of the mixed methods approach

In Part C, a quantitative method to forecast the turbine, component and material flows of different scenarios for multiple stakeholders in Denmark and Germany is developed (RQ5). The empirical data from Part B and already available market data are used as inputs of the forecasts. The method choice is justified on the awareness, that data-based modelling and extensive supply chain data are seen to be important for the decision-making of multiple stakeholders in sustainable resource management (Potočnik & Teixeira, 2023, pp. 7, 40; Wieland et al., 2016, p. 208). With providing different scenarios, informed by Part A and B, it does not eliminate the irrationality of the system but helps to make the decision-making more objective (Wieland et al., 2016, p. 208). The methodology and methods of Part C are further explained in chapter 6.1.

Evaluation criteria of research

The nature of the thesis's research is qualitative and as such criteria to assess the quality of qualitative research are guiding the assessment. However, as a mixed methods approach is taken, some elements are of quantitative nature and hence are assessed as those. The data sources and methods are described and evaluated throughout the respective chapters, 4.1, 5.1 and 6.1. That said, depending on the nature of the applied method, either qualitative techniques (e.g. triangulation) or quantitative techniques (e.g. testing through replication) are used for ensuring rigorous and systematic research (Lincoln & Guba, 1985, pp. 292).

To evaluate qualitative research, Lincoln and Guba (1985) argue that trustworthiness should be assessed with the evaluation criteria of credibility, transferability, dependability and confirmability. These criteria are internationally widely established (Döring & Bortz, 2016, pp. 108). In quantitative research, the counterpart is internal validity, external validity, reliability and objectivity (Döring & Bortz, 2016, pp. 109-110; Lincoln & Guba, 1985, p. 290). Table 4 provides a description of each evaluation criteria in regard to qualitative and quantitative research.

Table 4. Evaluation criteria of qualitative and quantitative research. Based on Lincoln & Guba (1985, p. 290), Döring & Borth (2016, pp. 109-110).

Qualitative evaluation criteria	Quantitative evaluation criteria
Credibility Is about showing that the researcher has "*represented those multiple constructions adequately*" (Lincoln & Guba, 1985, p. 296). Hence, the inquiry should be carried "*in such a way that the probability that the findings will be found to be credible is enhanced and, second, to demonstrate the credibility of the findings by having them approved by the constructors of the multiple realities being studied*" (Lincoln & Guba, 1985, p. 296).	**Internal validity** Is the "*extend to which variations in an outcome (dependent) variable can be attributed to controlled variation in an independent variable*" (Lincoln & Guba, 1985, p. 290).
Transferability Ensures that the research can be applied to other applications with contextual similarity (Lincoln & Guba, 1985, pp. 291, 296).	**External validity** Approximates to which extend the findings can be generalised to other contexts (Lincoln & Guba, 1985, p. 290).
Dependability Ensures that justifiable assumptions were made along the inquiry process that leads to coherent findings (Lincoln & Guba, 1985, pp. 298).	**Reliability** Means that results are "*consistent, dependable, and predictable*" and is seen "*as a precondition for validity*" (Lincoln & Guba, 1985, p. 292).
Confirmability Examines the objectivity of the data and the researcher or in other words the intersubjective agreement of a number of individuals (Lincoln & Guba, 1985, pp. 299).	**Objectivity** "*Refers to what a number of subjects or judges experience*" (Lincoln & Guba, 1985, p. 292).

Several techniques are applied to ensure the trustworthiness of qualitative research, amongst others triangulation (Döring & Bortz, 2016, p. 109; Lincoln & Guba, 1985, pp. 301; Schou et al., 2012, p. 2090). Triangulation is achieved in this thesis through choosing a mixed methods approach (see Figure 11), multiple methods (e.g. literature review, expert interviews) and multiple data sources (e.g. cases of Denmark and Germany). The design of the mixed methods approach enables trustworthiness of the results as a balance is struck between the advantages and limitations of the respective research methods (Golicic & Davis, 2012, p. 727). Moreover, through the step-by-step evolving research approach and the overarching discussion that also addresses the transferability to other industries (e.g. offshore wind, photovoltaic) and countries, it enhances the trustworthiness (Lincoln & Guba, 1985, pp. 301).

Next to triangulation, the assessment of "*truth value*" (Lincoln & Guba, 1985, p. 290) is moreover enabled through an extensive explanation of the purpose (chapter 1), the research process and the general and specific choice of methods (chapters 2.5, 4.1, 5.1, 6.1) (Schou et al., 2012, p. 2090). To assure that the methods suit the purpose of the thesis, the objectives and the scope of research is described prior to choosing the methodology and corresponding methods. By providing a '*thick description*' of the context of the thesis's investigations, a person who wants to apply it to a different context is able to sufficiently assess the applicability (Lincoln & Guba, 1985, p. 316). Hence, a '*thick description*' of the object under research and the research process is provided. For instance, by outlining the characteristics of the German and Danish wind turbine fleet (see chapters 2.2 and 6.2.1), other researchers can assess the applicability to other countries.

The consistency of research can, next to triangulation, be assessed through '*audits*', e.g. in a peer-reviewed publication process (Lincoln & Guba, 1985, pp. 317). The research design of the thesis is partially being audited as some results and the corresponding research process – in particular aspects of RQ1, RQ2, RQ3 and RQ5 – are published in peer-reviewed conference proceedings and in a journal (Kramer et al., 2024; Kramer & Beauson, 2023; Kramer & Schmidt, 2022, 2023). It is further operationalised by considering external feedback on the research design (or parts) from academic researchers (e.g. doctoral supervisors, senior researchers), practitioners (e.g. wind turbine manufacturer, decommissioning company, operator) and industry associations (e.g. GWEC, VDMA). Further comprehensive notes are taken on the researcher's thinking process for developing the research design of this thesis.

Finally, the confirmability is operationalised in the thesis, next to triangulation with multiple data sources, by presenting the perspective of multiple stakeholders and two countries as well as considering feedback from the experts. Further, by outlining different arguments and linking it to theories a degree of objectivity to the findings can be obtained. However, the object of investigation is complex and dynamic and as such uncertainties have to be accepted. Nevertheless, to further enhance confirmability, Denmark and Germany are chosen as pioneers in onshore wind energy. This increases the likelihood of access to comprehensive data and market research, and thus the ability to assess the trustworthiness (Saunders et al., 2019, pp. 448-449).

4 Part A: Conceptual Framework of CSCM in the Wind Industry

Part A of this thesis has the objective to contribute to the emerging theoretical understanding of circular supply chain management in the wind industry (research objective 1) by answering RQ1 and RQ2. Consequently, a conceptual framework of CSCM in the wind industry is developed and presented (RQ1), followed by detailing the theoretical understanding of circular supply chain processes along the lifecycle of a wind turbine and its blades (RQ2). It therefore addresses the identified research gap concerning the lack of systematic integration of circular thinking into SCM in the wind industry (see 2.4).

The chapter is divided into three subchapters, beginning with outlining the methodology in chapter 4.1. The results of the conceptual framework of CSCM in the wind industry are presented in 4.2. The last chapter, chapter 4.3, outlines the interim conclusions and leads over to Part B of the thesis, given the step-by-step evolving research methodology of the thesis.

4.1 Methodology

The methodology of Part A is set to develop a conceptual framework of CSCM in the wind industry by following the process outlined in Figure 12.

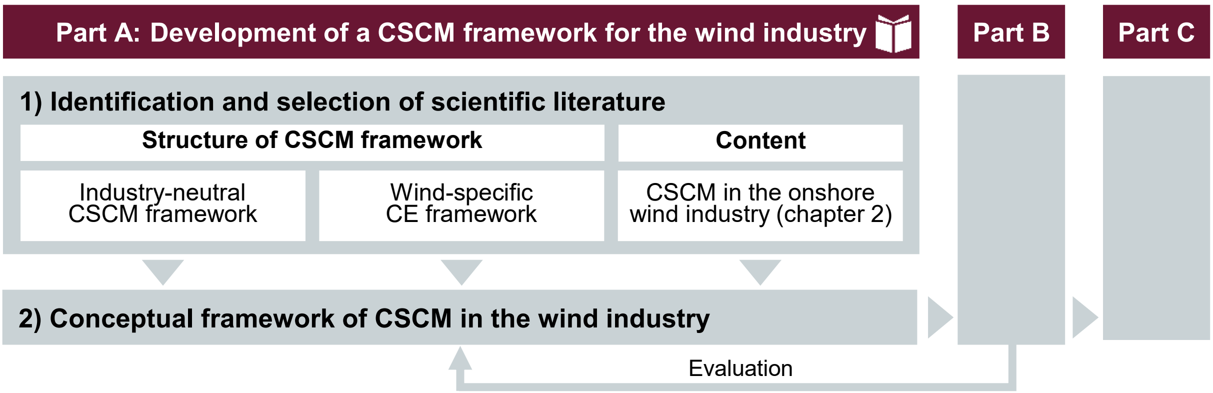


Figure 12. Part A's methodology of developing a conceptual framework of CSCM in the wind industry, inspired by Kramer & Schmidt (2022).

The first step is the identification and selection of scientific literature for the definition of the structure and content of the conceptual framework for CSCM in the wind industry. As a CSCM framework for the wind industry is not yet existing, as chapter 2.4.1 outlines, the structure of the CSCM framework is defined on the basis of an existing industry-neutral CSCM framework. In addition, wind-specific CE frameworks are identified and analysed for applicability to the development of a CSCM framework for the wind industry. Finally, scientific research on CSCM in the wind industry is selected, hence the research presented in chapter 2 is considered.

According to Figure 12, the second step of the methodology is the presentation of the results, which takes place in the next chapter 4.2. It particularly details the supply chain processes level of the CSCM framework to ensure an in-depths view on possible circular economy pathways by wind turbines and their blades. The evaluation is subsequently conducted in Part B.

Selection of an industry-neutral CSCM framework

To promote an easier transferability to other industries, the development of a wind-specific CSCM framework is based on an industry-neutral CSCM framework. Accordingly, a research search conducted in 2022 identified existing CSCM frameworks (Kramer & Schmidt, 2022, p. 65). In total, only four comprehensive frameworks were identified and further assed in regard to whether these address core aspects of a circular economy. The analysis is required as a circular economy and CSCM can be defined in various ways and a common understanding is not yet established (see 2.3). Therefore, the analysis reviews whether circular thinking has been sufficiently embedded in the proposed CSCM frameworks, as outlined in the following.

Batista et al. (2018) develop a conceptual understanding of circular supply chains by reviewing existing literature from sustainable supply chains narratives such as reverse logistics or close-loop supply chains. They assess to which extent the existing literature acknowledges the management of restorative and regenerative processes in supply chain design. As a result, they provide an archetype of a circular supply chain, in which they distinguish between primary, secondary and recovered flows of materials and products (Batista et al., 2018, p. 447). It is emphasised that these flows can occur in both closed and open loops. This acknowledges that the product may not necessarily be returned to the original manufacturer, but could alternatively involve a forward supply chain.

Farooque et al. (2019) provide a literature-based overview of circular supply chain management by introducing a definition which foresees the integration of circular thinking into SCM (see 2.3). The definition is in accordance with the understanding of Batista et al. (2018, pp. 446-447), although they outline that a more comprehensive integration of circular thinking and a zero-waste economy is required. Their conceptual understanding emphasises the necessity for a system-wide transformation of business models and supply chain functions. This is required in order to facilitate the restoration of technical materials and the regeneration of biological materials, thereby ensuring sustainable development. Accordingly, they provide an overview at a broad SCM level, of individual supply chain functions, business models and the role of technology (Farooque et al., 2019, p. 887). In this regard, the supply chain functions design, procurement, production, logistics, consumption and end-of-life (EoL)/waste management are addressed.

González-Sánchez et al. (2020) present a conceptual understanding of circular supply chains based on a literature review that highlights four dimensions for the design and implementation of circular supply chains: relational, technological, environmental, logistical and organisational. Accordingly, the relational dimension consists of a greater interaction with suppliers, customers and institutions, while the technological dimensions foresees the use of smart technologies (González-Sánchez et al., 2020, p. 15). Moreover, the environmental dimension accounts for sufficient legal requirements, fiscal tools and a new cultural framework. And finally, the logistics and organisational dimension outlines reverse logistics, industrial symbiosis and circular business models. Collectively, these dimensions impact the environmental and economic performance of a circular supply chain.

Montag et al. (2021) introduce a conceptual framework of circular supply chain maturity based on a systematic literature review. They outline a three-dimensional concept that integrates six archetypal elements of a circular economy, thereby embedding holistic systems thinking and linking it to overarching goal of sustainable development (Montag et al., 2021, p. 21). The three dimensions are organisation (strategic), products (tactical) and processes (operational), with further subdimensions for each:

- Organisational dimension: Management and information and technology
- Products dimension: Beginning-of-life, middle-of-life and end-of-life
- Processes dimension: Plan, source, make, deliver, use, return, recover and enable, in accordance to the supply chain processes of the extended SCOR-model by Vegter et al. (2020)

Montag et al. integrate the necessary paradigm shift towards a circular economy, a value focus and the R-principles, as well as restorative and regenerative cycles, in these dimensions. After the analysis of the four CSCM frameworks, it can be concluded that the CSCM framework by Montag et al. (2021, p. 21) is most suitable as a basis for the development of the CSCM framework in the wind industry (Kramer & Schmidt, 2022, p. 65). This is justified by the fact that it comprehensively integrates circular thinking into CSCM while providing practical guidance thanks to a detailed explanation of the various dimensions and supply chain processes. However, as an industry-neutral framework, it lacks the consideration of wind-specifics in the structure of the framework, leading to the need to identify and select a wind-specific CE framework.

Selection of wind-specific CE framework

A review of current literature on circular economy within wind energy research in 2.4 has introduced a few existing systemic views on circular thinking in the wind industry. However, only the study by Velenturf (2021, p. 13) outlines a wind-specific CE framework. She provides a comprehensive multi-level framework on circular strategies for offshore wind based on a systematic literature review, expert workshops and feedback loops. The framework consists of circular strategies for offshore wind (e.g. design for circularity, reuse, lifetime extension) that differ between the infrastructure, components and materials level. However, the focus is on offshore wind, although the applicability to onshore wind is mentioned. Therefore, the CE framework by Velenturf (2021, p. 13) is considered for the development of the wind-specific CSCM framework.

Summary of the selected research base

A summary of the selected research base for the development of a CSCM framework for the wind industry is given in Figure 13. Accordingly, in addition to the selection outlined, the scope of research and overview of current research presented in chapter 2 is also considered.

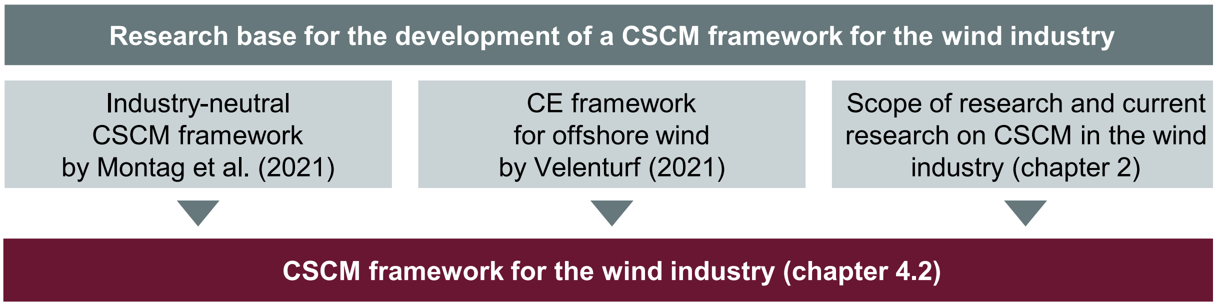


Figure 13. Overview of selected research base for the development of a CSCM framework for the onshore wind industry.

4.2 Circular supply chain management

The conceptual framework on circular supply chain management in the wind industry is illustrated in Figure 14 (Kramer & Schmidt, 2022).

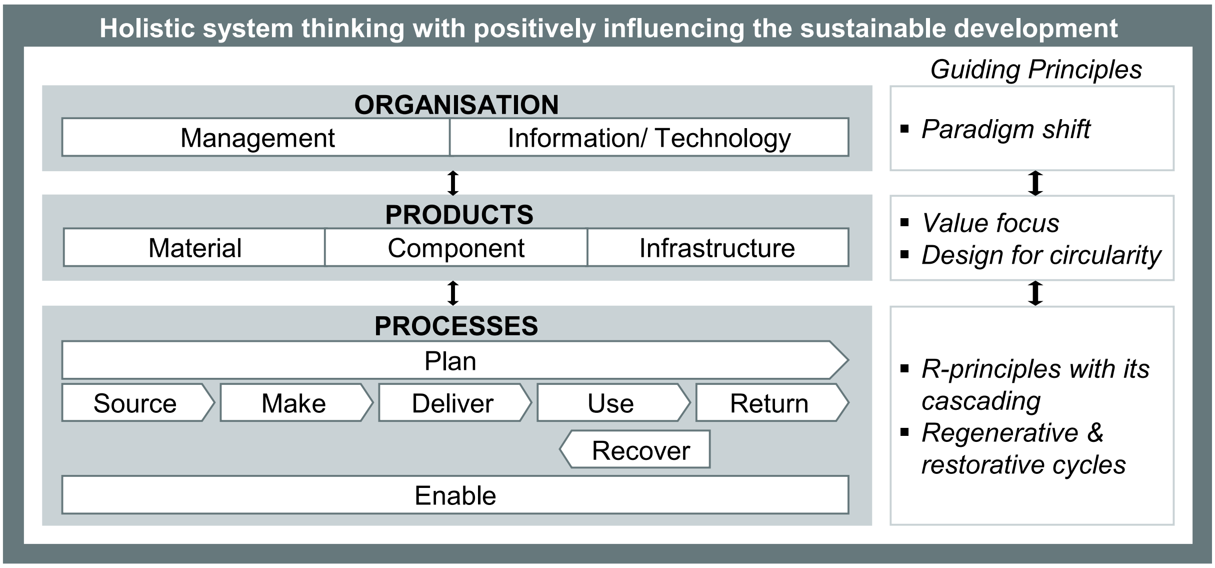


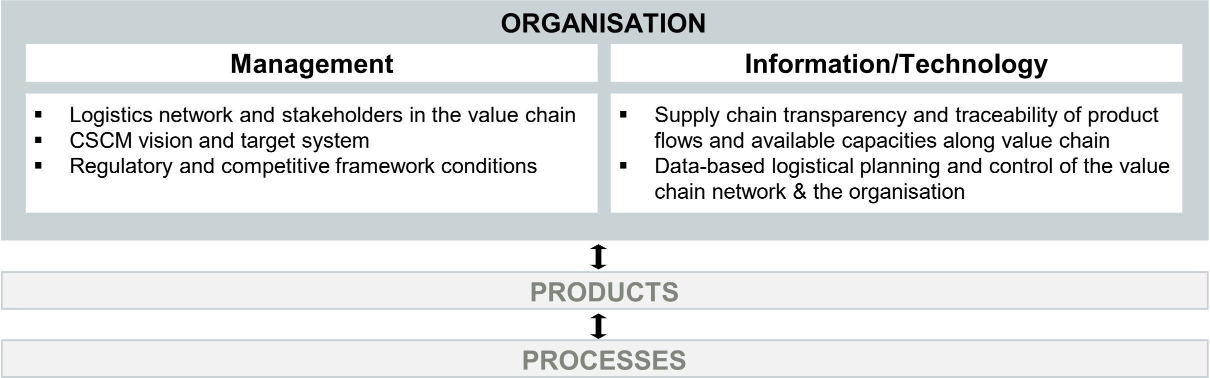
Figure 14. Conceptual framework of CSCM in the wind industry. Based on Kramer & Schmidt (2022). Inspired by Montag et al. (2021), Vegter et al. (2020), Velenturf (2021).

The framework embeds the circular thinking into SCM and consists of three levels, the organisational, products and processes level. Each level has further subdimensions that are interlinked with the different levels.

This structure considers the multi-level structure of the industry-neutral CSCM framework by Montag et al. (2021) and the subdimensions in the organisational and processes levels. The products level is structured in accordance to the wind-specific CE framework by Velenturf et al. (2021). In addition, the subdimensions are detailed in accordance to the scope of research and current literature of CSCM in the wind industry (see chapter 2) and are described below.

Organisational level

The organisational level consists of the two subdimensions, management and information/technology (Montag et al., 2021, p. 20). It is interconnected with the industry and the market, thus involving different stakeholders to enable a paradigm shift in the wind industry. Figure 15 outlines the key tasks associated with the two subdimensions and also indicates that the level is interlinked with the product and process levels.



ORGANISATION

Management	Information/Technology
▪ Logistics network and stakeholders in the value chain ▪ CSCM vision and target system ▪ Regulatory and competitive framework conditions	▪ Supply chain transparency and traceability of product flows and available capacities along value chain ▪ Data-based logistical planning and control of the value chain network & the organisation

Figure 15. Organisational level of the CSCM framework for the wind industry. Based on Kramer & Schmidt (2022), inspired by Montag et al. (2021).

Management

The key management tasks, shown on the left side of Figure 15, consist of three tasks, which are further explained below (Kramer & Schmidt, 2022, p. 70; Montag et al., 2021; Sehnem et al., 2019; A. P. M. Velenturf, 2021; Yadav et al., 2020).

The first management task is to describe, understand and develop the logistics network and the stakeholders in the value chain within and outside the wind industry.

Similar to other production networks, also the manufacturing process of wind turbines involves various suppliers in a global network (Kramer & Schmidt, 2022, p. 70; Surana et al., 2020, p. 4). Apart from that, it also includes a regional network of stakeholders for the installation, operation, maintenance and decommissioning of the wind turbines, as those functions are fulfilled at the project site (GWEC, 2022). It requires special skills and technical equipment from regional companies, such as trained personnel who can work at high altitudes (Poulsen & Lema, 2017). This also accounts for the transportation of the turbine components, e.g. planning transportation routes for large-scale blades (Bundesverband WindEnergie [BWE]; BWE, 2019). Moreover, depending on the taken pathway after decommissioning a wind turbine, the companies could be internationally or regional active. For example, the concrete of the foundation could be recycled for the use in the construction of new roads in the region or the components exported as spare parts (DIN SPEC 4866, 2020; Woo & Whale, 2022, pp. 1734-1735). In summary, the key supply chain actors along the value chain of wind turbines are as follows (Bonou et al., 2016, p. 4; Dahane et al., 2017, p. 1547; Koschate, 2020, p. 65; Surana et al., 2020, p. 4; A. P. M. Velenturf, 2021):

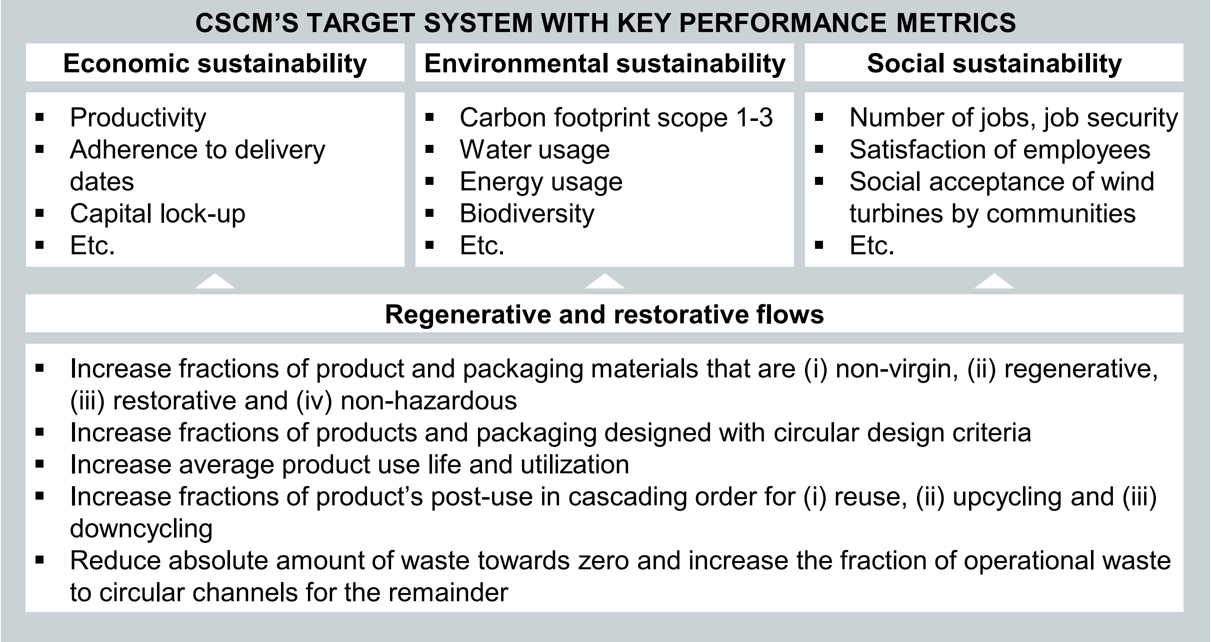
- Suppliers of raw materials and semi-finished products
- Wind turbine manufacturer/OEM
- Specialised installation companies
- Wind farm developer
- Wind farm operators
- Maintenance, repair and overhaul (MRO) companies
- Decommissioning companies
- Logistics companies
- Refurbishment and remanufacturing companies
- Repurposing companies
- Recycling and waste-handling companies

It should be noted that these different functions do not have to be performed by separate companies. In fact, one company often performs several functions in the value chain, e.g. an OEM also installs the wind turbine (Koschate, 2020, p. 62).

Once the key stakeholders have been identified, the existing and necessary economic and logistical relationships can be analysed to identify converging and conflicting interests and derive strategic measures (Kramer & Schmidt, 2022, p. 70; Montag et al., 2021, p. 20). For a CSCM, it is important to establish stakeholder relationships between those who manufacture components and service turbines and those involved in the post-decommissioning value chain. For example, the coordination of forward and reverse supply chains can ensure the availability of spare parts for wind turbine maintenance by sourcing remanufactured components (Dahane et al., 2017, p. 1547). Another example is the potential availability of recycled materials for the production of new parts and components (Graulich et al., 2021, p. 46). In this context, an important field of action is the identification of critical supply within the logistical network, as it can also impact the feasible design options of new turbines and their components (GWEC & BCG, 2023, p. 47; Kramer & Schmidt, 2022, p. 71). For example, the supply of rare earth materials such as neodymium and dysprosium is already considered critical in the EU (Alves Dias et al., 2020; Graulich et al., 2021, p. 46), encouraging the creation of new sourcing channels through recycling and the reduction of material use through changes in product design (Bonfante et al., 2021).

The second management task is the definition of a CSCM vision and target system with performance metrics (Montag et al., 2021, p. 20). Each organisation needs to formulate a long-term vision that embeds circular thinking into SCM and clearly links it to a target system (Farooque et al., 2019, p. 88; Kramer & Schmidt, 2022, p. 71).

In line with the definition of CSCM by Farooque et al. (2019, pp. 884-885), the target system proposed in Figure 16 consists of the three sustainability dimensions of economic, environmental and social, as well as the differentiation of the restorative and regenerative dimensions. Accordingly, the key metrics of the regenerative and restorative dimensions (Circular Economy Indicators Coalition [CEIC], 2023, p. 10) are aimed to contribute to the economic sustainability (e.g. increase productivity), environmental sustainability (e.g. decrease carbon footprint) and social sustainability (e.g. social acceptance of wind turbines) (Farooque et al., 2019, pp. 884-885; Vegter et al., 2020, p. 8). These metrics need to be measured and their impact on the sustainability dimensions assessed, e.g. whether they are aligned or conflicting (Kramer & Schmidt, 2022, p. 71; Vegter et al., 2020, p. 13).



CSCM'S TARGET SYSTEM WITH KEY PERFORMANCE METRICS

Economic sustainability	**Environmental sustainability**	**Social sustainability**
▪ Productivity ▪ Adherence to delivery dates ▪ Capital lock-up ▪ Etc.	▪ Carbon footprint scope 1-3 ▪ Water usage ▪ Energy usage ▪ Biodiversity ▪ Etc.	▪ Number of jobs, job security ▪ Satisfaction of employees ▪ Social acceptance of wind turbines by communities ▪ Etc.

Regenerative and restorative flows

- Increase fractions of product and packaging materials that are (i) non-virgin, (ii) regenerative, (iii) restorative and (iv) non-hazardous
- Increase fractions of products and packaging designed with circular design criteria
- Increase average product use life and utilization
- Increase fractions of product's post-use in cascading order for (i) reuse, (ii) upcycling and (iii) downcycling
- Reduce absolute amount of waste towards zero and increase the fraction of operational waste to circular channels for the remainder

Figure 16. Overview of key metrics in CSCM. Inspired by CEIC (2023, p. 10), Farooque et al. (2019, pp. 884-885), Vegter et al. (2020, p. 8).

In addition, further company-specific indicators may exist and the indicators presented could also be further detailed into indicators for specific products and supply chain processes. This highlights the interlinkage with the products level and processes level of the CSCM framework. It is also closely related to the management task of stakeholder management mentioned above, as the vision and target system should be agreed with key stakeholders to ensure that sub-optimums are not created in the circular supply chain network. For example, the European wind industry has agreed to ban the landfilling of blades by 2025 (WindEurope, 2020), which has led to the announcement of zero-landfill and recyclability targets for blades by various glass fibre manufacturers, blade manufacturers and operators (Kramer & Beauson, 2023, p. 9).

The third key management task is the characterisation of the requirements in regard to the overall regulatory and competitive conditions (Kramer & Schmidt, 2022, p. 70). Hence, the regional, national, European and international laws, guidelines and economic market conditions (e.g. subsidy schemes) are to be considered. Where current regulatory requirements and competitive conditions inhibit different aspects of CSCM, these need to be redefined in consultation with other stakeholders (Vegter et al., 2020, p. 8; A. P. M. Velenturf, 2021, p. 20). The example of the landfill ban for rotor blades also illustrates this aspect, as the joint agreement improves the competitive conditions for the development of blade recycling solutions (Kramer & Beauson, 2023). Another example is the German DIN Spec 4866, which sets out agreed industry standards for the decommissioning and recycling of wind turbines in Germany and aims to raise the bar for more sustainable practices (DIN SPEC 4866, 2020).

In summary, the management subdimension foresees a move from operating as a single organisation in a loosely collaborative network to a symbiotic network of stakeholders. In the symbiotic network, stakeholders have aligned visions and performance metrics and operate within appropriate regulatory and competitive frameworks.

Information/Technology

The subdimension of information/technology consists of two main tasks as shown on the right side of Figure 15 (Kramer & Schmidt, 2022, pp. 71-72; Montag et al., 2021, p. 20).

The first task is to create supply chain transparency and traceability of the product flows along the value chain, which can be put into context with the available stakeholder capacities. The product flows include the quantities of the various stages in regard to value creation, value retention and value extension (Montag et al., 2021, pp. 20-21). In principle, these flows may include (Beauson et al., 2022; Bonou et al., 2016; Kramer & Beauson, 2023; Kramer & Schmidt, 2022, p. 71, 2023; Potting et al., 2017, p. 15; A. P. M. Velenturf, 2021):

- Raw materials
- Manufactured parts, components and turbines
- Turbines in installation and operation
- Repaired parts, components and turbines
- Decommissioned turbines
- Turbines disassembled into components and parts
- Refurbished parts, components and turbines
- Remanufactured parts, components and turbines
- Reinstalled parts, components and turbines
- Repurposed parts and components
- Recycled materials

This is further illustrated with the example of product flows of decommissioned wind turbines. The flows are organised by cascading R-principles for decommissioned turbines in its entirety, components, parts and materials. In this light, Figure 17 zooms in on the flows of wind turbine blades and the R-principles that apply after the first lifecycle of a wind turbine (Kramer et al., 2024, p. 181).

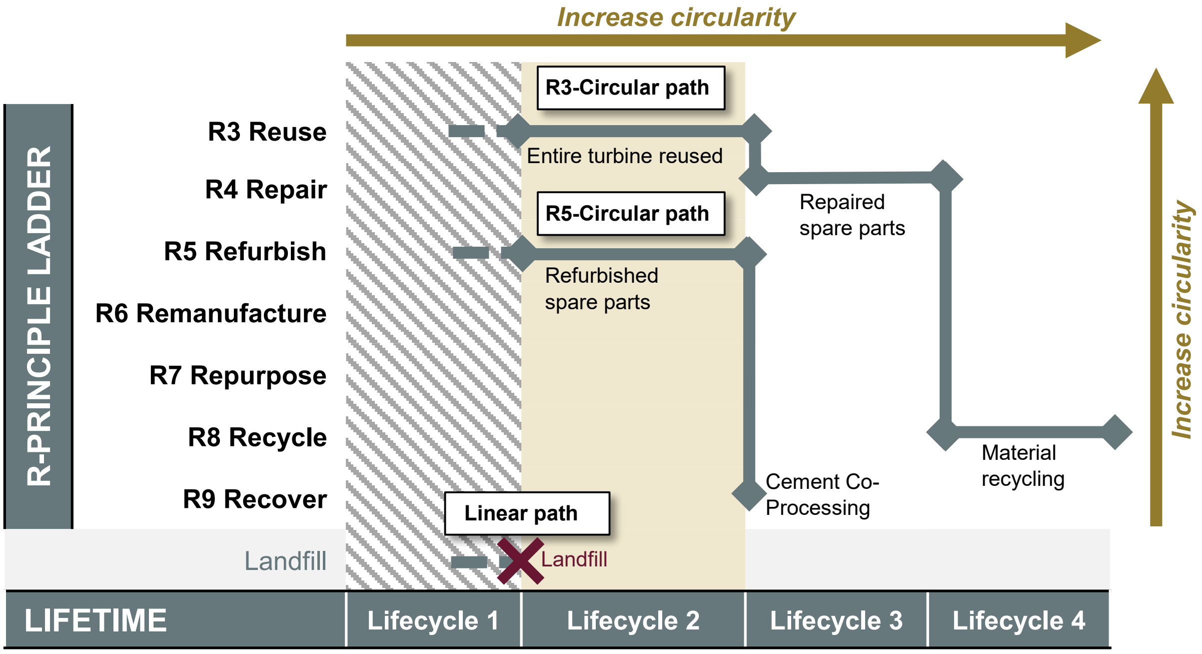


Figure 17. Circular economy pathways after the first lifecycle of a wind turbine blade. Based on Kramer et al. (2024, p. 181). Inspired by Kramer and Beauson (2023), Potting et al. (2017), Velenturf (2021).

Accordingly, the blade can undergo several lifecycles in the product's lifetime, as illustrated with the x-axis. In addition, demonstrated with the y-axis, several R-principles are applicable to the blade of the decommissioned turbine. As a result, there are a number of possible pathways of a wind turbine blade, of which the following three examples, defined by the R-principle chosen in the second lifecycle, are given for clarity (Kramer et al., 2024, p. 181):

- **Linear path:** In this example, the flow of the blade ends after the first lifecycle with landfill
- **R5-Circular path:** In this example, the blade enters a second lifecycle as refurbished spare part (R5) and after its second lifecycle the flow ends with cement co-processing (R9)
- **R3-Circular path:** In this example, the entire turbine and thus also the blade has a second lifecycle. The entire turbine is reused (R3) for a second lifecycle and then the blade is used as a repaired spare part (R4) in its third lifecycle. After the third lifecycle, the material is recycled (R8)

This makes it clear that the quantities of each possible pathway of a wind turbine and its blades should be tracked. It can help, for example, to maximise the use life and utilisation of the blade (see Figure 16). Accordingly, the transparency of product flows and available stakeholder capacities can be achieved through the use of information systems and digital technologies (BWE, 2019; Gebhardt et al., 2021; Mendoza et al., 2022; A. P. M. Velenturf, 2021).

In this context, key data sources include:

- Internal data systems such as the enterprise resource system or SCADA data from the wind turbines in operation (Dulman & Gupta, 2018, pp. 147-148)
- Product and process data of other companies
- Market registers by the government, e.g. register of master data of energy plants in Germany with various information such as the plants location, installed capacity, commissioning date and technical data (Bundesnetzagentur, 2022)
- Digital product passes, e.g. the European OEMs have agreed to share the blade dimensions and material composition per blade type (DecomBlades, 2023)
- Market data by research institutes, external companies and industry associations such as GWEC and WindEurope (GWEC, 2023a, 2023b)
- Geographic information system (Piel et al., 2019; Stetter et al., 2022)
- Unstructured data such as scientific papers, reports, newspaper articles and social media, e.g. to identify historical wind turbine accidents (Ertek et al., 2017)

For the establishment of an information platform, it is necessary for each organisation to define the information requirements, the scope of information to be shared and the access rights (Kramer & Schmidt, 2022, p. 71). Data sharing between stakeholders can be challenging due to confidentiality, e.g. detailed plans of the product design and the involved manufacturing processes are usually classified as confidential (Colicchia et al., 2019). Hence, stakeholders need be incentivised accordingly and an independently operated platform with different access rights used.

The second task of the subdimension ‘information/technology’ is the data-based logistical planning and control of the value chain network and each organisation (Gebhardt et al., 2021; Kramer & Schmidt, 2022, p. 72). The data on product flows, capacities and demands of supply chain actors can be used to conduct analyses of historical developments and for forecasts. This can lead to more precise demand forecasts for each supply chain actor and thus reduces the risk of a bullwhip effect (Gebhardt et al., 2021; Sahu et al., 2021). It can moreover support the investment decisions of various stakeholders in the wind industry in relation to long-term investments such as new remanufacturing or recycling facilities (Beauson et al., 2022, p. 13; A. P. M. Velenturf, 2021, p. 22). Besides organisational decisions, the data can also be used on the products and processes level. For example, predictive maintenance can reduce a turbine downtime, a maintenance strategy enabled by sensor data from the operating turbine and the use of advanced analytics such as machine learning methods (Dulman & Gupta, 2018). Data sharing between the turbine operator, the service company and the spare parts supplier therefore contributes to more effective capacity planning and thus a potentially higher utilisation of the turbine in operation.

In summary, the information/technology subdimension aims to support the management tasks, the products level and the processes level by establishing a comprehensive information platform for all actors in the value chain network.

Products level

The products level consists of three dimensions, the materials, components and infrastructure and thus is in accordance with Velenturf (2021, p. 12). The guiding principles on the products level is a value focus and the design for circularity (Kramer & Schmidt, 2022, p. 72; Montag et al., 2021, pp. 20-21). Accordingly, the design of the products should enable circular strategies along the entire product life (i.e. beginning of life, middle of life and end of life) to ensure value creation, value retention and value extension for sustainable development.

In Figure 18, the different dimensions with their main task of design for circularity is shown. In this context, the infrastructure is the highest aggregate, followed by components, parts and finally materials. For instance, the wind turbine in its entirety is part of the infrastructure dimension (right side of Figure 18), which consists of several key components such as blades, a gearbox and a generator (middle of Figure 18) (Manwell et al., 2009, pp. 3-4). Each of those key components are assembled with various parts and those are made with the use of raw materials (Bonou et al., 2016). For instance, the blade as a key component is made out of several parts that are joint (see Figure 3), consisting of materials for the fibre, resin and core (left side of Figure 18) (Mishnaevsky et al., 2017; Mølholt Jensen & Branner, 2013, p. 6). At each of these product stages, design decisions can be made in favour of circularity, with the scope varying depending on whether it is a material or a structural product (A. P. M. Velenturf, 2021, p. 23). In this sense, the R-principles can only be applied in their cascading order at the processes level when products are designed according to circularity criteria, which emphasises the interdependency between the products and processes levels (Bocken et al., 2016; Montag et al., 2021; A. P. M. Velenturf, 2021, p. 29). In addition, the products level is linked to the organisational level as it involves coordination with other supply chain actors such as suppliers and customers.

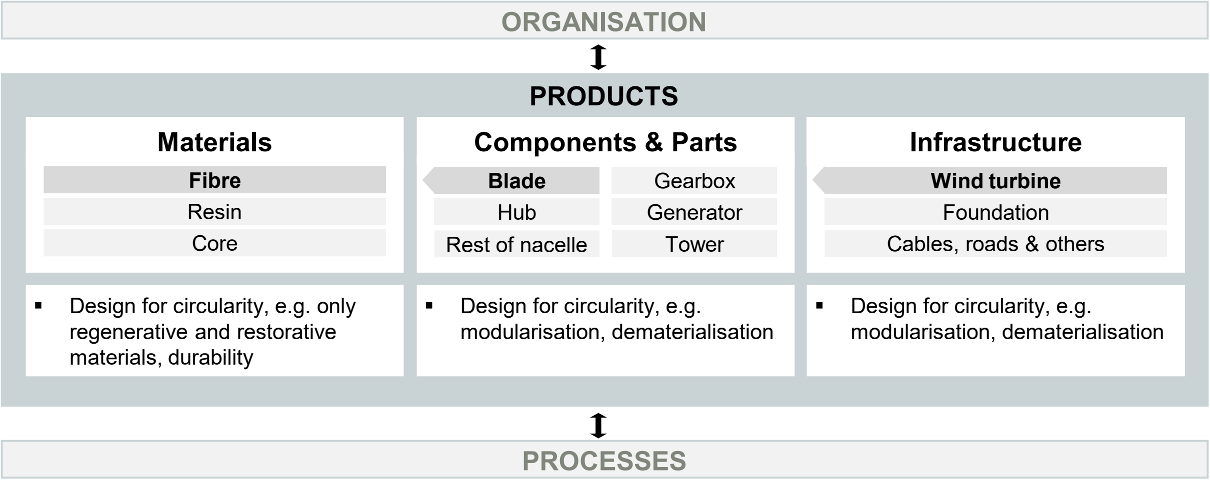


Figure 18. Products level of the CSCM framework for the wind industry. Based on Kramer & Schmidt (2022), inspired by Montag et al. (2021), Velenturf (2021).

Key design criteria for products are (Bocken et al., 2016; Farooque et al., 2019; Kramer & Schmidt, 2022; A. P. M. Velenturf, 2021):

- **Materials:**
    - No hazardous materials
    - Only regenerative and restorative materials
    - Pure, durable and sustainable materials as well as secondary materials
    - Standardisation across industries
- **Structural product:**
    - Dematerialisation
    - Structural design that allows for the cascading application of slowing and closing R-principles, i.e. modularisation, upgradeability, standardisation, durability, reliability, distinction between biological/regenerative and technological/restorative cycles

A wind turbine belongs mainly to the restorative cycles, with only a few regenerative materials (e.g. balsa wood) being used. A minimum design threshold is the elimination of product designs that can only be landfilled, incinerated or heavily downcycled, resulting in a loss of resources. The design should therefore enable efficient and effective repair & maintenance, reuse, refurbishment, remanufacturing, repurposing and recycling (Kramer & Schmidt, 2022; A. P. M. Velenturf, 2021). For example, a design that allows an easy access to parts that tend to break first, promotes repairability. The product design must therefore ensure that components and parts of an installed turbine can be replaced and upgraded, that the turbine can be decommissioned, and that components and parts can be disassembled (A. P. M. Velenturf, 2021, p. 19). Furthermore, a product design is required that allows for high-quality recycling and the use of secondary materials. For example, reducing the use of rare earths in the permanent magnet design and moreover using recycled neodymium and dysprosium would help to overcome the critical supply situation (Alves Dias et al., 2020). Another example are multilayer composite structures that are difficult to separate afterwards in a sufficient quality with ongoing research to find alternative materials and develop recycling technologies (see 2.4.2).

A product design criterion that benefits the application of various R-principles is modularisation (Mignacca et al., 2020; A. P. M. Velenturf, 2021, p. 19). According to Mignacca et al. (2020, p. 8) a modular design allows for decoupling the lifetime of different product stages, i.e. the life of the turbine is decoupled from the life of components and the life of parts is decoupled from the life of components. It moreover foresees "*the avoidance of irreversibly joining together different materials and components*" (A. P. M. Velenturf, 2021, p. 19) and is thus crucial for strategies such as repair, refurbishment, remanufacturing and recycling. For example, a modular design of large-scale components (e.g. blades) can reduce transport costs and hence could promote the recirculation (Kramer & Beauson, 2023, p. 4). Another design criterion to be mentioned in this context is the standardisation and compatibility of product designs (Bocken et al., 2016, pp. 310-311; Mignacca et al., 2020, p. 7). Accordingly, a smaller number of variants in materials, parts, components and turbine types helps to achieve economically viable thresholds for the quantities required for each R-principle (Bocken et al., 2016, p. 310). An example would be the use of a standard type of glass fibre across different industries, such as wind energy, automotive and aerospace, as this would lead to the possibility of aggregating volumes for a common recycling solution (Beauson et al., 2022, p. 13; Kramer & Beauson, 2023, p. 14).

In general, the design of a wind turbine is optimised by various objectives, e.g. cost-optimisation, efficiency and considers various conditions, e.g. wind, topography (Dykes & Meadows, 2011, p. 15; Schaffarczyk, 2023, pp. 181-197). For example, a different foundation design is required depending on whether the project site is on land, offshore near the coast or in deep water. As outlined in the organisational level of the CSCM framework, the design choices should contribute to an economic, environmental and social sustainability. However, some of the design criteria presented may contradict each other when considering the different product stages and the embedding in the energy system and different industries (A. P. M. Velenturf, 2021, p. 24). For example, the design of thinner tower walls results to the use of less materials, while negatively impacting the structural stability and thus the durability. This could lead to a shorter use life of the entire turbine. This emphasises that there is not one uniform circular economy and instead those trade-offs have to be identified and managed in accordance to the given conditions at a given time (A. P. Velenturf & Purnell, 2021, p. 17).

In summary, product design to narrow, slow and close resource flows for sustainable development is the core objective. This requires a systemic perspective to understand the interrelationships with different product stages and other products (e.g. the use of by-products), while also considering the requirements at the organisational and process levels.

Processes level

The processes level has the key task to design, plan and manage the circular flows of products (Kramer & Schmidt, 2022, p. 74; Vegter et al., 2020). In this light, the guiding principles for embedding circular thinking into the supply chain processes are the 9R-ladder and the distinction between regenerative and restorative cycles (Kramer & Schmidt, 2022, p. 74; Montag et al., 2021, p. 22; Potting et al., 2017, p. 15). The processes level consists of eight core processes that are in accordance to the extended SCOR-model by Vegter et al. (2020), as shown in Figure 19. Each of these supply chain processes must be designed, planned and managed for each product at the material, component and infrastructure levels. It is therefore closely linked to an appropriate circular product design at the products level and to the chosen business model at the organisational level (Kramer & Schmidt, 2022, p. 74).

In accordance to Figure 19, the processes consist of plan, source, make, deliver, use, return, recover and enable (Vegter et al., 2020, p. 5). The original SCOR-model does not consider the processes ‘use’ and ‘recover’ as main processes (The Supply Chain Council, 2012), but the extended SCOR-model does, thus promoting circular thinking (Vegter et al., 2020, pp. 5-7).

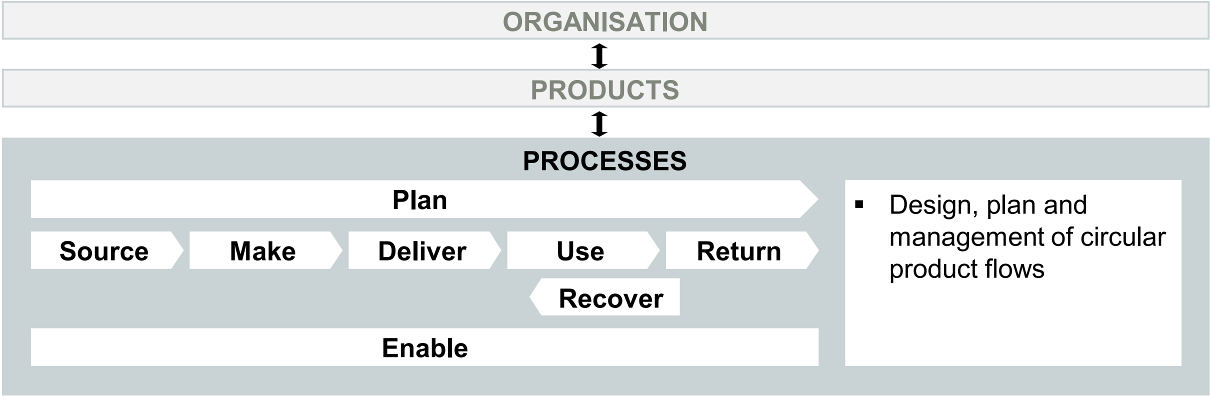


Figure 19. Processes level of the CSCM framework for the wind industry. Based on Kramer & Schmidt (2022), inspired by Montag et al. (2021), Vegter et al. (2020).

As the review of current research shows, SCM research for the wind industry has mainly focused on the plan processes, while post-use processes of the wind turbine, component or material have received the least attention (see Figure 8).

The main processes are described as follows (Kramer & Schmidt, 2022, p. 74; Montag et al., 2021, p. 22; Vegter et al., 2020, pp. 6-8; A. P. M. Velenturf, 2021, p. 13):

- **Plan:** Supply chain planning and the planning of the other seven main processes
- **Source:** Procurement of materials, semi-finished and finished parts, components and turbines from primary and secondary sources
- **Make:** Manufacturing of the components and their parts
- **Deliver:** Delivery of the manufactured components to the project site and then assembly and installation of the wind turbine
- **Use:** Operation of the turbine and corresponding MRO services
- **Return:** Source and deliver products after use phase, hence decommissioning, disassembly, transport to original manufacturer (closed system) or other companies (open system)
- **Recover:** Reuse, repair, refurbishment, remanufacturing, repurposing, recycling and energy recovery
- **Enable:** Organisation and communication of management in the circular supply chain, emphasising the link to the organisational level

Building on the processes outlined, Figure 20 proposes a circular supply chain design for the wind industry. It further details the main process of ‘recover’ in order to introduce an understanding of the circular flows of turbines, components, parts and materials in the wind industry.

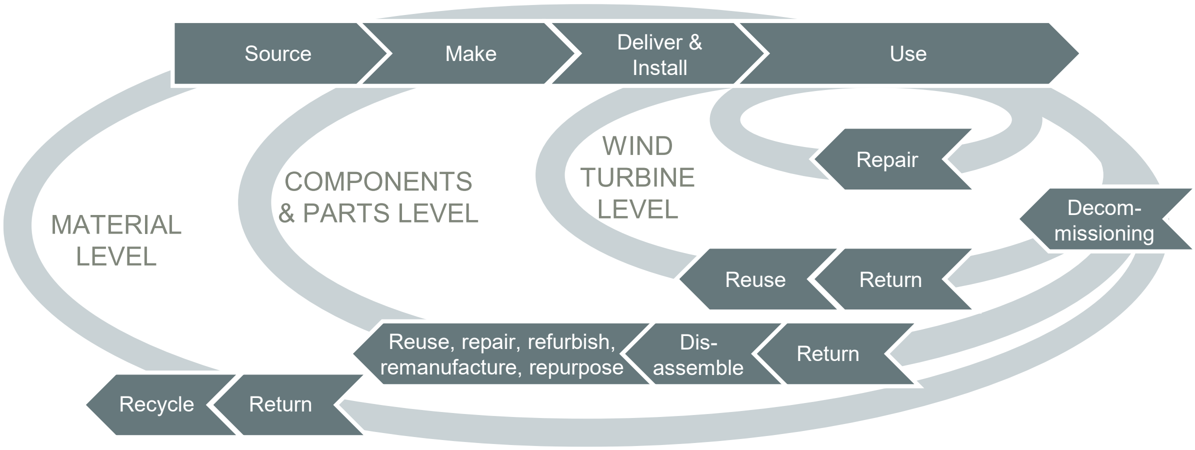


Figure 20. Circular supply chain processes in the wind industry. Inspired by Kramer & Beauson (2023), Kramer & Schmidt (2022, 2023).

The processes source, make, deliver, install and use are the forward supply chain processes in the wind industry. In comparison to the industry-neutral processes by Vegter et al. (2020), the process ‘install’ is added to acknowledge that the components of a wind turbine are delivered to the project site, followed by the installation of the wind turbine (Koschate, 2020, pp. 65-66). Another common supply chain process in the wind industry is the repair loop involving MRO services during the operation of the wind turbine (Kramer & Schmidt, 2022). The maintenance and repair of the turbine at the project site could be carried out with new, reused, repaired, refurbished or remanufactured spare parts. This can contribute to a higher level of utilisation of the turbine and can also ensure an extension of the period of use (Megahed & Goetschalckx, 2018, p. 287; Ziegler et al., 2018, p. 1267). Furthermore, after an initial use phase, the circular supply chain processes that belong to the main processes of ‘return’ and ‘recover’ are introduced. Accordingly, Figure 20 visualises the processes of decommissioning, return, direct reuse, repair, refurbishment, remanufacturing, repurposing and recycling (Potting et al., 2017, p. 15). First of all, the turbine is decommissioned and its components disassembled, followed by different possible circular strategies (Beauson et al., 2022, p. 2; Kramer & Beauson, 2023, p. 12; A. P. M. Velenturf, 2021, pp. 19-20). The loop at the turbine level foresees a direct reuse of the turbine at a new project site. The loop on the components and parts level comprises of a further disassembly or pre-processing to enable the direct reuse, repair, refurbishment, remanufacturing or repurposing of components and parts, also illustrated in Figure 17. And finally, the outer loop is on the material level and foresees the recycling at the highest possible quality. In this context, the review of current research on circular strategies for decommissioned onshore wind turbines and their blades (see 2.4.2) shows that research on second lifecycle pathways is rare. Moreover, in regard to end-of-life pathways, infrastructure for blades recycling is still to be established.

The circular flows can take place in a closed or open loop system, considering existing and new supply chain actors, as well as other industries in the case of repurposing, material recycling and energy recovery (Vegter et al., 2020, p. 12). It should be noted that the classification on the R-ladder decreases as the loops become larger (Potting et al., 2017, p. 15). Accordingly, the inner loops are classified higher in the R-ladder and can therefore, in principle, contribute to a higher structural value of the product. A product can moreover undergo multiple lifecycles, resulting in a cascading flow of a product (see Figure 17).

As supply chain planning, the subtask of the main process ‘plan’, is the first step towards circular flows in a circular supply chain network, this is further detailed below. Accordingly, to plan circular supply chains in more detail, the fulfilment of the following key tasks is required (Kramer & Schmidt, 2022, p. 75):

- Forecasting future quantities of installations, decommissioning and circular flows
- Design of the circular supply chain network, depending on defined target system
- Long-term capacity and inventory planning of the actors in the circular supply chain network.

The first task is to forecast the demand of the different product levels in their different life-phases. On the thesis scope of quantifying the circular flows of decommissioned onshore wind turbines in Denmark and Germany, no reliable overview of expected quantities is available (see 2.4.2). It should be noted, that a transformation towards a circular economy results to different timings of demand, e.g. an extension of the turbine lifetime postpones the demand for decommissioning capacities (Kramer & Schmidt, 2022, p. 75).

Secondly, a circular supply chain network is designed, detailing the proposed network in Figure 20. This takes place on the basis of the forecasted product flows, known capabilities and capacities of supply chain actors and the requirements that are determined by the product design. Depending on this and the defined target system, different structures of the supply chain network are possible (Sultan et al., 2018). A network design could, for example, involve the establishment of hubs for certain components of decommissioned turbines, from which companies providing MRO services could obtain spare parts (Kramer & Schmidt, 2022, p. 75). These returned components can be refurbished or remanufactured in the hubs, depending on demand. Furthermore, the network for decommissioned turbines can be designed on the basis of currently installed turbines or additionally on the basis of expected installations. If only installed turbines are considered, the product design cannot be changed, whereas for new installations, new product designs may be used.

Thirdly, this knowledge is crucial for the capacity and inventory planning of the supply chain actors, in particular for long-term investment decisions (e.g. new refurbishment facility) (Mendoza et al., 2022; Sultan et al., 2018; A. P. M. Velenturf, 2021, p. 22).

In summary, the circular supply chain processes aim for the circular flow of turbines, components, parts and materials in a network with closed and open loops. There are various ways to design, plan and operate a circular supply chain network, which depend on the interrelationships within the processes, but also with the organisational and products levels.

4.3 Interim conclusions

Part A of the thesis provides a theoretical understanding by proposing a multi-level CSCM framework for the wind industry. The framework was developed on the basis of an existing industry-neutral CSCM framework and was detailed and adapted using existing wind-specific research (see 4.1). The results (see 4.2) lead to a comprehensive response to RQ1 and RQ2, as the following two key contributions outline.

Contribution 1: Provision of a multi-level CSCM framework for the wind industry

RQ1 How does a circular supply chain management framework in the wind industry look like? ✓

The developed CSCM framework for the wind industry provides a systemic overview of the CSCM tasks in the interrelated dimensions of the organisational, products and processes levels (see Figure 14). It thereby emphasises the importance of collaborating with stakeholders in the circular value chain network to facilitate coordinated actions aimed at decoupling from resource use to contribute to an economic, environmental and social sustainability. Key aspects of CSCM in the wind industry are:

- Organisational level: Aligned circular business models and visions across stakeholders within and outside of the wind industry as well as support by information/technology to promote a paradigm shift.
- Products level: Circular product design to enable feasibility of R-principles for infrastructure, wind turbines, components, parts and materials.
- Processes level: Circular supply chain processes that facilitate circular flows of wind turbines and their components, parts and materials. This comprises the design, planning and operation of second-lifecycle supply chains and end-of-life supply chains.

Detailing the process level of the CSCM framework leads to the second key contribution of Part A and consequently the answer to RQ2.

Contribution 2: Outlining circular supply chain processes in the wind industry

RQ2 What are circular supply chain processes along the lifecycle of a wind turbine and their blades? ✓

The proposed design for a circular supply chain network considers the circular flows of wind turbines, components, parts and materials (see Figure 20). It acknowledges that the circular flows can occur in closed or open loops and that the aforementioned products can undergo various lifecycles, resulting in a cascading flow of the products. These potential circular economy pathways are illustrated using a rotor blade from a decommissioned onshore wind turbine (see Figure 17) and show that a rotor blade can have a second lifecycle, as follows:

- Turbine level: Reinstallation of the decommissioned turbine with its blades
- Component level: Reuse, repair and refurbishment of blades for reuse in a turbine

If it is not feasible to retain the structural value of the blade on either the turbine or component level, repurposing of structural parts or material recycling are considered.

In summary, the two key contributions of Part A result to the completion of the first research objective of the thesis, as they comprehensively address the research gap regarding the conceptual understanding of CSCM in the wind industry.

RO1 Contribute to the emerging theoretical understanding of circular supply chain management in the wind industry. ✓

To further understand the applicability of the developed CSCM framework for supply chain actors in the wind industry, the next part of the thesis, Part B, builds on Part A and conducts empirical research from a multi-stakeholder perspective. Accordingly, the research gap of a lack in empirical investigations of second lifecycle pathways is addressed, which moreover enables to evaluate Part A.

5 Part B: Quantifying and Exploring Second Lifecycle Pathways

Part B of this thesis has the objective to explore second lifecycle pathways in Denmark's and Germany's onshore wind markets from a multi-stakeholder perspective (research objective 2). To fulfil the second research objective of this thesis, the chosen pathways of the decommissioned turbines and their blades in Germany and Denmark are identified and quantified (RQ3), followed by a qualitative exploration of second lifecycle supply chain processes and factors influencing the development of second lifecycle supply chains (RQ4). This derives practical knowledge on whether second lifecycle pathways are common in the exemplary markets Denmark and Germany and moreover, which second lifecycle supply chains occur and what is influencing the development of them. Moreover, with fulfilling the second research objective, Part A can be evaluated by comparing the empirically investigated second lifecycle pathways to the theoretical understanding from Part A.

The chapter consists of four subchapters and begins by outlining the methodology (5.1), followed by the results (5.2). The chapter closes with an overall discussion of the findings (5.3) and an interim conclusion (5.4).

5.1 Methodology

Figure 21 outlines the methodology of Part B that consists of diverse methods for the data collection, analysis, visualisation, and evaluation, as also outlined in chapter 3.

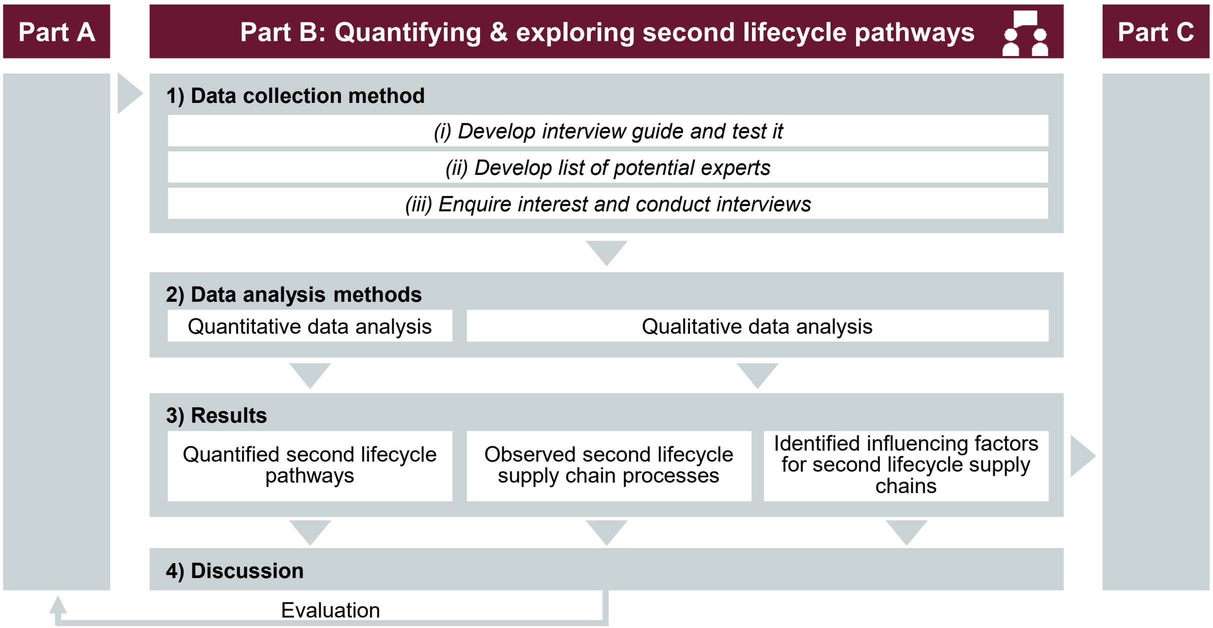


Figure 21. Part B's methodology of semi-structured expert interviews with quantitative and qualitative data analysis. Methods based on Gläser & Laudel (2010) and Mayring (2022).

The methodology consists of four parts and builds on the derived theoretical understanding of Part A that drew a conceptual framework of a CSCM in the wind industry and identified several different circular supply chain processes along the lifecycle. Furthermore, the findings of Part B are inputs to Part C (chapter 6).

The first part of Part B's methodology is the collection of empirical data through semi-structured interviews from multiple stakeholders that are involved in the decommissioning of onshore wind turbines in Denmark and Germany. The interview process is based on Gläser & Laudel (2010). The second part is the quantitative and qualitative data analysis. The quantitative data analysis is structured to answer RQ3, and the latter to answer RQ4 which occurs inductively according to Mayring (2022). Third, the results of the applied methodology are presented and discussed. This consists of the quantified circular economy pathways, the observed circular supply chain processes and identified factors influencing the development of circular supply chains. The focus is on the second lifecycle supply chain pathways, processes and influencing factors. Finally, the overall discussion of the methodology and findings in regards to the fulfilment of the second research objective is carried out. In this light, the findings are compared to Part A and the state of the art of other countries and industries.

The subsequent chapters further describe the rigorous and systematic process of data collection and analysis. Chapter 5.1.1 presents the data collection method of semi-structured interviews, chapter 5.1.2 outlines the method for the quantitative data analysis and finally, chapter 5.1.3 details the method for the qualitative data analysis.

5.1.1 Data collection with semi-structured interviews

The data collection process of semi-structured interviews consists – in accordance of Gläser & Laudel (2010, pp. 111) – of the following steps that are applied in Kramer et al. (2024): (i) development of an interview guide and its test, (ii) development of a list of potential experts and (iii) enquiry of interest and conducting the interviews (see Figure 21).

Development of interview guide and its test

The interview guide for the semi-structured interviews is developed first in English and then translated into Danish and German. To enable a theory-led approach, Gläser & Laudel (2010, p. 115) foresee to translate the identified need for information derived in Part A to topics and questions in the interview guide. Furthermore, to ensure that the experts are able to respond according to their knowledge, the questions are phrased clearly, simply, openly and neutrally (Gläser & Laudel, 2010, pp. 115, 131-142; Kramer et al., 2024, p. 183). Commonly the interview guide begins with basic biographical information (e.g. name and work title of expert) that supports the interviewer to conduct the remaining interview more personally linked to the expert (Döring & Bortz, 2016, p. 372). Moreover, it makes the expert comfortable in the interview situation (Gläser &

Laudel, 2010, p. 148). Table 5 presents the introduction question of the interview guide (Kramer et al., 2024). Question 1 and 2 are of biographical nature relating to the expert and question 3 aims at understanding the geographical scope of the interviewee's answers early on. As the study's scope is on Denmark and/or Germany, a rough split of the company's business across the company's operating countries is important.

Table 5. Introduction questions of the interview guide, based on Kramer et al. (2024).

Question 1	What is your and your company's name?
Question 2	What is your current job title?
Question 3	In which countries does your company operate?

To assess and ensure the suitability of the expert, the filter questions of Table 6 are formulated (Kramer et al., 2024). Question 4 aims at checking if the expert has been personally involved in the decommissioning of onshore wind turbines and its handling. In case the interviewee is not directly involved, it is asked if he/she has access to the information about the historical decommissioning projects or if another person at the company should instead be approached. In the latter case, the interview ends. Question 5 and 6 are asked to find out if the interviewee qualifies as an expert. If not, the interview would also end.

Table 6. Filter questions of the interview guide, based on Kramer et al. (2024).

Question 4	What is your personal role in decommissioning wind turbines and waste handling?
Question 5	How many years of working experience do you have with decommissioning and the waste handling of wind turbines?
Question 6	How many wind turbines onshore and offshore have you decommissioned and handled the waste? All at the same company or at which companies?

The key questions focus on decommissioned onshore wind turbines from Denmark and Germany (excluding small-scale turbine), hence in line with the defined scope of this thesis (refer to chapter 2). Typically, general questions of the subject of investigation are asked, followed by more detailed questions (Döring & Bortz, 2016, p. 372). More sensitive questions are asked at the end to higher the likelihood that the interviewee feels comfortable to give a response and to not risk that the interview is stopped in a worst case (Döring & Bortz, 2016, p. 372; Gläser & Laudel, 2010, p. 149). Therefore, specific questions regarding the business model and data requests, that are assumed to be more sensitive, are asked at a later stage in the interview. Even though the interviews' objectives are to account for the knowledge gaps that it is unknown if a second lifecycle is common or not (RQ3) and which factors influence its development (RQ4), questions are chosen to be as neutral and open as possible and hence address the entire scope of circular supply chain processes after an initial use phase of a wind turbine (refer to 4.2). With that, the interlinkages within circular supply chains are acknowledged. Using a broader scope additionally increases the likelihood that the experts can link their experience and knowledge to the asked questions. That is particularly important as the entire scope of CSCM is not yet well embedded in the wind energy industry and different understandings might exist (see 2.4).

First, key questions are formulated to collect information briefly on the company's business model (question 7, without going into detail) and on the handled quantities of decommissioned onshore turbines by the company (question 8-11), as summarised in Table 7 (Kramer et al., 2024). The questions help to describe the characteristics of the company's historical decommissioning and hence provide context for the exploration of the taken pathways. Different degrees of detail and units are considered to higher the likelihood for receiving information. At the minimum, a common unit (e.g. blade mass, number of turbines, installed capacity) of the different stakeholders is required for aggregation at national level for the quantification of the taken pathways per country.

Table 7. Key questions of the interview guide on the company's general handling process, Part 1, based on Kramer et al. (2024).

Question 7	How many years has the company been active with decommissioning and the waste handling of wind turbines? Which role does the company play? E.g. do you take down the turbines using your cranes etc. – Please explain.
Question 8	Is the company usually contracted to take care of the entire turbine or only of parts? If only parts, which? Does it differ from client to client?
Question 9	How many onshore wind turbines has the company decommissioned and handled the waste?
Question 10	How many of which turbine types has your company decommissioned?
Question 11	▪ Does the company handle turbines from one or several OEMs? ▪ Which size of turbines did the company decommission the most, what was the smallest and what was the largest? ▪ Which age had the decommissioned turbines typically? What was the minimum and what was the maximum age? How many were below the design life of 20 years and how many were above 20 years? ▪ In which year(s) did your company decommission turbines the most? How many and which size has your company decommissioned last year? ▪ How many turbines were decommissioned due to a breakdown/complete failure of the turbine?

Secondly, after the kind and quantities of decommissioned turbines is understood, questions focusing on exploring the handling process of the decommissioned turbines and the respective decision rationale are placed in the interview guide. Table 9 displays these questions (Kramer et al., 2024). Question 12 opens this part of the interview guide with an open-designed question. This is to ensure that the experts' understanding can be captured and that new processes of circular supply chains that might not yet be part of the theoretical understanding are identified (see Part A). It also helps the interviewer to put the next question into the familiar context of the expert, as question 13 asks which pathways were taken according to pre-defined pathways (see Appendix A1). The pre-defined pathways reflect the conceptual understanding of Part A by differentiating between different product levels and circular supply chain processes. The product levels (i) whole wind turbine, (ii) key components and (iii) materials of blades are chosen. To ask about every part of a wind turbine and every material would explode the length of the interview and is therefore neglected. To ease the thinking process of the expert, visuals of a wind turbine and the key components are added (see Appendix A1). In the CSCM framework in Part A, circular supply chain processes in accordance to the 9R-principles of Potting et al. (2017) were used but, despite this and as highlighted by Velenturf (2021, pp. 7-9), Kramer & Beauson (2023, p. 8) and Kramer & Schmidt (2023, p. 88), experts could differently define these terms. Additionally, asking for each of these processes could extend the expert's available time for the interview. Therefore, to increase the dependability and confirmability of the results, the circular supply chain processes are aggregated with still clearly linking to the research questions, as outlined in Table 8:

Table 8. Aggregation of circular supply chain processes.

1. Whole turbine level	sold as whole system		not sold as whole system	
2. Key components level	entire component kept by owner	entire component sold	other waste handling	unknown
3. Blade material level	energy recovery / incineration / landfill	material recycling		others

Again, to account for the newly emerging of the research field, in case the expert has difficulties to answer the question, the expert is asked if pathways are missing. Moreover, for the entire turbine and the blades, the fraction of a second lifecycle is split between domestic and export. Question 14 and 15 are further detailing the quantified pathways and ask for explanations of these splits. Question 15 focuses on a potential influencing factor, the age of turbines, that is often stated in existing literature, i.e. researchers see a 20-year lifetime as a threshold for entering the other-waste handling pathway (Andersen et al., 2016, p. 4; Tota-Maharaj & McMahon, 2021, p. 119; Volk et al., 2021, p. 4). Follow-up questions are narrowing the questions' scope to second lifecycle practices and to wind turbines and their blades, to increase the depth of the data collection.

Table 9. Key questions of the interview guide on the company's general handling process, Part 2, based on Kramer et al. (2024).

Question 12	How does the waste handling after decommissioning a wind turbine generally work at your company? Could you please briefly describe it?
Question 13	Referring to the below figure, could you please estimate which paths were chosen for the already decommissioned onshore wind turbines at your company? [Figure]
Question 14	Could you please explain what caused these splits?
Question 15	Does the threshold of the design lifetime, thus the age of 20 years, have an influence on the choice of the decommissioning path? At which age does it become difficult to sell an entire turbine or an entire blade?

Third, key questions about the company's business model that address the organisational level of the CSCM framework (see Figure 14 in chapter 4.2) are formulated, as shown in Table 10 (Kramer et al., 2024). The questions explore organisational aspects, e.g. other business areas and the business model of the company (question 16, 17), and the client's role in the decision-making of handling decommissioned turbines (question 17-19).

Table 10. Key questions of the interview guide on the company's business model, based on Kramer et al. (2024).

Question 16	Are the company or related companies involved in other activities along the end-of-lifecycle or end-of-life supply chain of wind turbines?
Question 17	Does the client sell the turbine/parts to you OR does the ownership stay with the client? Please explain how it usually works.
Question 18	Were the waste handling pathways specified by the client?
Question 19	Did you report back on the taken paths to the client?

Finally, key questions regarding the outlook are formulated and bring the interview to an end, see Table 11 (Kramer et al., 2024). These address future expectations (question 20), the track record from previous employers (question 21), additional comments (question 22), request for sharing a list of projects (question 23) and recommendations for further experts (question 24).

Table 11. Key questions of the interview guide on the outlook, based on Kramer et al. (2024).

Question 20	Referring to the figure of question 13, which development do you expect in the next 10 years in Germany and or Denmark?
Question 21	In case the answer to question 6 was that the person handled decommissioning projects also for other companies: Do you mind if we quickly have a look at your given answers and check if they would look different for the company you were previously employed by?
Question 22	Is there anything else you would like to say?
Question 23	Do you mind sharing which projects your company has decommissioned so far? As mentioned at the beginning of the interview, this would be treated confidentially. If we could identify your projects and the ones from the other interviewees, we would be able to draw conclusions about the market. The drawn overall market insights will be provided to you. If yes, could I perhaps leave a list of projects/turbines and ask you to mark the ones your company has decommissioned?
Question 24	Is there anyone else we should speak to?

All in all, the interview guide consists of 24 questions and is divided into questions related to an introduction (intro), assessing the suitability of the interviewee (filter) and key questions (key). The interview guide is tested beforehand with an industry expert to check if the questions are clear to the expert, as such an understandable language was used (Döring & Bortz, 2016, p. 372). Moreover, the trial helps to assess if the order of questions is suitable and the planned duration is realistic. These learnings are then reflected in the interview guide. For instance, it becomes apparent that the interview guide is quite extensive and it can therefore be difficult to keep the planned time of 45-60 minutes (Gläser & Laudel, 2010, p. 144). This is accepted as it is assumed that the experts could be willing to a maximum duration of 60-120 minutes. Reducing the variety of topics in the interview guide would contradict the subject of research. Instead, it is assumed that the chosen questions enable a lively conversation with the expert and guide the interviewer in the complex and not well explored research subject. To minimise the risk that not every expert is able to participate for more than 60 minutes, the most critical questions for the research are asked early on (Döring & Bortz, 2016, p. 375). The final interview guide with a foreword on the interview's objective, request for recording and information on the data usage is filed in Appendix A1.

Develop a list of potential experts

The choice of interview partners has a significant influence on the kind and quality of collected information (Gläser & Laudel, 2010, p. 117). Gläser & Laudel suggest to conduct interviews with several interview partners and to determine the suitability of each expert. Experts are considered suitable to contribute to the objectives and scope of the study if their employer plays a major role in the decommissioning in Denmark and/or Germany and the handling of the decommissioned wind turbines. For instance, decommissioning companies, operators, service companies, OEMs and recycling companies could be of relevance. Companies are considered to play a major role when having an overview of the taken decisions along the decommissioning and handling process, e.g. when being responsible for the project management. Complementary, the potential expert(s) of each identified company should have completed at least one decommissioning project. Experts must be personally involved with the decommissioning process of the turbines (e.g. as a project manager) or must have access to the historical data of the company's decommissioning activities (e.g. managing director).

For Denmark and Germany, the list of potential experts is gathered through an internet search and industry networks. For instance, the websites of the Danish wind energy association Green Power Denmark, the German decommissioning association RDRWind e.V. and www.wind-turbine.com help to identify potential experts. Moreover, companies and experts listed as authors of the DIN SPEC 4866, a pre-standard on decommissioning wind turbines in Germany, are checked for suitability. After identifying potential companies, a search for the adequate expert is done on the company's website and through the support of other experts and industry associations. To avoid a bias when selecting potential experts and ensuring key stakeholders are not overlooked, experts from industry networks in Denmark and Germany are asked for feedback (Saunders et al., 2019, pp. 296). Furthermore, snowballing during the expert interviews is carried out by asking the interviewees for recommendations of further experts (see question 24 in Table 11) (Gläser & Laudel, 2010, p. 118). A total of 21 experts were identified for the Danish market and 24 experts were identified for the German market, some of whom cover both markets.

Enquire interest and conduct interviews

The experts from the list are contacted via e-mail by introducing the research objective, use of data and the involved partners of the study. To increase the chances of reply and thus reduce a potential participant bias (Saunders et al., 2019, p. 448), potential interviewees are called via telephone (Gläser & Laudel, 2010, pp. 161). Moreover, the setting for the interview is kept relatively flexible since the intention is to increase the likelihood that an expert agrees to schedule an interview (Döring & Bortz, 2016, pp. 375). A meeting with the video conference tool Teams is preferred over a telephone call as the tool enables the recording, automates the transcription and eases the interview process as also non-verbal communication is possible. Nevertheless, if not otherwise possible, also telephone calls are conducted. Moreover, if invited to the company's office, this is preferred, although an automated transcription is not possible. However, it is well acknowledged in qualitative research that personal contact can ease the comfort of the expert and thus his/her depth of given answers (Gläser & Laudel, 2010, pp. 153). Typically, interviews of 60-120 minutes with 10-20 persons are conducted (Döring & Bortz, 2016, p. 373), however, the suitable number of interviews depends on the study's object and the scope of the aimed analysis (Gläser & Laudel, 2010, pp. 104; Saunders et al., 2019, pp. 315). It should be set to support credibility of the findings and avoid inappropriate transferability of collected data (Lincoln & Guba, 1985, p. 292). For this study, a suitable number of interviews is reached when a significant market share (~50 %) of the historical decommissioning in the respective countries is covered by the interviewed experts. A further indication is when additional interviews do not lead to the emergence of new findings for the study's objectives (Saunders et al., 2019, pp. 315). In total, 18 interviews of in total 29 hours are conducted. The intended length is 45-60 minutes and the interviews are either conducted in German, Danish or English. The questionnaire guides the interviewer, but the interviewer can spontaneously skip questions, change the order of the questions or add further questions or themes during the interview to react to the interviewee's answers and the setting of the interview (Döring & Bortz, 2016, p. 372; Gläser & Laudel, 2010, pp. 172). In addition, answers or questions can be repeated to assess that the given answers are understood by the interviewer. Furthermore, following the interview guide also intends to limit a potential interviewer bias as the questions are neutrally formulated (Saunders et al., 2019, pp. 447). Also, an eventually appearing interviewee bias is addressed with the chosen type of questions and its order. It cannot be guaranteed that each expert shares all his/her observations (e.g. due to confidentiality reasons) with the interviewer. This risk is limited through the general research approach of asking qualitative and quantitative questions to multiple stakeholders, but still considered when analysing the data.

When allowed, the interviews are recorded and automatically transcribed. If not allowed or not possible out of organisational reasons (e.g. personal meeting or telephone call), a memo is prepared. The transcript or memo is checked for completeness after the interview, if available supported by the video recording (see Appendix E). Moreover, the transcripts and memos are anonymized by deleting personal information and the transcripts are prepared according to general transcription rules (Dresing & Pehl, 2018, pp. 20). For instance, stuttering is smoothed out or omitted; half sentences that are not completed are marked with a "/" and words signalling active listening (e.g. “hmm”, “yes”) are not transcribed.

5.1.2 Quantitative data analysis to derive second lifecycle fraction

The quantitative data analysis foresees to answer RQ3 “*Which paths are taken for onshore wind turbines and their blades after decommissioning in Denmark and Germany? Is a second lifecycle common or not?*”. Therefore, the analysis aims to quantify the circular economy pathways taken by the decommissioned onshore wind turbines in Denmark and Germany by analysing the conducted interviews. As outlined in 5.1.1, the pathways are distinguished between (i) second lifecycle of the entire turbine, (ii) second lifecycle of the blades as spare parts, and (iii) other-waste handling.

To assess whether a second lifecycle was common in the countries under investigation, the pathways taken per interview are to be aggregated to a country level. It is further distinguished between a second lifecycle taking place domestically or abroad. The method is presented and applied for each market in Kramer et al. (2024) and is briefly described as follows. To begin with, as different stakeholders are interviewed, the risk of double-counting needs to be addressed. Hence, OEMs, service companies, project developers and operators that hired a decommissioning company for turnkey projects are excluded from the aggregation, when the contracted decommissioning companies were also interviewed or when it is unknown. The shares of pathways taken per interviewee in relation to the number of their handled turbines are aggregated per country level. Hence, the reported fractions of interviewees with a large number of handled turbines impact the country’s fractions more heavily than an interviewee who only handled a minor number of turbines in the respective country. The results per interviewee and the average fraction are visualised with a scatter chart to ensure that the sensitivity of the average fraction to expert’s responses is visible. In this light, as the weight of each interview to the average fraction depends on the interview’s market share and to warrant anonymity of the experts at the same time, three clusters are formed: companies with a market share (i) smaller than 1 %, (ii) 1-10 % and (iii) above 10 %. Moreover, to visualise the fraction of turbines and blades entering a second lifecycle abroad, a Sankey diagram is used. This visualisation method is commonly used for component and material flows and is suitable to make the most prominent pathways easily identifiable (Brunner & Rechberger, 2004, p. 64).

Moreover, to grasp whether a second lifecycle was common among the various stakeholder groups and whether there are differences between the stakeholders, the pathways taken by the individual stakeholder groups are determined. In this case, no interview is disregarded for calculating the aggregate per stakeholder group. The aim is not to determine representative figures for each stakeholder group – as no information is available on the total number of turbines per stakeholder group – but rather to identify initial indicative patterns that are then further assessed throughout the qualitative analysis (see 5.1.3). Four stakeholder groups are defined according to the core business of each company that is represented in the interviews: (i) recycler & dismantler, (ii) decommissioning company wind turbines, (iii) project developer & operator or service company, and (iv) OEM. The average distribution of the circular economy pathways per stakeholder group is calculated by weighting each expert's response of the respective stakeholder group according to the handled number of turbines. The results are also visualised with a scatter plot, but without disclosing the market shares, as otherwise the anonymity of the interviews cannot be guaranteed.

Beyond that the data collection is set-up to ensure the trustworthiness of the research (see 5.1.1), the results of the quantitative data analysis are to be evaluated. To ensure the internal validity of the quantified pathways per country, the data collection foresees to cover a significant share of each market and moreover, the participants of the study are asked for feedback on the collected data about their pathways taken. In addition, a sensitivity analysis is carried out to assess what impact variations in the share of pathways taken by companies that were not part of the interviews would have on the aggregated shares (Lincoln & Guba, 1985, p. 290). For instance, in order to quantify the potential maximum and minimum of the aggregated reuse fraction being exported in Denmark and Germany, it is assumed that the turbines not covered in the interviews would all enter a second lifecycle or all the other-waste handling pathway. With this, the effect of a potential selection and participant bias is quantified. The external validity of the quantitative results is addressed by the research design of two cases (Denmark and Germany), which enables an evaluation of a potential transferability of the results. Moreover, findings from other sources and studies about other countries and industries are discussed in this regard. To ensure that reliable results were generated, the data collection and data analysis process is stepwise documented and is audited in the review process for publishing the journal article from Kramer et al. (2024). Additionally, the research design of exploring two countries, covering a significant market share of each country, having a multi-stakeholder perspective, and also conducting a qualitative analysis contributes to safeguarding that reliable and objective results are found.

5.1.3 Qualitative data analysis to explore second lifecycle pathways

To identify factors that influence the development of second lifecycle supply chains for onshore wind turbines from Denmark and Germany (RQ4) a qualitative analysis of the conducted interviews is carried out. As reasoned in chapter 3, the qualitative content analysis method according to Mayring (2022) is used. In line with the qualitative nature of RQ4, the analysis technique is inductive category formation (Mayring, 2014, pp. 79, 2022, pp. 84). In contrast to a deductive approach, it ensures that aspects that are not yet existing in theory can still be identified in the interviews. Hence, it opens up the possibility of comparing the theoretical understanding of Part A with the practical explorations from the interviews. Key element of the method is a process model that enables a structured and dependable way of carrying out the analysis. Figure 22 illustrates the process model with seven process steps.

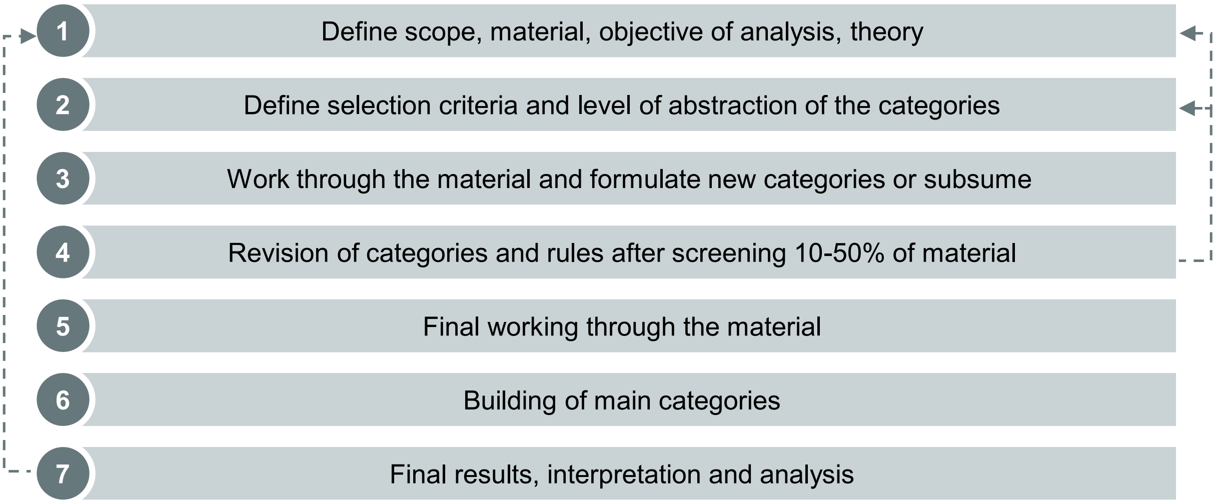


Figure 22. Process model of inductive category development. Method based on Mayring (2022, p. 85).

Define scope, material, objective of analysis, theory

The first step is to define the scope, material, objective of analysis and link to theory (Mayring, 2022, pp. 85). As evolved in Part A, in principle several circular economy pathways (see Figure 17) could be taken by a wind turbine and its blades after its initial use phase. In this context, the development of second lifecycle supply chains is influenced by several factors of different levels, i.e. market and regulation, organisation, product and processes (see Figure 14) that occur at various points along the value chain (see Figure 20). Complementing the findings from the quantitative analysis (see chapter 5.1.2), the qualitative analysis focuses on second lifecycle pathways and aims to investigate which supply chain processes exist in practice and which factors influence the development of second lifecycle supply chains. Accordingly, the analysis is twofold. First, the circular supply chain processes are identified, which enables a comparison between the theoretical understanding and the observations from practice. Secondly, factors that influence the decision to enter a second lifecycle pathway are identified, which allows to answer RQ4.

The materials for analysis are transcripts and memos of the conducted interviews that followed a semi-structured approach with a link to the literature-based conceptual understanding in Part A (as described in chapter 5.1.1). In principle, all the conducted interviews can be used for the analysis and do not need to be filtered out. The analysis of the interviews is carried out per country, first Denmark, then Germany and finally interviews that address both countries. The interviews are analysed by stakeholder group and to acknowledge that transcripts are most suitable for a qualitative content analysis, these are analysed prior to the memo-based interviews (Gläser & Laudel, 2010, pp. 192).

Define selection criteria and level of abstraction of the categories

The second step of the process model is to define the selection criteria of text passages and formulate the abstraction level of the categories (Mayring, 2014, p. 80, 2022, p. 86). Text passages are selected that address second lifecycle processes of decommissioned onshore wind turbines and their blades as well as factors influencing this pathway taken. To grasp the interlinkages of circular supply chain processes, also text passages about the decommissioning of wind turbines and the general handling of decommissioned turbines and their key components (e.g. also passages on pathways of other-waste handling processes) are extracted. Passages with embellishing or incidental stories are disregarded. For instance, the answer "*In the beginning, most of the turbines went to Eastern Europe. But in the last ten years, Italy and Ireland have nearly taken everything*" (I2) is extracted as it is about the export of decommissioned turbines in their entirety for a second lifecycle. Another example is that Q1 asked "*Should I explain the question or?*" and I2 responded "*Yes, yes.*"; here the entire text is not selected as it is outside the selection frame.

As described in the first step of the process model, categories in this study are circular supply chain processes and factors influencing the decision-making. As a variety of questions are addressed to multiple experts (see chapter 5.1.1), the experts can talk about the decision-making at different levels in CSCM and along different circular supply chain processes. Depending on what is addressed, different levels of detail are considered for the development of categories, i.e. formulation of circular supply chain processes and influencing factors. For aspects that belong to the core of the analysis objective, categories are developed with a higher level of detail than for aspects outside this. The examples in Table 12 further illustrate the approach.

Table 12. Examples of inductive category development.

Text passage	**Circular supply chain processes category**
"In the beginning, most of the turbines went to Eastern Europe. But in the last ten years, Italy and Ireland have nearly taken everything." (I2)	Export decommissioned turbine
"Also Fundamententfernung, Kabelentfernung usw." (I11)	Remove foundation and restore land
"we are also doing a recycling of primarily the concrete coming out of foundations. (…)" (I9)	Recycling of other components materials
Text passage	**Category for influencing factor**
"*(…) it was in this repowering program. But you could transfer the power to a new one so. (…)*" (I2)	Repowering bonus
"*(…) die Anlage wird zu dem Zeitpunkt gerade irgendwie gefragt auf dem Markt, hat man da natürlich Glück (…)*" (I11)	Availability of a buyer at the time of decommissioning
"*(…) it is more about finding the spare parts*" (I6)	Availability of spare parts for operating second lifecycle turbine

Work through the material and formulate new categories or subsume

The third step foresees to work through the material line by line, to formulate new categories or to subsume to already developed categories (Mayring, 2014, p. 81). Building on the examples of Table 12, the following text passage contains two new categories: "*But actually we do buy wind farms and then decommission and inspect if we can refurbish for a second life (…)*" (I15). This cannot be subsumed to the derived circular supply chain processes categories, but instead would form the new categories "*refurbish turbine*" and "*inspection of turbine*". In contrast, the text passage "*(…) and then depending on what the customer wants, we do take out foundations, piles, in case required windfarm cabling, crane stands and bring back to the original status (…)*" (I15) can be subsumed to the category "*Remove foundation and restore land*".

Revision of categories and rules after screening 10-50 % of material

Then, the fourth step, is to revise the category system after ~10-50 % of the material is screened (Mayring, 2014, p. 81) that could lead to restart the process with step 1 or 2 (refer to Figure 22). In this study, a revision takes place after screening the first two interviews and thereafter, whenever a new stakeholder is added as well as when all interviews of Denmark are screened.

Final working through the material

This leads to a final category system that is used to conduct a final screening of the material in the fifth step of the process model (Mayring, 2014, p. 81). Hence, after this step, the circular supply chain processes, particularly of second lifecycle supply chains, and the factors influencing the development of such supply chains are identified. The steps 1-5 are first processed for the inductive category development of the circular supply chain processes and then carried out for the influencing factors. This makes it possible to take the derived circular supply chain processes into account when identifying the influencing factors. Consequently, the factors that influence the occurrence of a second lifecycle can be located at the respective point in the process chain. For instance, the factor "*repowering bonus*" promotes the decision to decommission a wind turbine. Another example is that "*the availability of a buyer at the time of decommissioning*" influences the choice of the to-be-taken pathway for the decommissioned turbine.

Building main categories

Moreover, to further ease the interpretation and analysis of the identified influencing factors, main categories are built, as illustrated with the sixth step in Figure 22 (Mayring, 2022, p. 89). In this study the main categories (i) technical, (ii) legal/regulatory, (iii) economical, (iv) market and (v) organisational are applied. This is in line with the developed CSCM wind framework (Part A) and the following studies that use similar categories: Beauson et al. (2022, p. 3) differentiate between economic, technical feasibility, legislation and environmental impacts for characterising the decision points along the end-of-life value chain for wind turbine blades. De Laurentis et al. (2024, p. 8) associate influencing factors on the decision to decommission a wind turbine in Italy to one of the following categories: (i) design lifetime and technical issues, (ii) economic and financial, (iii) legislative and regulatory and (iv) business environment. The exemplary factor from above, the "*repowering bonus*", is linked to the decision to decommission the turbine and belongs to the main category "*economics*".

Final results, interpretation and analysis

The final category systems and the main categories are shown in the results chapter (see 5.2.3). The derived categories are interpreted and analysed in regard to the question of analysis, thus looping back to step 1 of the process model (Mayring, 2022, pp. 85). First, the final category system of the circular supply chain processes that bases on all interviews is visualised with a process chart and described. Additionally, the similarities and differences across countries and between stakeholder groups are analysed and interpreted (see 5.2.3.1). Secondly, the influencing factors and the associated main categories for the decision-making of the handling of decommissioned wind turbines are described and interpreted (see 5.2.3.2). It is analysed which of the key influencing factors are associated to which process or multiple processes of the drawn circular supply chain process model and which interlinkages between them exist.

Evaluation

It should be noted that not all existing processes or influencing factors are necessarily found in every interview or in the entirety of the interviews, as this data may not be collected. Reasons could be that the questioner does not specifically ask about the aspect or a different focus is set in the interview, also since multiple stakeholders are interviewed. Moreover, it could occur that the expert does not raise it either, e.g. due to not being aware, being out of scope or not wanting to address it. The nature of the research object is the exploration of a complex system with the objective not to identify every detail, but rather to contribute to the understanding of the overall system.

To support the inquiry process, the inquirer keeps a protocol while carrying out each step of the process model (Saunders et al., 2019, pp. 450). According to Saunders et al. a protocol helps to regular challenge the inquirer's thinking process and thus contributes to credible and dependable findings, as well as an increase of objectivity. Moreover, participants are asked for feedback when core interview statements appear to be not clearly understood. To add to that, triangulating the findings across the interviews – thanks to the research design of interviewing multiple stakeholders and covering two countries – as well as with the quantitative analysis and assessing further sources contributes to revealing trustworthy findings. This is particularly important for contradicting findings across the interviews. The transferability to other regions is addressed by the research design, as two countries are chosen.

5.2 Results

This chapter presents the results of the methodology applied to the onshore wind market in Denmark and Germany. First, the 18 semi-structured interviews are described (5.2.1), followed by presenting the results of the quantitative analysis (5.2.2) and qualitative analysis (5.2.3).

5.2.1 Description of conducted interviews

In total, 18 interviews are conducted with 23 experts between 21/09/2023-26/02/2024. The experts represent 19 companies that addressed the historical decommissioning and handling of the decommissioned onshore wind turbines and their blades in Denmark and Germany. The interviews I1-I16 are used in Kramer et al. (2024). Thanks to further responses, two additional interviews (I17-I18) took place and I14 provided additional information on Denmark. In nine interviews also, another researcher participated. 13 of the interviews are held with a video conference tool, four by telephone and two as an in-person meeting.[1] The meetings lasted an average of 90 minutes with a range of 40-120 minutes, with the exception of four outliers lasting 15 minutes, 20 minutes and twice four hours. The in-person meetings were longer than the telephone calls and video conferences as it also involved a visit of the facilities. Two telephone calls lasted only 15-20 minutes and as such not the entire interview guide was addressed. In such cases, the focus was put on identifying the number of handled turbines, taken pathways of the decommissioned wind turbines and the role of the expert and company. 12 interviews are recorded and transcribed and the remainder is documented with a memo. Figure 23 shows the distribution of the conducted interviews by covered country, stakeholder group and the experts' position.

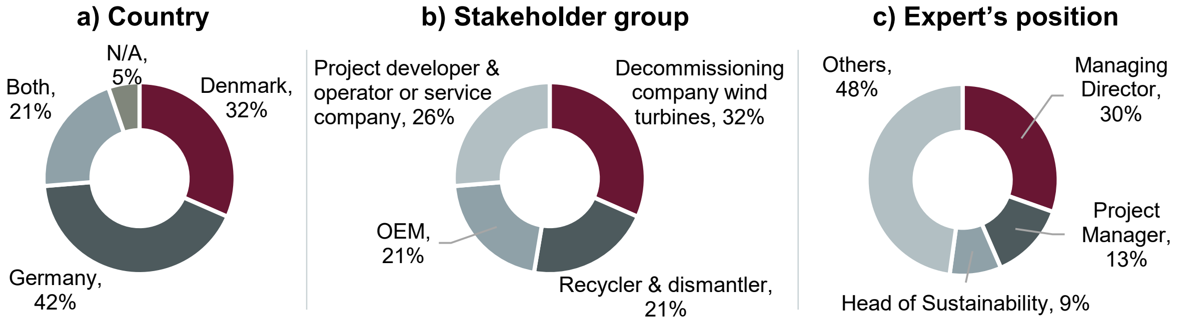


Figure 23. Distribution of conducted interviews by country, stakeholder group and expert's position.

---

[1] One interview was split in two meetings, a video conference and a meeting in person.

The graph shows that 31.6 % of the interviews address the Danish, 42.1 % the German and 21.05 % both markets, represented by multiple stakeholders. The remainder (5.25 %) is an OEM that is active in both markets, however not with decommissioning or handling of decommissioned turbines and as such is labelled as “N/A”. 31.6 % of the interviews are conducted with companies that have their (or their parent company’s) core business in decommissioning wind turbines. 21.05 % of the interviews are represented by companies that offer recycling and dismantling and as such offer the decommissioning and handling of wind turbines as part of their business. And finally, 21.05 % of the interviews represent OEMs and 26.3 % are either project developers and operators or service companies. The expert’s position varies across the interviews with the majority of experts being a Managing Director (30.4 %), Project Manager (13.0 %) or Head of Sustainability (8.7 %). The following gives a brief description of each conducted expert interview (also see Table 38 in Appendix A2):

- Interviewee 1 (I1) works in Senior Management[2] of a Danish recycling, dismantling and demolition company (Company A) that offers amongst others the decommissioning of wind turbines and material handling. They cover approx. 19-22 % of the 3,195 decommissioned turbines in Denmark (DEA, 2022).
- Interviewee 2 (I2) is an Executive of a decommissioning company for wind turbines (Company B). The expert has decommissioned and handled ~25 % of the total decommissioned turbines in Denmark.
- Interviewee 3 (I3) is an Executive of a company operating an own wind turbine fleet (Company C). The company was involved in less than 1 % of the total decommissioning in Denmark and has hired decommissioning companies to carry out the job. In addition, the company is active in project development of new wind energy projects.
- Interviewee 4 (I4) is an Executive of a decommissioning company for wind turbines (Company D) that has handled ~16 % of the decommissioned turbines in Denmark and ~11 % of the 4,500 decommissioned turbines in Germany (Deutsche WindGuard, 2023).
- Interviewee 5 (I5) is in Senior Management of an OEM (Company E) that has been involved in ~2 % of the Danish decommissioning market and a neglectable share in the German market.
- Interviewee 6 (I6) is an Executive of a decommissioning company for wind turbines (Company F) that has handled ~3 % of the decommissioned turbines in Denmark.
- Interviewee 7 (I7) is an Executive of a company that develops, operates and decommissions wind turbines (Company G) and has handled ~2-3 % of Denmark’s total decommissioning.
- The eights interview is conducted with the Senior Managers Interviewee 8A (I8-A), Interviewee 8B (I8-B), Interviewee 8C (I8-C) and Interviewee 8D (I8-D) of an OEM

---

[2] To ensure anonymity of the experts, the positions were clustered to Executive, Senior Manager and Mid Manager.

(Company H). They are involved with the handling of < 1 % of Denmark's market and ~3 % from the German market.

- Interviewee 9 (I9) is in Senior Management of a recycling and dismantling company (Company I). The company is responsible for handling less than 1 % of the total decommissioning in Denmark.
- Interviewee 10 (I10) is an Executive for decommissioning wind turbines in a company associated to the stakeholder group recycler & dismantler (Company K) as it also offers the planning, realisation and operation of waste-handling equipment. Prior to that, I10 has decommissioned and handled turbines also for a service company, Company J. In total, I10's track record represents ~9 % of the total decommissioning in Germany.
- Interviewee 11 (I11) is a Senior Manager in a service company (Company L) that handled ~3-4 % of the historical decommissioning in Germany.
- Interviewee 12 (I12) is an Executive of a decommissioning company for wind turbines (Company M) that represents ~3 % of Germany's decommissioned wind turbines.
- Interviewee 13 (I13) is an Executive of a recycling and dismantling company for industrial facilities (Company N) that historically handled a marginal number of decommissioning projects of wind turbines (<1 % of Germany's market).
- Interviewee 14 (I14) is a Senior Manager of a decommissioning company for wind turbines (Company O), which has handled ~22 % of the decommissioned wind turbines in Germany.
- Interviewee 15 (I15) is an Executive of a decommissioning company for wind turbines (Company P) that decommissioned ~1-2 % of Denmark's market and less than 1 % in Germany. However, the company has handled a significant number of turbines in other countries.
- The sixteenth interview is conducted with Interviewee 16-A (I16-A), Interviewee 16-B (I16-B) and Interviewee 16-C (I16-C), who are Senior Managers at an OEM (Company Q). The company has been involved with the handling of ~12 % of the historical decommissioning in Germany.
- Interviewee 17 (I17) is working in Mid Management of an OEM (Company R). The company has not been actively involved in the decommissioning of wind turbines in Germany or Denmark. However, the expert does provide insights into the company's activities related to the handling of decommissioned turbines or components (e.g. refurbishment).
- Interviewee 18 (I18) is an Executive of a service company for wind turbines (Company S) that was involved in ~1 % of the decommissioned turbines in Germany. Additionally, the company is active in the development of new wind energy projects.

As most interviewees have not filed their history sufficiently in a data system or have not got the resources to prepare a comprehensive list of their decommissioned projects, a comparison of the sample to the market developments is only to a limited extend possible (see 6.2.1). For Denmark, the interviewed experts cover the entire historical time period of decommissioning. Moreover, they mostly decommissioned wind turbines of up to 1 MW and of an average age between 18-30 years; hence in line with the overall market developments (see Figure 64 in 6.2.1). For Germany, the experts represent the last 12-14 years of history and as such not the entire history of decommissioning since 2000 (see Figure 64 and 6.2.1). However, the years not covered by the interviews only had marginal annual decommissioning according to Deutsche WindGuard (2023, p. 4). The decommissioned turbines of the interviewees have an average of 15-20 years and range between 55 kW and 3 MW of installed capacity. Moreover, it is possible to check whether a significant market share was covered through the interviews. In total, around 5,130-5,430 decommissioned turbines were covered through the interviews. The four companies associated to the “Recycler & dismantler” stakeholder group addressed ~730-840 turbines, the six companies of the group “Decommissioning company wind turbines” ~3,110 turbines, “Project developer & operator or service company” stakeholder group with five companies addressed ~570-660 turbines and the four OEMs covered ~720-820 turbines. The market shares of the interviewees vary between less than 1 % to ~25 % for Denmark and less than 1 % to ~22 % for Germany. It should be noted that the stakeholders cover different processes of the value chain and some subcontract for decommissioning and handling, leading to the risk of double counting when calculating the overall market coverage (Kramer et al., 2024). Hence, not every interview is considered and as such I3, I5, I8, I16, I17 and I18 are excluded for the calculation. The remaining 13 companies, result to a coverage of 2100-2200 decommissioned turbines for Denmark and 2,200-2,300 for Germany. Thus, ~66-70 % of the in total decommissioned turbines of 3,195 in Denmark and ~49-51 % of the ~4,500 turbines in Germany were covered. Hence, a significant share of each market is covered by the interviews and consequently the criterium for ending the data collection process is fulfilled (see 5.1.1).

5.2.2 Quantification of second lifecycle pathways

To answer RQ3, this chapter presents the results of the quantitative analysis on circular economy pathways taken by the decommissioned onshore wind turbines in Denmark and Germany. Some results have been published in Kramer et al. (2024), but the data analysis herein is updated with the further collected data (see 5.2.1) and extended by further analyses, e.g. regarding the stakeholder groups (see 5.1.2). Kramer et al. note that the majority of the Danish experts submitted feedback on their quantified pathways, and that all experts from Germany provided feedback. First, the results on country level and of the aggregate of both countries are presented, followed by the results per stakeholder group.

As outlined in 5.2.1, 13 companies are considered for the calculation of the aggregated country fractions of the taken circular economy pathways, that represent a significant market coverage in each country. Figure 24 shows the results for both countries, aggregated and for each country.

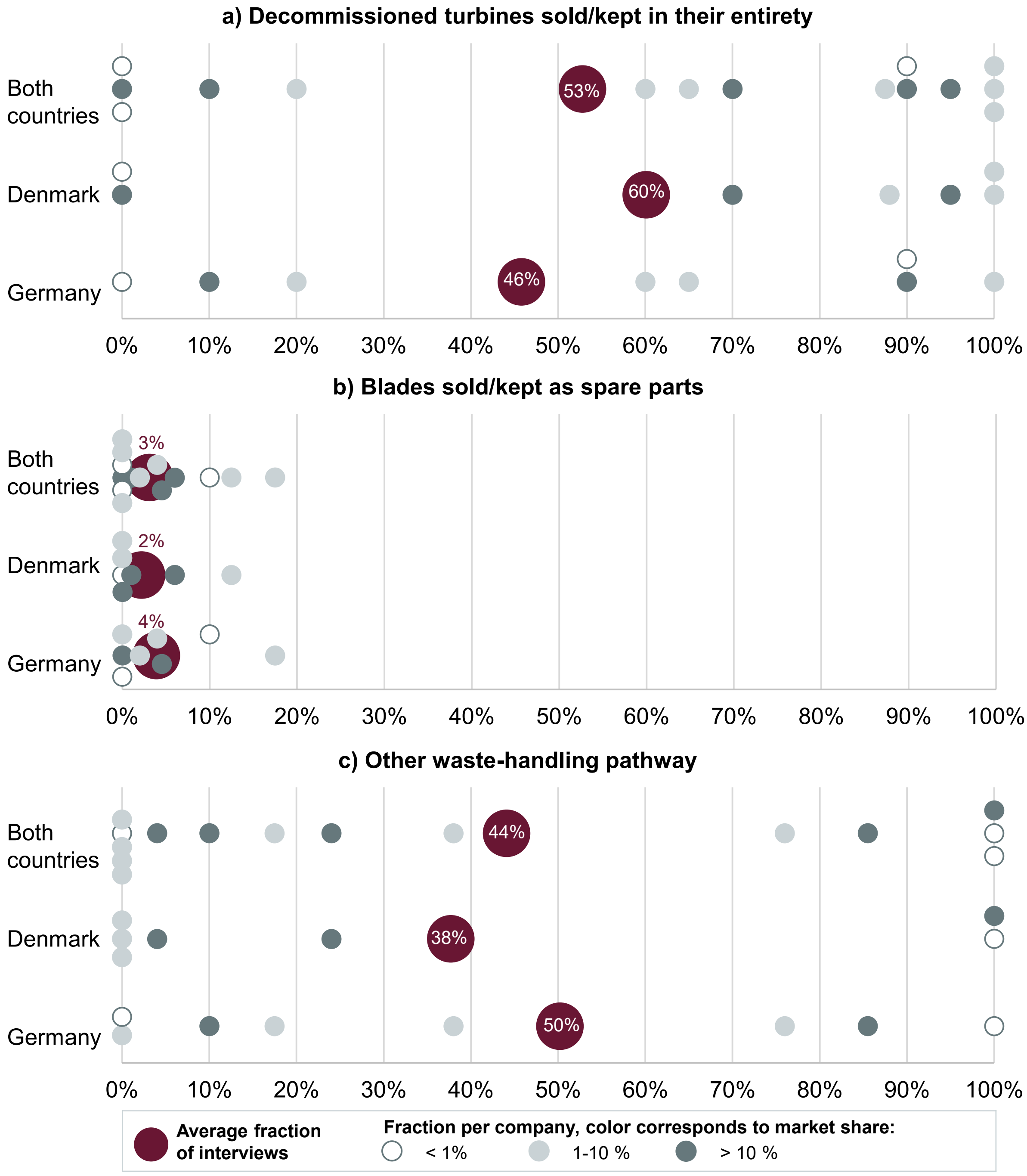


Figure 24. Fraction of decommissioned turbine blades by a) turbine sold/kept in its entirety, b) sold/kept as spare parts, or c) other waste-handling per country. Based on conducted interviews.

Along the circular economy pathways, a) second lifecycle of entire turbine, b) second lifecycle of blade as spare part and c) other-waste handling of composites, it becomes visible for both countries that the majority of decommissioned turbines entered the first stated pathway (~52.8 %), followed by the other-waste handling pathway (~44.1 %) and only a minor fraction of blades being sold/kept as spare parts (~3.1 %).

First, referring to a) in Figure 24, a second lifecycle of the decommissioned turbines has been significant in both countries, but occurred more often in Denmark (~60.1 %)

than in Germany (~45.8 %). Responses range from 0 % to 100 % in both countries. For Denmark, the ones influencing the average fraction (red point) the most, due to their significant market shares (dark grey points), had a reuse fraction for entire turbines of 0 %, ~70 % and ~95 %. In Germany, two companies have a market share of more than 10 % (dark grey points), one stating ~10 % and one ~90 %. Overall, it is visible that two thirds of the data points are between ~60-100 % and one third between ~0-20 %.

Second, a second lifecycle of blades as spare parts is the least followed pathway of the decommissioned turbines in Denmark (~2.2 %) and Germany (~3.9 %), accounting to ~3.1 % aggregated for both countries (see b) in Figure 24). Hence, Germany has a slightly larger share than Denmark, but the data points for Germany have also a slightly larger spread with ranging between ~0-17.5 %, in contrast to Denmark which ranges between ~0-12.5 %. In total, the data points that represent the interviewed companies with the most significant market shares vary between ~0-6 %. For the companies that have not sold all wind turbines in its entirety or sent everything into the other-waste handling pathway, the split between b) and c) vary from 5-100 % being sold or kept as spare parts and consequently 0-95 % entering the other-waste handling pathway. The experts that covered a market share of above 10 %, sold or kept 5-20 % of the blades as spare parts and hence sent 80-95 % to other-waste handling. To add to this, I11 quotes that a common rule of thumb is to keep 1-2 sets of blades per blade type as spare part.

Third, as illustrated in c) of Figure 24, the other-waste handling pathway was taken by approximately ~50.2 % of Germany’s decommissioned turbine blades and hence more frequently than in Denmark, which indicates a fraction of ~37.7 %. Aggregated across both countries, ~44.1 % of the turbine blades entered this pathway with data points ranging from 0 % to 100 %. The companies with the largest market shares have reported different fractions of their decommissioned turbines. The three Danish companies with the largest market shares have indicated that ~4 %, ~24 % and ~100 % of their business entered the other-waste handling pathway. In Germany, the fractions are ~10 % and ~85.5 %. Overall, it is visible that two-thirds of the data points vary between ~0-38 % and one-third to ~76-100 %.

The focus is on blades, nevertheless, depending on the available time of the interviewed person, the experts were also asked if they b) sold or kept other components as spare parts or if they were sent into c) other-waste handling (see question 13 of the interview guide, Appendix A1). Two experts always sold the entire turbine and moreover two have sent every component into the other-waste handling pathway. Six experts provided an answer, who represent roughly 60 % of the total number of turbines covered in the interviews. All of these experts reported that the tower normally went to other-waste handling. Some experts stated that they sold the entire nacelle (in particular from small turbines) and if not, then the nacelle cover normally went into the other-waste handling pathway. Useful components (or parts) inside the nacelle like the gearbox and generator were stated by several experts to be used as spare parts. For reusing the gearbox and the generator, four experts stated a reuse fraction of 50 % to up to 100 % for the turbines that were not sold/kept in its entirety. To add to this, one expert reported 10 % and one did not quantify it for the gearbox, but stated that the generator was normally scrapped. For the hub, it was reported that this is normally not demanded and would be scrapped, but sometimes being sold together with the blades or the entire nacelle.

As already stated, the interviews cover a significant part of both markets, but not the entirety. Hence, an analysis is conducted to assess the sensitivity of the quantified pathways per country. Accordingly, it is analysed what would happen if the number of turbines not included in the interviews do not correspond to the average. It is assumed that those decommissioned onshore wind turbines would all enter only one of the pathways. The derived fractions would range as displayed in Table 13. The following reading example (bold-marked cells) provides further guidance: For Denmark roughly 1,000 of the 3,195 decommissioned onshore wind turbines (~32 %) were not covered by the interviews. If those would have all entered the pathway of a) turbine sold/kept in its entirety, then the fraction for Denmark would equal to ~72.8 % turbines sold/kept in its entirety, ~1.5 % blades sold/kept as spare parts and ~25.7 % other-waste handling. The sensitivity analysis shows that the German fractions are more sensitive than the Danish fractions, as for Denmark a higher share of the market is covered by the interviews. For instance, for Denmark the fraction of entire turbines to be sold/kept would vary from 41.0 % to 72.8 % and in Germany from 23.0 % to 72.8 %.

Table 13. Sensitivity analysis on pathways taken by turbines not covered in the interviews. The bold-marked cells are the reading example.

		How would the quantified paths differ if the turbines in Denmark and Germany that were not included in the surveys had all taken one of the following paths?		
Denmark	**Average fraction**	**a) Turbine sold/kept in its entirety**	**b) Blades sold/kept as spare parts**	**c) Other-waste handling**
a) Turbines sold/kept in their entirety	60.1 %	72.8 %	41.0 %	41.0 %
b) Blades sold/kept as spare parts	2.2 %	1.5 %	33.3 %	1.5 %
c) Other-waste handling	37.7 %	25.7 %	25.7 %	57.5 %
Germany				
a) Turbines sold/kept in their entirety	45.8 %	72.8 %	23.0 %	23.0 %
b) Blades sold/kept as spare parts	4.0 %	2.0 %	51.8 %	2.0 %
c) Other-waste handling	50.2 %	25.2 %	25.2 %	75.0 %

Furthermore, to illustrate whether turbines and their blades were exported or remained in the country, Figure 25 sows the split of the taken pathways of the decommissioned turbines in Denmark and Germany.

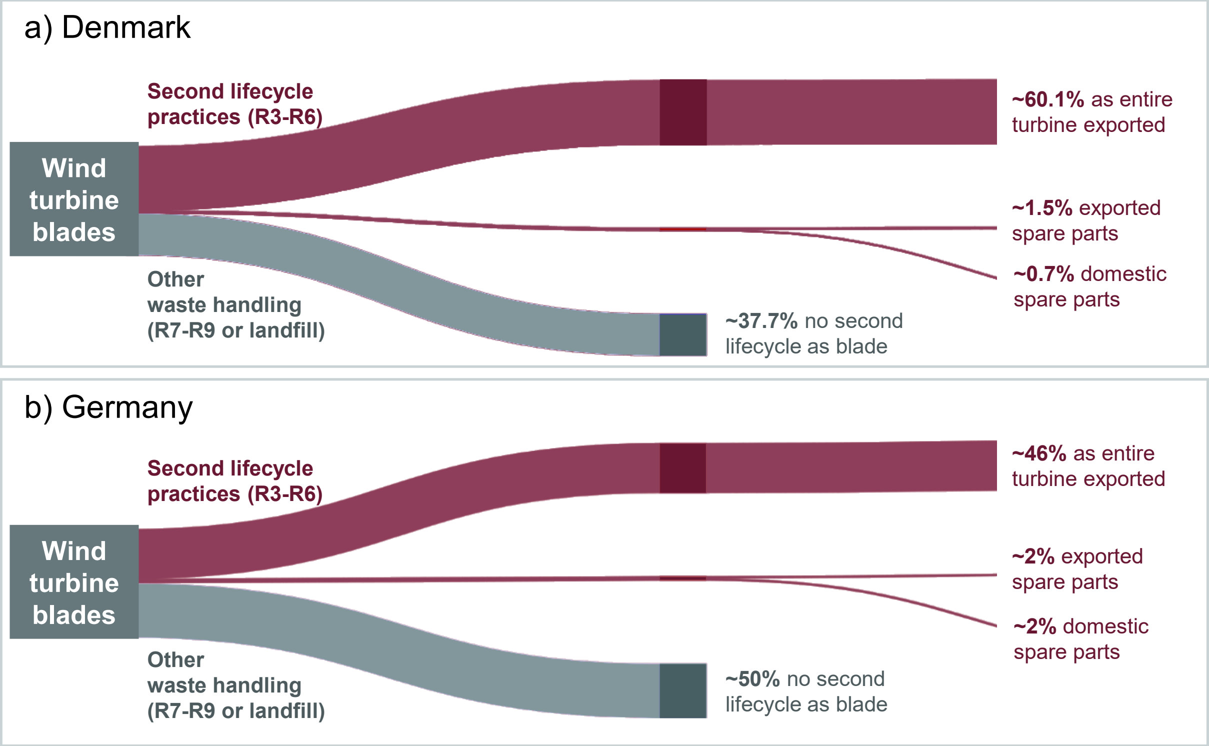


Figure 25. Pathways of blades from decommissioned onshore wind turbines in Denmark and Germany, based on conducted interviews and Kramer et al. (2024). Graphs prepared with www.sankeyart.com.

In Denmark, ~61.6 % of the decommissioned onshore wind turbine blades have been exported, ~60.1 % as entire turbine and ~1.5 % as spare part. Entire turbines did not remain in the domestic markets and were always exported and blades entering a second lifecycle as spare parts (~2.2 %) stayed in ~0.7 % of the overall cases in Denmark. Most experts that have exported decommissioned wind turbines, stated that they exported roughly 90-97 % to European countries (preliminary within the EU). In comparison to Denmark, in Germany a slightly lower fraction of turbines and blades was exported (~48 %), also mostly to European countries. Similar to Denmark, the majority was exported as entire turbine (~46 %) and a minor share as spare parts (~2 %). Moreover, if entire turbines were sold or kept, then these were always exported and in the case of spare parts only in half of the cases exported. When assuming that the decommissioned onshore wind turbines that have not been covered by the interviews, would all be exported in its entirety or all remain in the domestic country for other-waste handling, the fraction for a second lifecycle abroad would range for Denmark between ~42-74 % and for Germany between ~24-74 %. The spread for Germany is larger as the market coverage through the interviews is smaller than in Denmark, nevertheless for both markets it is above 50 % (see 5.2.1).

Moreover, Figure 26 shows the taken pathways quantified for the different stakeholder groups.

Figure 26. Fraction of decommissioned turbines being a) sold/kept in its entirety, b) sold/kept as spare parts, and entering c) the other waste-handling pathway per stakeholder group. Based on conducted interviews.

The visualisation is only used to see whether companies that belong to the same stakeholder group in this sample tend to make similar decisions on the paths, but not to generalise stakeholder groups. It can be noted that variations between the stakeholder groups become visible. Most prominent is that the stakeholder group “Recycler & dismantler” reported only a minor fraction entering a second lifecycle and the majority (~96.5 %) entering the other-waste handling pathway, which is in contrast to the other stakeholder groups. However, it should be noted that two of the experts have only handled a minor number of turbines to date. Also, for the stakeholder group “OEM” only two experts reported data points and the other two experts did not know the fraction of the pathways taken. Moreover, Figure 26 shows that for the group “Decommissioning company wind turbines” and “Project developer & operator or service company” that the spread of the stated fractions is narrower in comparison to the total figure, but with a single outlier each (see Figure 24). For instance, the answers of the group “Decommissioning company wind turbines” range between ~80-100 % and in addition with a data point at ~10 % for decommissioned turbines being sold/kept. Moreover, it can be seen that the group “Project developer & operator or service company” have a slightly higher share of second-lifecycle spare parts than the other stakeholder groups.

In summary, RQ3 can be answered as the study’s findings show for both countries that a second lifecycle of turbines was common abroad (~53 %), mostly in European countries. A second lifecycle of blades as spare parts was not that common (~3 %) and hence those then normally went to other-waste handling. In total, ~62 % of the turbine blades from Denmark entered a second lifecycle abroad and for Germany it was in the order of magnitude of ~48 %. In absolute numbers, ~1,921 decommissioned onshore wind turbines from Denmark and ~2,062 turbines from Germany were sold in its entirety, when assuming the average fractions of the countries (see Figure 24). Components of the remaining ~1,274 turbines in Denmark and ~2,438 turbines in Germany either entered the pathway of a second lifecycle as spare parts or the other-waste handling pathway. For blades, ~70 sets of blades from Denmark’s decommissioned wind turbines were kept/sold and ~1,204 went into other-waste handling. For Germany those figures equal to ~177 sets of blades as spare parts and ~2,261 sets sent into other-waste handling.

5.2.3 Exploration of second lifecycle pathways

To answer RQ4, this chapter presents the results of the qualitative analysis and hence explores the supply chain processes (5.2.3.1) and influencing factors regarding the handling of decommissioned wind turbines (5.2.3.2) in Denmark and Germany. The results are detailed per country and stakeholder group.

5.2.3.1 Circular supply chain processes in practice

The circular supply chain processes were inductively derived by analysing the conducted expert interviews. The final model of the observed circular supply chain processes is illustrated in Figure 27 (larger format in Appendix B1).

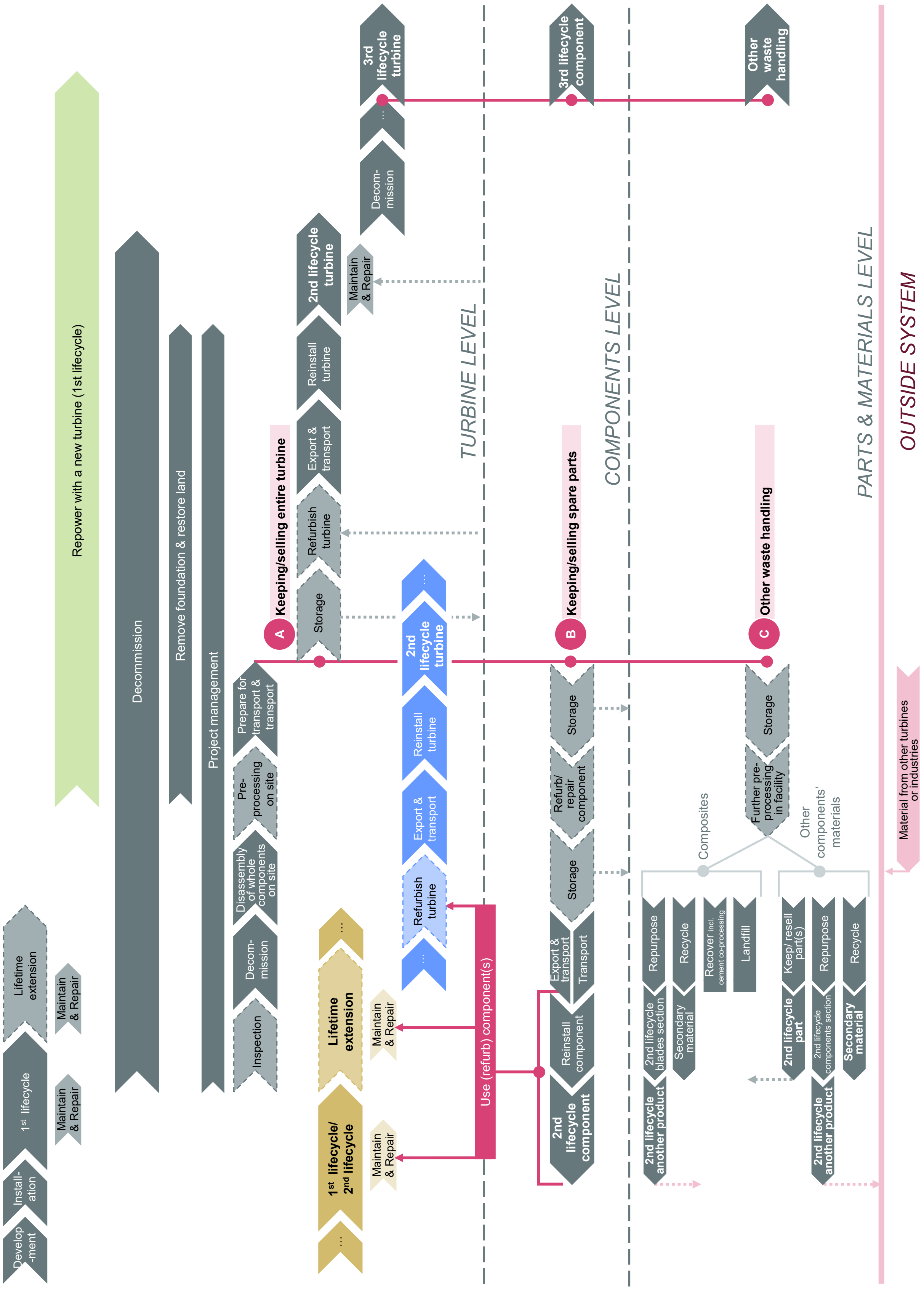


Figure 27. Overview of observed circular supply chain processes. Based on conducted interviews.

The starting point of the exploration is the first lifecycle of the wind turbine (top left in the Figure 27), followed by decommissioning and handling of the decommissioned turbine. In line with the interview guide, the options for handling the decommissioned turbine are aggregated to three pathways, (a) keeping/selling the entire turbine, (b) keeping/selling components as spare parts and (c) other-waste handling. In other words, these pathways differentiate between the handling on turbine level, component level or material level. The processes are described in the following and differences as well as similarities between countries and stakeholders are highlighted for the second lifecycle supply chain processes.

Decommissioning

According to the conducted interviews, a decommissioning project comprises of the decommissioning of the turbine and its handling as well as civil works that include the removal of the foundation, crane stands and the cabling. It can also be part of a repowering project, requiring a coordination between the works at the site regarding the decommissioning of the old turbines and the installation of the new turbines. In the interviews, the decommissioning project is either coordinated by the operator/owner or through contracting a company for decommissioning and handling the decommissioned turbine. In the latter case, the to-be-decommissioned turbine is either sold or the service of handling is remunerated. The contracted companies have different business backgrounds, e.g. stem from decommissioning of wind turbines, or have their core business in manufacturing, servicing or recycling of wind turbines. The experts stated that they normally handle turnkey projects, but often subcontract for some tasks (e.g. crane). Next to project management, the observed process chain at the project site, applicable for both countries, is the inspection, actual decommissioning of the turbine, the disassembly, optional pre-processing and transport for further handling (see Figure 28).

Figure 28. Chain of processes for decommissioning onshore wind turbines and handling at site. Based on conducted interviews.

The inspection was not mentioned by each expert, but when it was, they explained that they do a visual inspection, hence a site visit during the quotation process and prior to carrying out the actual decommissioning. Another form of inspection that was mentioned is the inspection of the available documentation, e.g. time of last repair or replacement of components. Throughout the interviews, three approaches for the actual decommissioning were mentioned: (i) using a crane, (ii) cutting the turbine at the bottom or (iii) exploding. Most commonly the experts used a crane to decommission the onshore wind turbine, but were also aware of the other market practices. Only one interviewee used the second approach and explained it by comparing it to the cutting of a tree, hence cutting the turbine at the bottom to let it fall.

After the different components are taken to the ground, these are further disassembled on site to enable the transport. Then optional, further pre-processing procedures (e.g. cutting, sorting, shredding) for other waste-handling is carried out on site. For instance, if the blades are not sold or kept for a second lifecycle, a common pre-processing step is to cut the blades into parts of standard transport sizes. If a second lifecycle is foreseen, the blades is transported as a whole. Other components might be further disassembled in parts to ease transportation. Finally, the turbine components or pre-processed components and materials are transported away from the site.

Second-lifecycle handling of the decommissioned wind turbine in its entirety

In the case that (a) the entire turbine is kept by the owner or sold, the following process chain was identified in both countries by analysing the interviews: optional storage, optional refurbishment of turbine, export and transport to new site, reinstallation of turbine at new site, and operation of the turbine for a second lifecycle (see Figure 29).

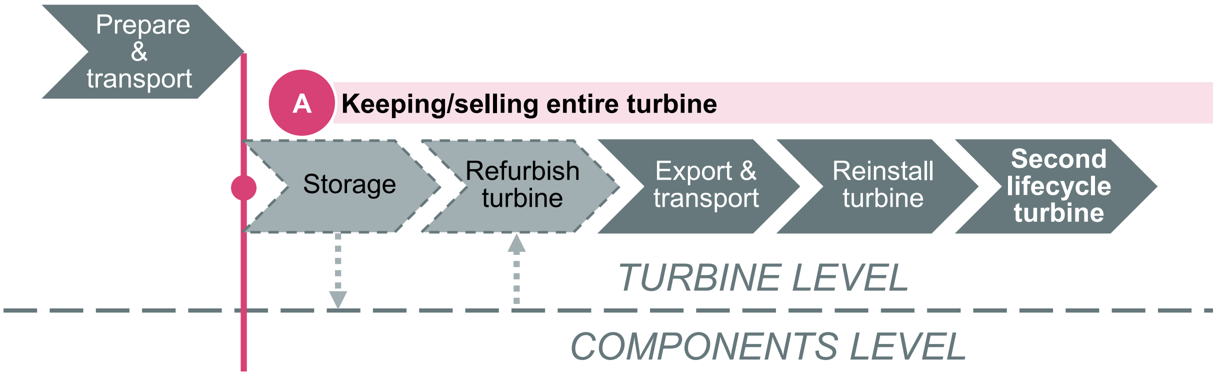


Figure 29. Chain of processes for decommissioned onshore wind turbines entering the pathway of the entire turbine being kept by the owner or sold. Based on conducted interviews.

Some of the interviewees mentioned the possibility to store the components of an entire turbine, depending on the component either outdoor or inside a warehouse. In case the owner of the turbine does not want to keep the turbine anymore or it cannot be sold in its entirety by the company which handles the decommissioned turbine, then the turbine enters one of the other levels, (b) the components level or (c) the parts and materials level (dashed grey arrow in Figure 29). Alternatively, instead of storing, the turbine can be directly transported to the new site or to a refurbishment facility. The direct transport is the most commonly mentioned process flow in both countries and it was acknowledged in all stakeholder groups, either as an own practice or a known market practice. Four experts from the stakeholder groups “recycler & dismantler”, “decommissioning company wind turbines” and “OEM” reported that they could store entire turbines. For the refurbishment of a turbine, which is done by two experts, broken parts are repaired or replaced with new spare parts or second lifecycle spare parts from other turbines. Moreover, the experts mentioned the provision of a product guarantee. That said, the decommissioned turbine is either (i) directly transported from the original site, (ii) delivered from the storage site or (iii) transported from the refurbishment facility to the new project site for reinstallation. Neither for Denmark nor for Germany did any expert state that the turbines had remained in the country for a second lifecycle, but that they had all been exported, mostly by road transport. Consequently, turbines were exported to various countries (e.g. Ireland, Italy, Kazakhstan, Moldavia, Poland) to be reinstalled for a second lifecycle, either as a single turbine or as part of a wind park. One expert mentioned that they test the turbine in operation prior to handing it over to the new owner.

Second-lifecycle handling of components of the decommissioned wind turbine

In the case, (b) components of the decommissioned wind turbine are kept by the owner or sold as spare parts, the level of observation changes from the turbine level to the component level. The following process chain was observed by analysing the interviews: optional storage, optional refurbishment/repairment, optional storage, transport to site either with or without exporting, reinstall component in turbine, and operation of the component for a second lifecycle (see bottom of Figure 30). In addition, the process chain observed in Denmark and Germany is similar, while there are differences between the stakeholders.

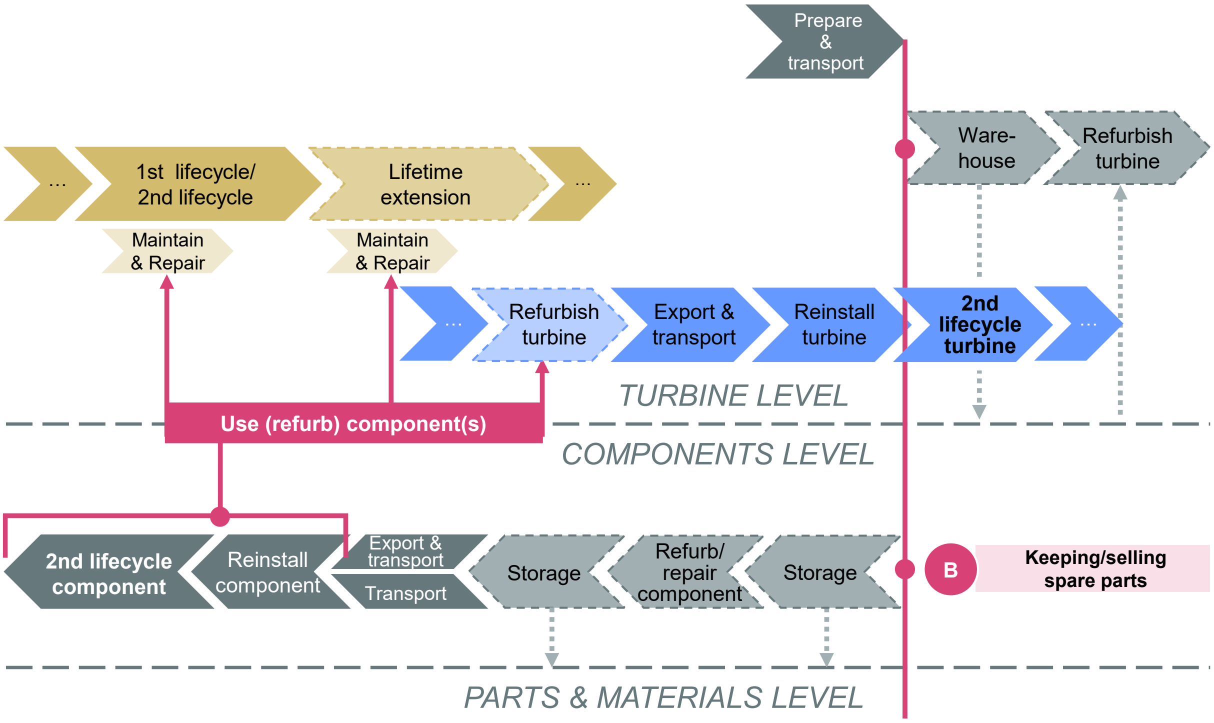


Figure 30. Chain of processes for components of decommissioned onshore wind turbines entering the pathway of being kept by the owner or sold as spare parts. Based on conducted interviews.

Similar to the optional storage for selling the components for reinstallation as an entire turbine, this also takes place for single components for reinstallation. Some companies kept the components for their own service business and hence either for direct reinstallation or storage in their spare parts warehouse, i.e. from the stakeholder groups “project developer & operator or service company” and “OEM”. Moreover, most of the interviewed companies that sell decommissioned spare parts have a warehouse. If the stored components are not needed by the owner at one point or cannot be sold, they might enter the parts and materials level and hence (c) the other-waste handling pathway (dashed grey arrow in Figure 30). Instead of storing, the components can also directly be transported from the site to the new site for replacement, which is also observed in both countries. A further optional process is the refurbishment or repairing of components prior to reusing them in a turbine. For the blades, for instance the repairment with leading edge protection was mentioned by one expert. For the gearbox and generator, a refurbishment was stated by several experts, e.g. by the OEMs, service providers, and companies doing solely wind turbine decommissioning and its handling. For the tower, this process step was not observed and instead those normally went into the other-waste handling path. Optional after refurbishing or repairing, is again a storage. In contrast to the turbine level, a component as spare part is either transported to a site in the domestic market (i.e. Denmark or Germany) or exported (e.g. to UK, Italy, Netherlands, Poland, Australia). The component is reinstalled in a turbine, either (i) to repair a turbine in its first lifecycle (with or without lifetime extension), (ii) to refurbish another decommissioned turbine for reinstallation as a second lifecycle or (iii) to repair or maintain a turbine in its second lifecycle. In all scenarios, the component is given a second lifecycle.

Third-lifecycle handling of turbines and components

Moreover, two interviewees reported a third lifecycle of the turbine or its components (see right side of Figure 27). In one case, after the second lifecycle of a wind turbine in a European country, components of this turbine were reimported and refurbished to be used as spare parts for repairing a turbine. In the other case, after the second lifecycle of a wind turbine in a European country, the turbine was exported to another European country for a third lifecycle of the entire turbine. However, it should be noted, that a third lifecycle or in more general terms, multiple lifecycles were out of scope for this study and hence not part of the interview guide. Therefore, it is not known if the other interviewed experts also have experienced a third lifecycle.

Handling via the other-waste handling pathway

In the case that components of the decommissioned wind turbine enter (c) the other-waste handling pathway, again the level of observation changes, here to the parts and materials level (see Figure 31). As the focus of the interviews is on second lifecycle supply chains for turbines and blades, a detailed overview of the processes on the parts and materials level is not available. However, one expert stated that optional storage and further pre-processing at the recycling site can occur prior to the further handling.

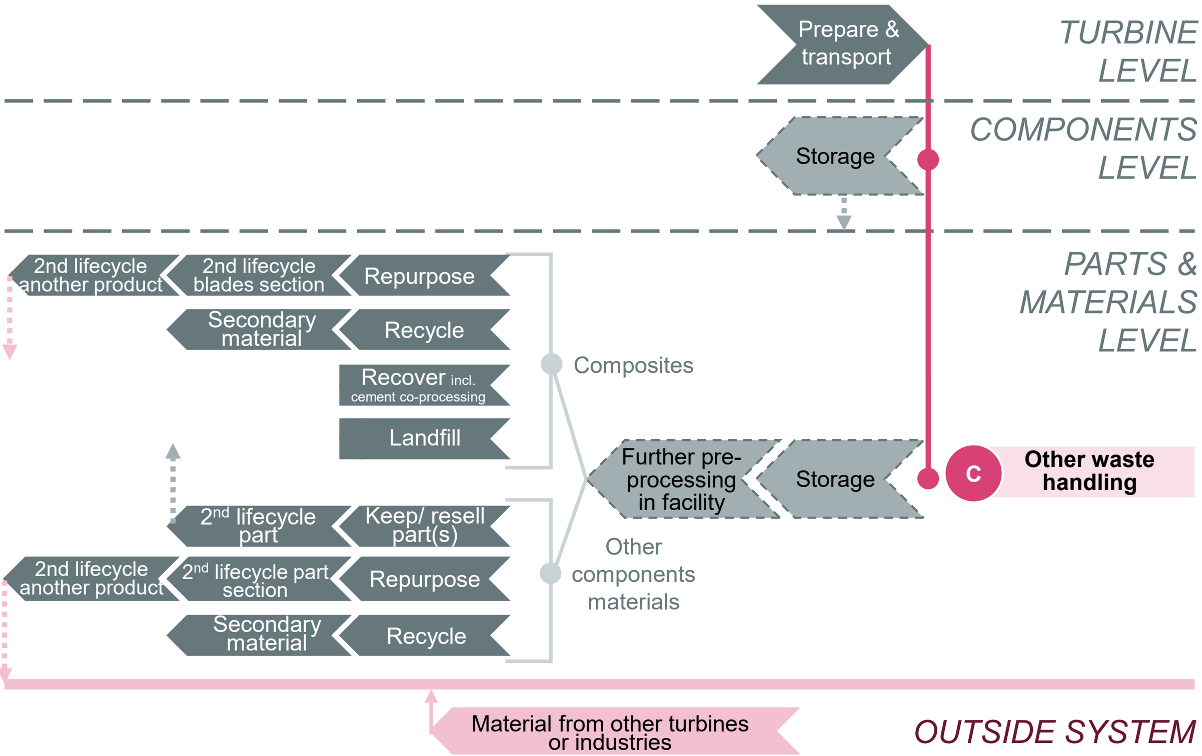


Figure 31. Chain of processes for components and materials of decommissioned onshore wind turbines entering the pathway of other-waste handling. Based on conducted interviews.

Some handling options of the other-waste handling pathway were identified throughout the interviews, but should not be understood as a comprehensive listing. For instance, for blades and their composite materials, experts have mentioned repurposing, recycling and downcycling, energy recovery and cement co-processing, and landfilling or just called it more generally “scrapping”. For other components’ materials, experts stated that they sold parts out of key components, repurposed, or recycled or did not detail the other-waste handling pathway. For recycling materials, such as metals and concrete, it entered recycling pathways that are also used by other industries (e.g. construction industry). In addition, none of the experts covering Germany has mentioned repurposing for blades or other components, but otherwise the listed options are the same in Denmark and Germany.

Conclusion

Overall, this section provides an understanding of the observed processes of decommissioning and handling decommissioned onshore wind turbines in Denmark and Germany from a multi-stakeholder perspective. Experts of both countries and experts of each stakeholder group have acknowledged the existence of the three handling pathways, i.e. handling the a) entire turbine, b) components and c) parts and materials. They have mentioned the three pathways, either as being part of the company’s associated processes or known processes in the market. When focussing at the handling pathways which only the expert's company, their subcontractors or customers consider, also the majority (12 experts) mentioned all three pathways. These observations are in line with the quantifications by the experts for entire turbines and blades (see Figure 25). Nevertheless, for instance one expert mentioned the pathway of selling components as spare parts as part of their business activities, but not for blades. It is also interesting to note that two experts from the stakeholder group "recycler & dismantler" only mentioned the other-waste handling pathway, and both stated that the second-hand market is currently not part of their business. In contrast, two other experts who belong to the stakeholder groups "decommissioning company wind turbines" and "project developer & operator or service company" only stated (a) the pathway to sell entire turbines. One of those experts, claimed that the company purely focuses on the resale of decommissioned wind turbines. Another interesting aspect when comparing the different stakeholder groups is that most OEMs (with one exception), the service companies and one of the operators are involved in the decommissioning of wind turbines on the one hand and demand second-lifecycle spare parts for their service business on the other. This could eventually also explain the slightly larger reuse fraction for blades as spare parts for the stakeholder group "project developer & operator or service company" (see Figure 26).

The analysis focused on the second lifecycle supply chains of the entire turbine and key components, but also sketched the upstream and downstream processes. The interviewed experts expressed similar second-lifecycle supply chains in Denmark and Germany, however differences between the stakeholders became visible. The analysis shows that the decommissioning and each handling pathway involve different processes, making multiple routes possible:

- Supply chain processes for a second lifecycle of a turbine: It is observed that the decommissioned turbines were either directly reused or refurbished prior reinstallation at a new site abroad.
- Supply chain processes for a second lifecycle of the components: The analysis shows that the components were either directly reused or repaired/refurbished for meeting the demand for spare parts of (i) first lifecycle turbines in operation, (ii) second lifecycle turbines in operation and (iii) for refurbishing decommissioned first-lifecycle turbines. In this light, some companies were able to store the components of an entire turbine or parts of it. The spare parts remained either in the domestic country or were exported.

To further explore what is influencing the development of second-lifecycle supply chains for onshore wind turbines from Denmark and Germany, the next section outlines factors that influence the decision-making along the drawn circular supply chain processes.

5.2.3.2 Factors influencing the development of second-lifecycle supply chains

Factors that influence the choice of a second lifecycle of the entire turbine or the blades as spare parts were inductively derived on the basis of the interviews conducted with multiple stakeholders. The results are presented according to the approach shown in Figure 32, which is consistent with the theoretical understanding of Part A and the process chains identified in 5.2.3.1.

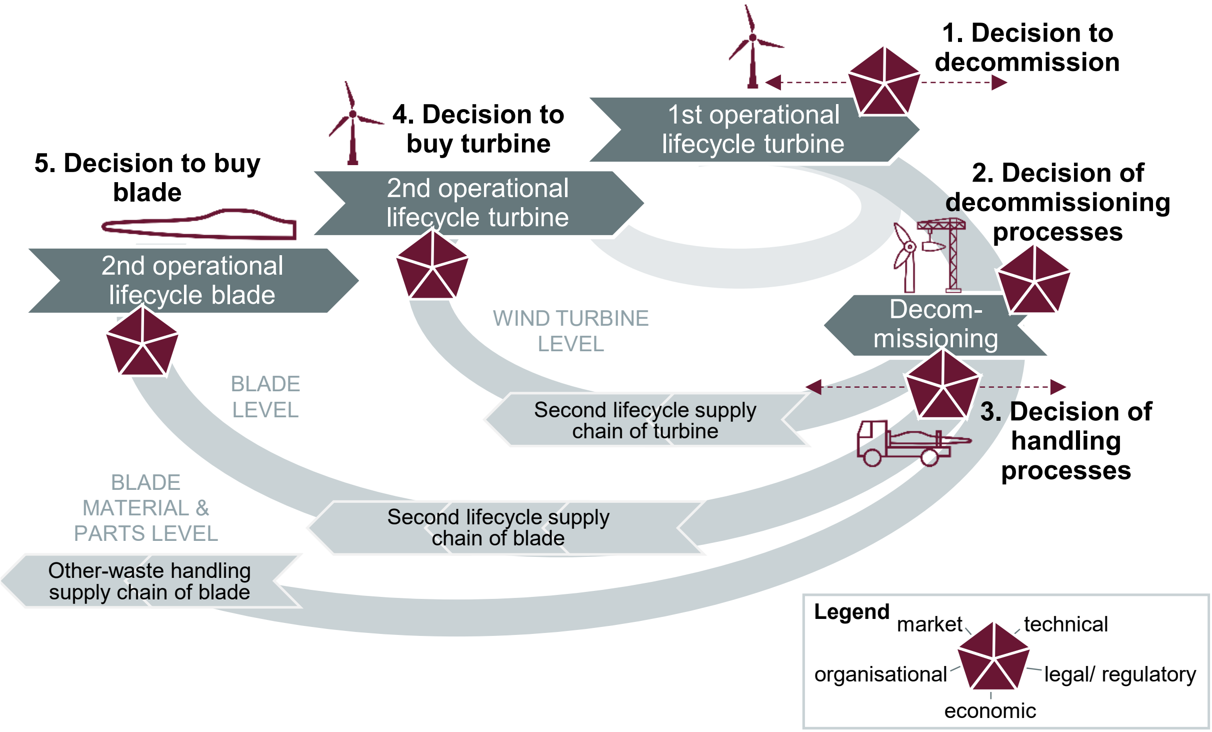


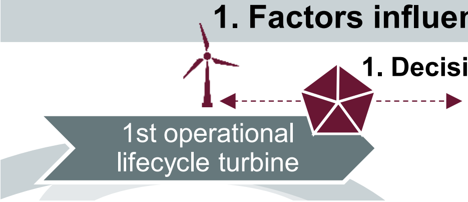
Figure 32. Dimensions of the influencing factors positioned in the circular supply chain network.

Accordingly, factors are associated with either (1) the first operational lifecycle of the turbine, (2) decommissioning, disassembly and pre-processing at the site, (3) handling of the decommissioned turbine, (4) the second lifecycle of the turbine and (5) its blades. The factors are divided into technical, legal/regulatory, economic, organisational and market dimensions. The results are presented and described below, while Table 39 in Appendix B2 provides a summary of the influencing factors.

Factors influencing the decision to decommission a wind turbine

Figure 33 presents that the operator's decision to decommission in the first turbine's lifecycle is based on technical, legal/regulatory, economic, organisational and market factors.

1. Factors influencing the decision to decommission



Technical	Legal/regulatory	Economic	Organisational	Market
▪ Turbine design ▪ Turbine condition ▪ Wind conditions at project site ▪ Availability of spare parts	▪ Compensation ▪ Land lease ▪ Requirements for repowering ▪ Requirements for lifetime extension	▪ Economic feasibility to continue operation ▪ Economic feasibility to repower	▪ Operator's business strategy	▪ Number of operating turbines per turbine type ▪ Ownership structure ▪ Size of wind farm

Figure 33. Factors influencing the decision to decommission a wind turbine. Based on conducted interviews.

Technical factors influencing the decision to decommission a wind turbine

Technical factors

- Turbine design
- Turbine condition
- Wind conditions at project site
- Availability of spare parts

Figure 34. Technical factors influencing the decision to decommission a wind turbine. Based on conducted interviews.

As shown in Figure 34, technical factors identified are the turbine condition, the turbine design and the wind conditions at the project site. In some cases, it could be that the turbine condition is the decisive factor for deciding to decommission. For instance, if the turbine is not operating anymore due to a component failure (e.g. gearbox) or a lightning strike (e.g. the case for ~2-3 % of decommissioned turbines by I10) and it is either not technical (e.g. if tower's structural stability at risk) or economically feasible (e.g. large component failure vs expected remaining time of operation) to repair. To enable a repair of the turbine, the availability of spare parts for that turbine type is stressed to be important by the experts. The turbine condition is impacted by the turbine design and the wind conditions at the site, but also by the chosen maintenance and operation strategy. For instance, a robust design of the turbine/turbine type positively impacts the technical lifetime of a turbine (e.g. I11 expressed this for old Vestas turbines). The wind conditions at the project site can negatively influence the turbine's condition if for instance unplanned strong and turbulent winds occurred. Alternatively, it can have a positive impact, if the actual wind conditions of the site were lower than the estimated loads in the wind turbine's design, as the following outlines for older turbine models.

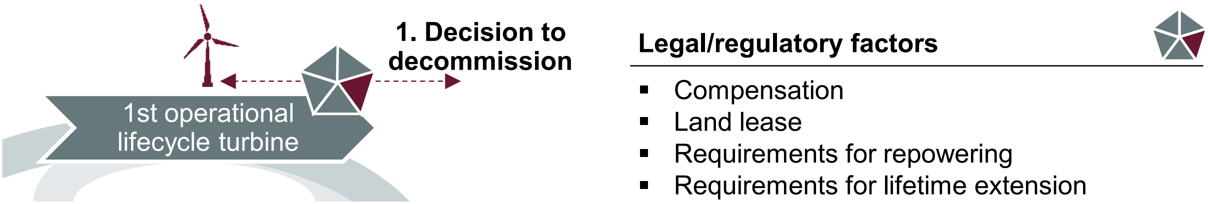
> *"(…) on the old turbines it is really significant more than 20 years, but on the newer turbines, I do believe that we will see a decrease in lifetime because (…) the loads on those turbines are really designed for specific sites, specific wind*

> *conditions etc."* (Denmark, stakeholder 'project developer & operator or service company')[3]

On a general note, experts reported a significant technical lifetime of the turbines they have decommissioned, although not applicable to every turbine type. The analytical analysis by 8.2 Consulting confirms this with an average lifetime varying between 22.6 years to 40 years depending on the turbine type (8.2 Group, 2021). However, it is not known how the statistics evolve for the newer turbine types – that are not yet being decommissioned – as comprehensive data is not yet available. Overall, these technical factors have a significant impact on the technical feasible power output of the turbine at the given site. In this context, good wind conditions might promote operators to assess the potential for repowering early on, for instance expressed by an expert as follows:

> *"So, the really good [wind] locations, of course, you look at them much earlier and with the 'bad' ones you say let the old ones run and do it towards the end, [...], there's just a hierarchy."* (Germany, stakeholder 'project developer & operator or service company')

Legal and regulatory factors influencing the decision to decommission a wind turbine



Legal/regulatory factors

- Compensation
- Land lease
- Requirements for repowering
- Requirements for lifetime extension

Figure 35. Legal and regulatory factors influencing the decision to decommission a wind turbine. Based on conducted interviews.

As shown in Figure 35, a legal/regulatory reason for decommissioning can be the requirement of a municipality to decommission an operating wind turbine as compensation for the granting of a licence for a new wind project. Another reason can be the expiry of the land lease. Furthermore, legal requirements for a repowering project or a lifetime extension beyond the turbine's design life influence whether the turbine is decommissioned as part of a repowering project or the operation is continued. For instance, experts for both countries stated that the provision of a repowering bonus by the government – that was given for a limited time period in Denmark and Germany, but at different years – promoted decommissioning. Denmark financially supported decommissioning of wind turbines of up to 150 kW from 1999-2003 (BEK nr 187 af 16/03/2001, 2001) and in Germany a repowering bonus existed from 2004 to 2014, but only a regulatory change of the EEG in 2009 led to an increase of repowering projects, as new turbines received 0.5 Cent per kWh (Quentin & Sudhaus, 2016, p. 11; Ziegler

---

[3] All citations from text passages of the transcripts or memos are provided in English. In some cases, the interviews were conducted in German or Danish. However, for ensuring anonymity and better readability of the chapter, those are also shown in English.

et al., 2018, p. 1265). Before stopping the financial incentive in 2014, a further amendment was made in 2012, which introduced the requirement that a repowering project must lead to a doubling of the installed capacity without increasing the number of turbines. Moreover, experts expressed that eases in the permitting process of repowering projects could shorten the permitting time, although, this has not yet existed in the past. In addition to simplifying the permitting procedure, the easing of restrictions on the installation of wind turbines could lead to a wind power project being considered for repowering in the first place. The experts of both countries mentioned, for example, restrictions regarding the turbine's height and required distances to residential housing, as well as environmental conditions. In addition, an overall limit of to-be-installed wind turbines exists in Denmark. Experts for Germany mention that the repowering business has slowly increased over time, particularly since 2020/21, and also going forward they expect good conditions for repowering projects due to simplifications in the permitting process, triggered by RePowerEU and national initiatives. For instance, an expert of the German market said:

> *"That's also what we're seeing, in 20/21, when repowering started to take off more and more in Germany and then our business also progressed."* (Germany, stakeholder 'project developer & operator or service company')

For Denmark, some experts state that there are no projects available for repowering anymore, as the repowering potential of existing sites has mostly been realised and instead new project sites are being used for the development of wind farms. As a counterpart to promoting repowering, governments actions might hinder or ease a continued operation after surpassing the design life of 20 years. Germany and Denmark differ in their regulation on lifetime extensions, as only Germany demands an external assessment of the turbine's stability and Denmark only foresees annual inspections within the maintenance routine (Ziegler et al., 2018, p. 1265). An expert explained that depending on the turbine's condition, a permit for continued operation in Germany is either refused, granted without conditions or granted subject to conditions and is valid for a certain period of time.

Economic factors influencing the decision to decommission a wind turbine

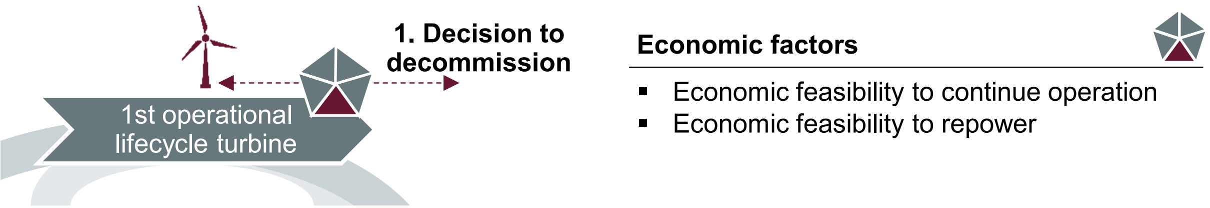


Figure 36. Economic factors influencing the decision to decommission a wind turbine. Based on conducted interviews.

As illustrated in Figure 36, economic factors influencing the decision to decommission are highlighted throughout all stakeholder groups and for both countries. Accordingly, a turbine might be decommissioned if it is not economically feasible to continue operation, which is the case when operational expenses are larger than the expected revenues. In this regard, the experts mentioned that the recent increase in electricity prices improved the business case significantly in Denmark, and also in Germany for the turbines for which feed-in payments have expired. However, some experts pointed out that in the current energy system design, negative prices occur for the operation of wind turbines on some days with strong winds.

Furthermore, if an alternative turbine type is economically more attractive to operate at that site than the current turbine type and if legally allowed at that site, a repowering project might be pursued, i.e. the installation of larger, more profitable turbines. The assessment is influenced by factors from the other dimensions. For instance, in both countries repowering was promoted by a decommissioning/repowering bonus paid for decommissioning turbines for a specific time period (see legal/regulatory factors).

Organisational factor influencing the decision to decommission a wind turbine

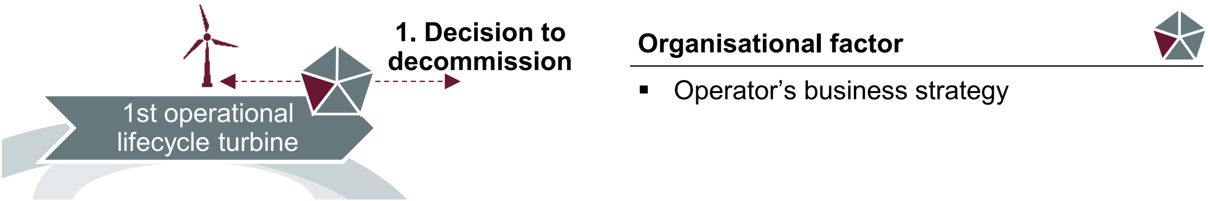


Figure 37. Organisational factors influencing the decision to decommission a wind turbine. Based on conducted interviews.

As shown in Figure 37, the organisational factor is that the owner's business strategy either promotes a continued operation, hence a lifetime extension beyond the design life, or a repowering. Different strategies of the interviewed experts and stakeholder groups were observed. From the interviewed experts that also develop and operate wind turbines, one company pursues the strategy to acquire old wind turbines for continued operation of the original design lifetime of 20 years, as the following statement reveals:

> *"There are companies now looking at life extensions for turbines, and we also looking into that because of course the business models, we, I can't tell you what is in our business model, how long we think the design life of a turbine is but I can say that it's significantly more than 20 years."* (Denmark, stakeholder 'project developer & operator or service company')

In contrast, another company focuses on the project development of new projects and hence buys old turbines in order to repower:

> *"If there are any turbines that stand in the way of making the new project, then of course we have to take them down."* (Denmark, stakeholder 'project developer & operator or service company')

On that note, the original owner sold its operating wind project to a new owner (e.g. project developer) and hence, transferred the decommissioning decision to the new owner. Moreover, decommissioning companies and recycler reported that they have seen different strategies by their clients depending on the type of owner, usually differentiating between individuals (e.g. farmers) and professionals (e.g. large utilities). As such, not every company might look into the potential of repowering or/and lifetime extension.

Market factors influencing the decision to decommission a wind turbine

Market factors

- Number of operating turbines per turbine type
- Ownership structure
- Size of wind farm

Figure 38. Market factors influencing the decision to decommission a wind turbine. Based on conducted interviews.

As illustrated in Figure 38, as a market factor the number of operating turbines per turbine type and a change of the ownership types is mentioned. For example, I13 reported a low overall business flow for decommissioning wind turbines, as they are only active in southern Germany and only small quantities were installed there. I2 mentioned that overall in Denmark not much was decommissioned in the last year. Moreover, some experts stated that specific turbine types (e.g. E40 in Germany) have been installed in large quantities and therefore have a large share in decommissioning. This is in line with market data for both markets (see 6.2.1). Also, according to decommissioning experts from both markets, the structure of owners and number of turbines per wind park has developed over time. For both markets it is stated that at the beginning primarily single turbines by private persons (e.g. farmers) were decommissioned, and in the last years the share of wind parks from professional owners (e.g. utilities) has increased.

Conclusion

All in all, the reason to decommission and hence also the time of decommissioning varies (red arrow in Figure 32) across projects, operators and countries and might often have been a combination of reasons. Stated reasons for decommissioning are repowering, economically unviable continued operation (e.g. due to component failures), decommissioning after the originally planned project lifetime (e.g. due to expiry of land lease) and, for a few turbines, a lightning strike. It should be noted, that the current available history of decommissioning is not yet reflecting the full magnitude of turbines being decommissioned after continued operation beyond 20 years, especially in Germany. With Denmark's longer history of installing onshore wind turbines, a large fraction of decommissioned turbines beyond 20 years is visible (see Figure 65). Also, for the German market, it is recognisable that 29.4 % of the operational onshore wind turbines are more than 20 years old and as such are operated beyond the design life (see Figure 66). As such, the typical project's lifetime and turbine's age at decommissioning in Denmark and Germany is difficult to determine on the basis of current available information and data.

Nevertheless, decommissioning was promoted in Denmark and Germany – frequently stressed by the interviewed experts, particularly for Denmark, and shown in the market data in chapter 6.2.1 – with the financial bonus for decommissioning/repowering. Moreover, it seems that good wind conditions at the project site and a positive legal/regulatory setting to repower, likely result to an early assessment of a potential repowering:

> *"If the regulatory setting for repowering is good and wind conditions of the site worth it, you start to look into repowering early on"* (expert active in Germany)

In contrast, if the turbine is in a good condition, legal/regulatory setting allows for continued operation and economics are sufficient, then the operation of the wind turbine is likely to be continued, also beyond the original project lifetime.

Available options for the subsequent handling of the to-be-decommissioned wind turbines was not stated as a factor that has influenced the decision to decommission. But the decision to decommission determines the time of decommissioning and consequently specifies the number of turbines per turbine type that theoretically enter the second-hand market at a given time.

Factors influencing the decommissioning, disassembly and pre-processing processes at the project site

Figure 39 outlines the factors that influence taken decommissioning, disassembly and pre-processing processes at the project site. The company responsible for the decommissioning is deciding and might be influenced by the owner/operator of the project site, legal authorities, and the subsequent handling. The following outlines the observed technical, legal/regulatory, economical, organisational and market factors.

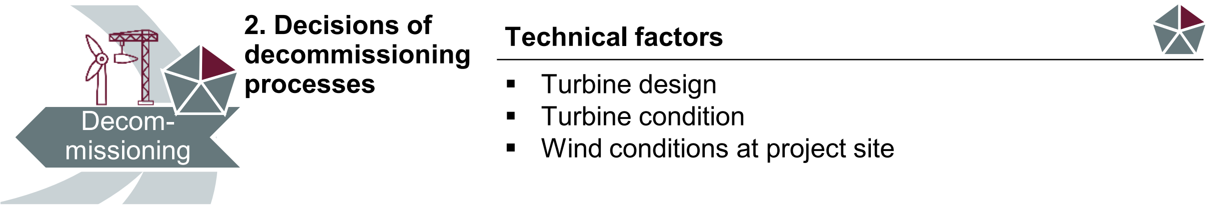
2. Factors influencing the decommissioning processes

2. Decisions related to decommissioning, disassembly and pre-processing processes at the project site

Technical	Legal/regulatory	Economic	Organisational	Market
▪ Turbine design ▪ Turbine condition ▪ Wind conditions at project site	▪ Requirements of public authorities ▪ Monitoring of authorities ▪ Standardisation across authorities	▪ Decommissioning costs ▪ Disassemble costs ▪ Pre-processing costs	▪ Choices of operator on scope & responsible company ▪ Business model & strategy of responsible company ▪ Time window for decision-making and execution ▪ Access to lifting data & gear ▪ Skills & standards of responsible company ▪ Chosen handling pathway	▪ Industry standards

Figure 39. Factors influencing the decommissioning, disassembly and pre-processing processes at the project site. Based on conducted interviews.

Technical factors influencing the decommissioning, disassembly and pre-processing processes at the project site



2. Decisions of decommissioning processes

Technical factors

- Turbine design
- Turbine condition
- Wind conditions at project site

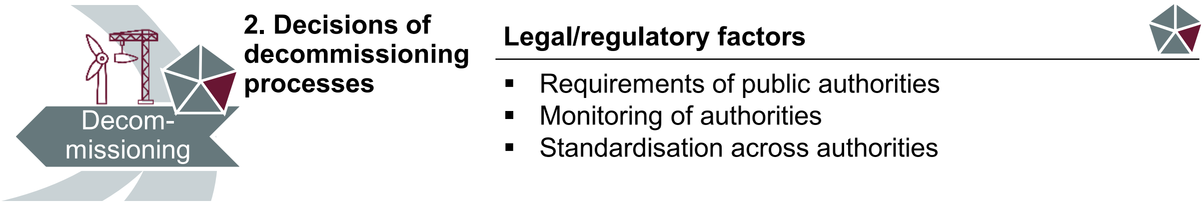
Figure 40. Technical factors influencing the decommissioning, disassembly and pre-processing processes at the project site. Based on conducted interviews.

As shown in Figure 40, technical factors are primary the turbine design and the turbine condition. The turbine design influences the costs and the ability to decommission or disassembly components. For example, an expert from a decommissioning company and one from the stakeholder group “project developer & operator or service company” mention that not all turbine types are designed for decommissioning and hence eligible for reusing the entire turbine. For example, some turbine types are made with a concrete tower which cannot be disassembled and instead is demolished and enters the other-waste handling pathway, ideally locally. Another decommissioning company, active in the German market, noted that the disassembly of some parts and components is for some turbine types more difficult, e.g. the switchgear cabinet in the E70 is difficult to access. As such, the design for disassembly is an influencing factor.

A further technical factor is the turbine condition, in case the turbine is in such a bad condition that work safety cannot be guaranteed, a special skilled team and procedures are necessary, e.g. of a burnt turbine caused through a lightning strike (e.g. I10).

The wind conditions at the site are not determining which process is taken, but when the project can be executed, as a crane can for example not be operated in too turbulent winds.

Legal and regulatory factors influencing the decommissioning, disassembly and pre-processing processes at the project site



2. Decisions of decommissioning processes

Legal/regulatory factors

- Requirements of public authorities
- Monitoring of authorities
- Standardisation across authorities

Figure 41. Legal and regulatory factors influencing the decommissioning, disassembly and pre-processing processes at the project site. Based on conducted interviews.

As illustrated in Figure 41, the experts of both countries mentioned requirements of public authorities, monitoring by authorities, and standardisation across regions as legal/regulatory factors. Authorities for instance might define to which degree the foundation has to be removed, which environmental measures need to be considered or request a decommissioning plan prior to carrying out the work. On the side of companies carrying out the decommissioning, some reported that not all market actors follow sustainable practices and one expert thus concludes that a better monitoring by the local authorities would promote compliance with industry standards in the first place. However, this expert also stresses that requirements by local authorities in Germany vary across regions and a standardisation would make things easier.

Economic factors influencing the decommissioning, disassembly and pre-processing processes at the project site

2. Decisions of decommissioning processes

Economic factors

- Decommissioning costs
- Disassemble costs
- Pre-processing costs

Figure 42. Economic factors influencing the decommissioning, disassembly and pre-processing processes at the project site. Based on conducted interviews.

As shown in Figure 42, economic factors are factors that influence the economic feasibility for the client and the responsible company. This is determined by the costs for carrying out the decommissioning project at the wind turbine's site, consisting of decommissioning, disassembly and pre-processing costs. Furthermore, the costs and revenues from handling the decommissioned turbine are considered, that is further detailed in the section on handling (p. 96).

The costs to decommission the turbine mostly consists of the costs for the crane and is influenced by the turbine design, especially its height, dimensions and weights. Most experts subcontract a crane company, while one expert from a decommissioning company in Denmark stated that they owned a crane in their busy years, but later sold it as it was no longer sufficiently utilised. The costs for using the crane at the site can further increase due to weather-caused delays, which are normally carried by the operator of the project site. The majority of experts did not consider alternatives to a crane, however one company belonging to the stakeholder group of "recycler & dismantler" state that they prefer to cut the turbine as it is faster and cheaper. Other interviewed experts stated that they have seen those practices by other market players, but would not do it themselves.

The disassembly costs are mainly driven by the costs for the disassembly team and the extent to which the turbine and its components are disassembled. If a second lifecycle of the turbine is foreseen, then a high-quality disassembly (e.g. including labelling the disassembled components and parts) is important, while on the other-hand no further pre-processing costs for other-waste handling would be required. Depending on the subsequent transportation costs and the available time at the project site, components might be further disassembled to parts. A common stated example is to either transport the entire nacelle or disassembly at site to transport only components or parts that are foreseen for the second-hand market and scrap the rest (e.g. nacelle cover). An expert explains it as follows:

> *"[…] hub, nacelle cover, rest of nacelle, tower, that are the things that would actually always be scrapped or only parts used. This decision is always very much associated with transport costs. So, we always look at what is cheaper? How can we get it out of there? Of course, it would be nicer to just pick up the whole nacelle and put it in the yard, then it can rain and everything is dry inside, but the transport costs are just so high and it needs special transport […] from one megawatt upwards."* (Germany, stakeholder 'project developer & operator or service company')

The existing blade types cannot be further disassembled and therefore, these would be further processed at the site. Hence, pre-processing costs for preparing the other-waste handling, such as cutting of blades, occur. Overall, experts expressed that projects can achieve economies of scale depending on the number of turbines per park or neighbouring projects. In addition, experts who offered more than the decommissioning of wind turbines were able to create synergies with existing business units (e.g. utilisation of skilled workers) and reported less dependence on wind turbine decommissioning in relation to their overall business. Furthermore, two decommissioning experts from small companies that have been operating in Denmark for a long time explained that the amount of documentation requested has recently increased, especially from large companies, and this has driven up their costs to such an extent that they have in some cased rejected such projects.

Organisational factors influencing the decommissioning, disassembly and pre-processing processes at the project site

2. Decisions of decommissioning processes

Organisational factors

- Choices of operator on scope & responsible company
- Business model & strategy of responsible company
- Time window for decision-making and execution
- Access to lifting data & gear
- Skills & standards of responsible company
- Chosen handling pathway

Figure 43. Organisational factors influencing the decommissioning, disassembly and pre-processing processes at the project site. Based on conducted interviews.

As illustrated in Figure 43, various organisational factors exist that relate to the operator's choices, the available time and the responsible decommissioning company with its business model, strategy, skills and standards. Further factors are the access to lifting data and gear, and the chosen handling pathway. The operator defines the scope of the decommissioning project, e.g. regarding the timing or at some decommissioning projects, turbines or components were kept for own spare parts management and hence the dismantling and handling route (or part of it) was already pre-defined by the operator.

The operator's choice of a decommissioning company is influenced by various factors, amongst others, an economical attractive quote, agreed business conditions, and available capacity of the decommissioning companies and their sub-contractors (i.e.

crane). Further factors were access to a buyer for the to-be-decommissioned turbine, an already established, positive business relationship with the decommissioning company and the perception of their compliance to industry and legal standards. For example, if the owner of the turbine used its own network to sell the turbine on the second-hand market, then typically a decommissioning company was chosen that was known for being able to decommission and handle the turbine in such a way that it could be reinstalled again (e.g. proper packaging for transport). Moreover, an interviewed expert that hires decommissioning companies in the German market said that it is important that the company has the skills to operate safely and professionally at the project site, also to ensure satisfaction of land owners and municipalities, and therefore they prefer companies with which they already had positive experiences. Decommissioning experts from both countries confirm this, adding that large companies in particular take this factor into account. Moreover, an interviewed decommissioner added that some operators are in the phase of undertaking their first decommissioning project, and are therefore still building in-house knowledge on how to assess potential decommissioning companies. Still, experts for both markets underline that the overall economics of the turnkey project (i.e. decommissioning on site and handling of decommissioned turbine) are of importance. This could eventually be a reason why a decommissioning expert from the German market believes that the decommissioning company who has access to a buyer for the to-be-decommissioned turbine and offers reasonable decommissioning costs has the best chances to get hired for the decommissioning project. In this context, several experts of both countries reported that their company acquired the to-be-decommissioned turbine for further handling.

The business model and strategy of the company responsible for decommissioning varies and hence attracts different kind of projects and operators. Next to a regional scope (e.g. I13's regional focus on southern Germany and I12 is active internationally), also a technical scope could be applicable. However, none of the interviewed persons narrowed their decommissioning scope only to specific turbine types. The time window for decision-making and execution of the decommissioning project by the responsible company depends, on the one hand, on how early before the planned execution date the client contracts a decommissioning company and on the other hand, how flexible or fixed the planned execution date is and hence room for manoeuvre is given (e.g. to find a potential buyer on the second-hand market). The actual execution date is amongst others dependent on available crane capacity and weather conditions. In case the decommissioning project is part of a repowering project, then time is a more critical factor as a delay in the decommissioning project could cause a delay in installing the new turbines.

Skills/know-how to decommission different turbine types is not reported as a problem for decommissioning companies, as they often hire a crane company. However, an OEM added that for rarely installed turbine types and for the new generation of turbines, the decommissioning companies may lack expertise or, in the latter case, may not yet have built it up and then they would do it. In this light, access to lifting data and lifting gear is crucial. Two experts state that for larger turbines specific crane traverses are required and one of them adds that also from safety reasons access to lifting guidelines becomes more important. Moreover, two decommissioning experts mentioned that they have manually re-measured fixing points at the nacelle, as detailed and accurate measurements were missing. Another example is whether the companies define standards of their company processes (e.g. ISO-certified) or regarding their decommissioning business (e.g. always use crane or define that blades are cut on the crane stand and measures are followed to avoid spreading of glass fibre in the field).

Moreover, the chosen handling pathway of the to-be-decommissioned turbine had an impact, not that much on the decommissioning, but on the disassembly and pre-processing. Most experts stressed that they always use a crane to ensure an environmentally friendly decommissioning. Only one expert from the Danish market – an expert who did not consider any second lifecycle pathways – also uses other decommissioning practices (e.g. tipping the turbine). In regards, to the degree of disassembly and further pre-processing, it however made a difference across several interviewed experts whether a second lifecycle was considered or not. Several interviews stated that they usually cut the blades at the site in the decommissioning projects of the last years if they did not have a buyer for the blades as part of selling the entire turbine or as spare parts.

<u>Market factor influencing the decommissioning, disassembly and pre-processing processes at the project site</u>

Figure 44. Market factor influencing the decommissioning, disassembly and pre-processing pro-cesses at the project site. Based on conducted interviews.

In reference to Figure 44, the market factor identified is the existence of industry standards and their documentation. Some experts referred to the DIN Spec 4866 and the currently ongoing process of transforming it to a DIN and also international efforts on standardising decommissioning projects. In this light, they note that the industry standards have increased over the years. A decommissioning company that has decommissioned in both markets, adds to that:

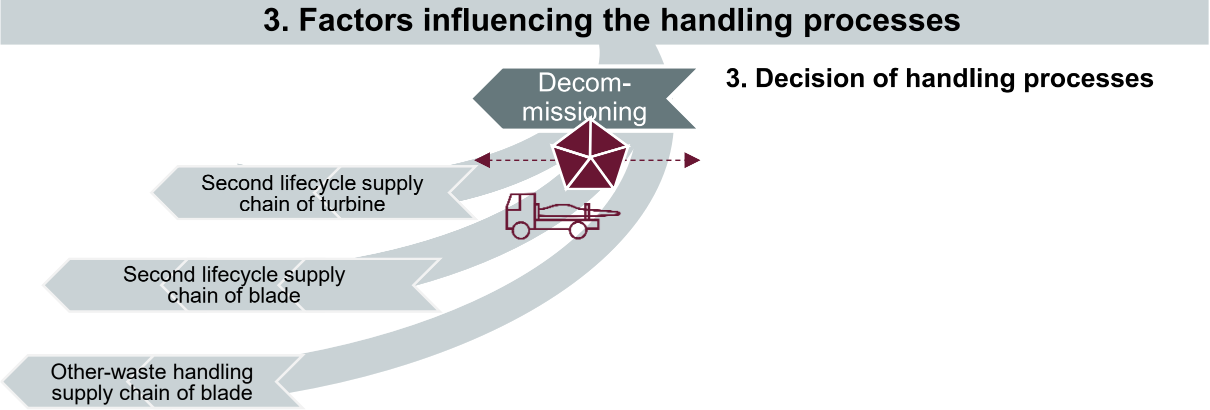
> *"We always use a crane as so there was, of course Cowboys in our industry and where they were just cutting in the bottom and that was not so very smart, especially in Germany it has be done a lot of times and it has now been blocked with the Din Spec and that's helped a lot. So, it is actually backwards installation."* (Germany and Denmark, stakeholder 'decommissioning company wind turbines')

Conclusion

All in all, the operator impacts the subsequent handling, either through pre-defining the handling or indirectly through its selection of a decommissioning company. The choice of a decommissioning company influences the handling as usually the company is responsible for the decommissioning at site and the handling of the decommissioned turbine (turnkey project). The handling for a second lifecycle is negatively impacted or even prevented if the turbine is not appropriately decommissioned and disassembled. This is the case for turbines that anyway have almost no structural value left (e.g. burnt due to lightning strike), are not designed for decommissioning (e.g. concrete tower) or are caused by the business practices of the executing decommissioning company and its subcontractors. Moreover, if there is no buyer for the entire turbine or the blades available, the blades are usually cut to size on site to reduce the cost of subsequent handling. This makes it clear that the time window for finding potential buyers is often limited to the time of the upcoming transport from the site.

Factors influencing the handling processes of the decommissioned wind turbine

Figure 45 presents the factors that influence the decisions regarding the handling of the decommissioned wind turbine. In line with the research scope, it focuses on the handling processes for a second lifecycle of the turbine or the blades.



Technical	Legal/regulatory	Economic	Organisational	Market
▪ Turbine design ▪ Turbine condition & expected remaining lifetime	▪ Transport requirements ▪ Export requirements ▪ Waste handling regulation and classification ▪ Product guarantee & warranty	▪ Purchase price ▪ Transportation costs ▪ Storage costs ▪ Costs for refurbishment, repair or upgrading ▪ Sales price ▪ Economics of alternative handling options	▪ Business model & strategy of responsible company ▪ Time window for decision-making and execution ▪ Access to operational & design data ▪ Skills & standards of responsible company ▪ Access to potential buyers on second-hand market	▪ Safety situation of countries ▪ Industry standards ▪ Supply and demand situation at time window of sale

Figure 45. Factors influencing the handling processes of the decommissioned wind turbine. Based on conducted interviews.

The previous process steps with the various influencing factors likely have pre-defined the handling pathway (e.g. owner wants to keep turbines for spare parts management) or narrowed the possible handling pathways (e.g. scope of company responsible for decommissioning). This can lead to a situation where decision-making takes place at different stages in the process chain (see red arrow in Figure 45). Factors of each dimension are presented from the perspective of the company responsible for the handling.

<u>Technical factors influencing the handling processes of the decommissioned wind turbine</u>

3. Decision of handling processes

Technical factors

- Turbine design
- Turbine condition & expected remaining lifetime

Figure 46. Technical factors influencing the handling processes of the decommissioned wind turbine. Based on conducted interviews.

Shown in Figure 46, technical factors are the turbine design, the turbine condition and the expected remaining lifetime. Relevant turbine design criteria were a robust design of the turbine type which is beneficial for the transport and reinstallation as well as the turbine's dimensions and weight. The latter results in different transportation and reinstallation requirements that might also lead to whether a transport is technically or economically feasible, e.g. logistical restrictions might occur in mountain areas or areas with narrow roads.

The condition of the turbine might – in addition to the described factors that occur during the first lifecycle – be negatively impacted through the transport and reinstallation of the turbine and positively impacted through repair, refurbishment or upgrades. Only turbines that are in a functionable condition and not-burnt would be considered for second-lifecycle handling, whereby if a turbine is not functionable, the broken parts could be repaired, refurbished or replaced, which is further described at the section on organisational factors.

For handling on the second-hand market, it is moreover important to estimate the expected remaining lifetime of the turbine at time of decommissioning. Some of the interviewed OEMs expressed that they are able to conduct this kind of analysis and/or are working on improving it. Also, experts of all stakeholder groups and countries underlined that the actual technical lifetime of many turbine types is beyond 20 years for the decommissioned wind turbine types, figures stated varied between 35 to 50 years. Thus, indicating a significant remaining lifetime of decommissioned turbines.

Legal and regulatory factors influencing the handling processes of the decommissioned wind turbine

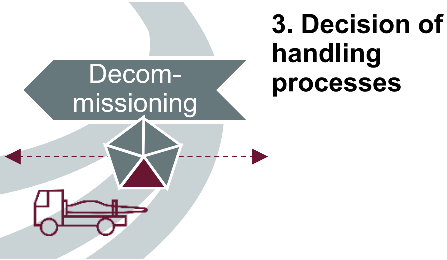
Legal/regulatory factors

- Transport requirements
- Export requirements
- Waste handling regulation and classification
- Product guarantee & warranty

Figure 47. Legal and regulatory factors influencing the handling processes of the decommissioned wind turbine. Based on conducted interviews.

As shown in Figure 47, legal and regulatory factors are the regulation on how to handle waste and requirements for transport and export, as well as regulation on product warranties. The EU Waste Framework Directive defines the cascading management of the waste and further material specific requirements exists, e.g. the disposal of wind turbine blades is not allowed in Germany (Directive 2008/98/EC, 2008; Kühne et al., 2022, p. 42). Also, the European wind industry promotes a European-wide ban on landfilling blades from 2025 onwards (WindEurope, 2020, p. 8). One expert from the German market details that an entire turbine or components can be sold under the classification of being waste and that the buyer then has to move it out of the Waste Hierarchy. As such, the handling varies whether a product guarantee and warranties are provided or not. None of the experts mentioned any export limitations of second-hand turbines or components from Denmark or Germany, but this was also not proactively asked by the questioner of the interviews. One German expert mentioned the requirement to document any export and moreover, for turbine's components that do not fit in a standard truck, transport permission is necessary for road transport in a special-purpose vehicle. Several experts stated that the inflexible permitting process for German roads that takes around three months is driving transport costs and handling times that could in turn result in unfeasible economics for second-lifecycle handling. Also, the permitting process for sea transport is stated to take around three months.

Economic factors influencing the handling processes of the decommissioned wind turbine



Economic factors

- Purchase price
- Transportation costs
- Storage costs
- Costs for refurbishment, repair or upgrading
- Sales price
- Economics of alternative handling options

Figure 48. Economic factors influencing the handling processes of the decommissioned wind turbine. Based on conducted interviews.

As illustrated in Figure 48, various economic factors influence the decision on whether to handle the turbine or its blades on the second-hand market or to enter the other-waste handling pathway. The financial valuation comprises of the revenues for reselling the turbine, components and/or materials, the costs for decommissioning, disassembly, pre-processing, and the subsequent handling.

First of all, it depends on how the profits and risks are shared between the operator of the initial site, the company decommissioning and handling the turbine and the buyer of the second-lifecycle turbine or blades. As such, the company responsible for the handling requires a competitive purchase price on the one side and an attractive sales price on the other side, which is on both sides influenced by market competition and current demand. Most decommissioning experts quoted a purchase price, while a recycler – who is in the client's interest active on the second-hand market – did not purchase the turbines from the customers. Instead if the turbines were resold, the company was financially compensated for the lost revenue from the scrap handling.

The handling costs is expressed as a crucial factor for the likelihood to successfully sell the turbine or its blades on the second-hand market. These costs can consist of transport and storage costs and moreover of costs associated to the assessment of the turbine's condition, refurbishment, and upgrade. As the outline of the circular supply chain processes (see 5.2.3.1) showed, not every expert considered the storage, refurbishment or upgrade of the turbine. The experts agree that transport costs have risen over time in line with the increased size of turbines and are seen as a critical factor for the future development of the secondary market. The increase is not linear, but rather erratic, with a distinction being made between turbines that fit on a standard lorry and those that require a special vehicle and thus more complex logistical planning (including permits). Within the latter, a further split is made between turbines whose dimensions are within or above the clearance gauge. As such the turbine design and more precisely the transport volume of the disassembled components (height, length, width) and weight influences the transport costs. This is underlined by the following two statements:

> *"Transport will have a negative impact on the resale rate in the future. As soon as the systems or components are above the clearance gauge, it becomes difficult."* (Germany, stakeholder 'decommissioning company wind turbines')
>
> *"For the very small turbines, we of course pack the whole nacelle on the lorry, because it is exactly 2.50 metres wide, we can put it on a normal cheap lorry and that arrives at our facility. And then, from a megawatt upwards, it is no longer possible."* (Germany, stakeholder 'project developer & operator or service company')

Moreover, the costs are impacted by the transport distances and market prices for freight and road transport. One interviewee that exports with sea freight stated that the freight prices are very volatile, for instance during Covid-19, which complicates the planning. Another expert pointed out that road transport in Germany, for example, has recently been affected by the rise in petrol prices and since beginning of 2024 the road tolls were significantly raised. Increased transport costs are also the reason why the experts stated that they would not consider storage as an option at all, or only in a few cases, because otherwise further transport routes would be necessary. Storage costs are driven by the size of the turbine and the costs of the storage facility. It also takes into account the amount of capital tied up in inventory and the risk that the turbine and its components become dead stock or take up space for more profitable or high-demand parts. Dead stock means that there is no demand for the turbine for an individually defined period of time, which would result in the turbine being written off and entering a handling path at the component, part or material level. From the perspective of a service company, this is emphasised by the following:

> *"So, this quota of dead parts that you actually have, parts that you once took somewhere because you thought you needed them and then didn't need them, always poses a great risk. […]. With us, it's the case that we keep a lot of new parts in stock for our service jobs, and the storage capacities are therefore limited."* (Germany, stakeholder 'project developer & operator or service company')

Furthermore, costs for the assessment of the turbine's condition and its remaining lifetime as well as costs for repair, refurbishment or upgrades occur, depending on the demand. For instance, one decommissioning expert, covering Denmark and Germany, mentioned that for some turbine types they would be able to upgrade the turbine to ensure compliance to the grid codes of the demanding country. On an overall note, an expert from an OEM observed that it is currently difficult to generate sufficient synergies across projects, as the handling of second-hand turbines is relatively complex and varies across projects with a lack in standardisation. Next to the economics for second-hand handling, also the economics of alternative handling routes were considered by many experts. One expert provided the example of soaring market price for scraped metals in 2022 that made it during this time economically more attractive to scrap the turbine than to sell it. Otherwise, this expert stated that it was economically more attractive to sell the turbine.

Organisational factors influencing the handling processes of the decommissioned wind turbine

3. Decision of handling processes

Organisational factors

- Business model & strategy of responsible company
- Time window for decision-making and execution
- Access to operational & design data
- Skills & standards of responsible company
- Access to potential buyers on second-hand market

Figure 49. Organisational factors influencing the handling processes of the decommissioned wind turbine. Based on conducted interviews.

As shown in Figure 49, organisational factors are the business model of the company handling the decommissioned turbine, the time window for decision-making and execution, and access to operational and design data. Further factors are skills and standards of the responsible company, and access to a potential buyer on the second-hand market.

First, the business model and strategy of the responsible company can vary, as also already expressed in the previous paragraph. Whether the company considers the second-hand market for turbines or blades as part of their business portfolio, impacts the chosen handling pathway. The differences are illustrated by the following text passages from a variety of stakeholders:

> *"Decommissioning and exporting second-hand turbines is our only business"* (Germany, stakeholder 'decommissioning company wind turbines')
>
> *"Selling the turbine on the second-hand market is preferable for the owner and as we are interested to get contracted for future projects, we try to resell"* (Germany, stakeholder 'recycler & dismantler')
>
> *"We try to find a buyer for the entire turbine and otherwise focus on reselling spare parts"* (Germany, stakeholder 'decommissioning company wind turbines')
>
> *"We are a recycler, we come into play when no structural value remains"* (Germany, stakeholder 'recycler & dismantler')
>
> *"Normally all the turbines that we take down, we strip for parts and then we reuse them for our existing fleet."* (Denmark, stakeholder 'project developer & operator or service company')

The business model and strategy also vary depending on whether further processes such as refurbishment or storage are considered for the turbine type, e.g.:

> *"Refurbishment is not part of our business, we are a logistic company and cannot provide a product guarantee."* (Germany, stakeholder 'decommissioning company wind turbines')
>
> *"Actually, we do buy wind farms and then decommission and inspect if we can refurbish for a second life and see if this is technical and economical feasible and if not, we go for recycling."* (Denmark & Germany, stakeholder 'decommissioning company wind turbines')

This exemplifies that the handling options considered depend on the core business activities of the responsible company, whether synergies can be created, and the risk-return-profile that the company is seeking.

Secondly, the time window for taking the decision and to execute the handling of the decommissioned turbine is influenced by several factors. On the one hand, if the responsible company does not have sufficient preparation time they might not have enough time to get the transport permits and to contact potential buyers. A German decommissioner referenced to ideal 6-12 months of preparation time (including finding a buyer) before decommissioning and another one requires 5-6 months for the planning. On the other hand, it was also noted that the demand situation on the second-hand market varies and it is therefore not advisable to look for a buyer too early; according to two experts, around 3-6 months before decommissioning is the earliest. Most of the experts stated that they determine the handling path – second lifecycle or other waste-handling pathway – before or during the actual decommissioning, while one company operating in Denmark stated that it does not want to get pushed to settle on a handling pathway and therefore decouples through interim storage. Other experts who had the ability to store at their facilities would only store an entire turbine if they already had a buyer, and others had no capability to store. However, in some cases the operator of the site, is allowing for interim storage at the project site.

Third, access to operational and design data of the turbine positively impacts the accuracy of assessing the remaining lifetime of the turbine. In this context, a decommissioning company with a large market share in the German market reported that it always requests information from the customer about when components or parts were last replaced or repaired. Another expert that has decommissioned in Denmark and Germany, also mentioned that they often are able to get access to the maintenance and operation history, as this would be important to assess the potential for the second-hand market.

Forth, skills/knowhow (e.g. on export procedures, refurbishment of specific turbine types) and standards of the responsible company are influencing the handling processes taken. The company standards were usually defined by legal and regulatory requirements, but the decision-making process might be company-specific, e.g. if you store a turbine for a specific time period prior to selling of components and spare parts or not.

Fifth, access to potential buyers on second-hand market, either per online market platform or bilateral. As such, a German recycler highlighted that a completely different kind of network would be required, as the second-hand market is a global market and the recycling market a local market. Indeed, experts active on the second-hand market for turbines or spare parts confirmed that they predominately export. Next to having a common language with the potential buyer or broker, a strong partner network is stated as an important factor throughout the majority of the interviews. Most experts exclusively used their own network with established and trusted business relationships to reduce the risk of a contractual default or project delays. For example, three experts that have decommissioned significant amounts of turbines in Germany reported that several brokers are only pretending to have a buyer for the turbine or try to re-negotiate after the order was accepted.

Market factors influencing the handling processes of the decommissioned wind turbine

3. Decision of handling processes

Market factors

- Safety situation of countries
- Industry standards
- Supply and demand situation at time window of sale

Figure 50. Market factors influencing the handling processes of the decommissioned wind turbine. Based on conducted interviews.

In accordance with Figure 50, one market factor that is mentioned by the experts was the security situation of the countries through which the turbine is transported and re-installed. For example, prior to the war in the Ukraine, second-lifecycle turbines were transported through the Ukraine and Russia to Kazakhstan, which has stopped since then. In addition, a factor observed by an OEM is a lack of industry standards in the handling of second-hand turbines. Another identified factor is the expected and actual supply-demand situation at the available time window of sale. Experts that sold second-hand turbines explained that for specific turbine types the demand used to be greater than the supply, but this has now shifted, as more and more turbines per turbine type are decommissioned and therefore the buyer more often can cherry pick across turbines. Despite, an expert added that thanks to their established network of resellers, they know the demand, which enables them to assess the likelihood of reselling the to-be-decommissioned turbines and hence determine the handling pathway. However, it was recognised that the demand side could also further grow with new markets to be developed. However, most interviewed experts of the handling companies were uncertain or pessimistic for the future development, as just recently markets have closed.

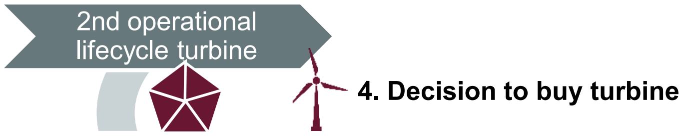
Conclusion

All in all, the person deciding on the handling pathway of a decommissioned wind turbine evaluates available handling options within their business scope, with profitability being the most prominent criteria, but depending on the client and project, also execution time and reputation play a role, according to the interviewed experts. Most prominently mentioned were the handling costs (particularly transport costs), which often determine whether a project is economically viable or not, and demand for the turbine type through their own trusted network of established business partners within the relatively narrow time window.

Factors influencing the demand for second-lifecycle turbines

Figure 51 shows the factors that influence the demand for second-lifecycle turbines and hence the decision-making of the buyer.

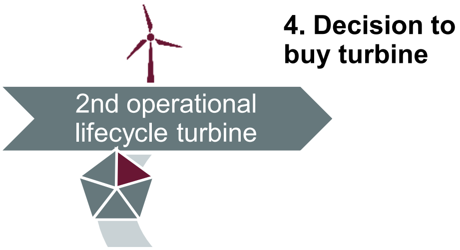
4. Factors influencing the demand for second-lifecycle turbines



Technical	Legal/regulatory	Economic	Organisational	Market
▪ Turbine design ▪ Turbine condition & expected remaining lifetime ▪ Expected maintenance plan ▪ Wind conditions at new project site ▪ Availability of spare parts	▪ Import requirements ▪ Available grid connection at site ▪ Grid code of country ▪ Requirements for certification beyond design lifetime ▪ Permitting requirements (e.g. minimum distances to households, height restrictions, environmental standards)	Economic feasibility of project: ▪ Initial investment ▪ Expected income ▪ Expected operational costs ▪ Expected decommissioning costs Economics of alternative turbines	▪ Skills of responsible company ▪ Type of buyer	▪ Crane infrastructure in country ▪ Available land in country ▪ Safety situation in country ▪ Experience with second-hand turbines ▪ Energy system & long-term planning ▪ Economic status of country ▪ Grid voltage

Figure 51. Factors influencing the demand for second-lifecycle turbines. Based on conducted interviews.

Technical factors influencing the demand for second-lifecycle turbines



Technical factors

- Turbine design
- Turbine condition & expected remaining lifetime
- Expected maintenance plan
- Wind conditions at new project site
- Availability of spare parts

Figure 52. Technical factors influencing the demand for second-lifecycle turbines. Based on conducted interviews.

According to Figure 52, technical factors identified are the turbine design, turbine condition and its expected remaining lifetime. Further factors are the expected maintenance and repair frequency, and the wind conditions at the new project site.

The turbine type is mentioned throughout all interviews as decisive criterion whether a turbine is demanded on the second-hand market. Some of the design criteria mentioned by the experts as having stimulated demand are shown in Table 14. These were, for example, specific turbine heights and dimensions, specific OEMs and/or robustness in the presence of extreme weather conditions. Also, expressed criteria were less complexity in design, type of control system, grid compliance, and known average technical lifetime. The examples in Table 14 illustrate that some of these criteria are linked to the handling processes (e.g. logistical restrictions in mountain areas) and others to the other dimensions described below (e.g. subsidy for wind turbines of small power output). Therefore, the design criteria are not necessarily applicable to the different framework conditions of countries, buyers and project locations.

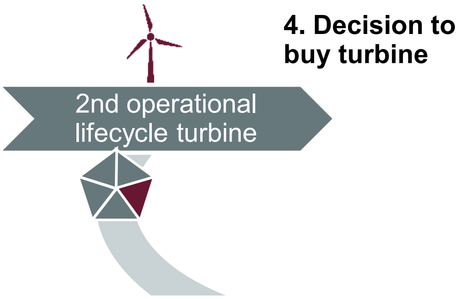
Table 14. Overview of turbine type's criteria that led to demand on second-hand market. Based on conducted interviews.

Turbine design criteria	Examples given by interviewed experts
Specific turbine height and dimension	▪ Small turbines (e.g. E40) in UK, Italy ▪ Mountain areas, where large turbines cannot access ▪ Attractive transport size (e.g. standard truck, below clearance gauge)
Particular OEM	▪ OEMs with positive track record in access to spare parts (e.g. Vestas) ▪ OEMs with service infrastructure in country (e.g. Vestas in Italy) ▪ Brand's reputation ("*they want the 'Volkswagen' of the wind industry*") ▪ OEM still in business (e.g. Enercon) and not closed-down
More mechanical parts instead of software parts	▪ Turbines with more mechanical parts can also be maintained by engineers that have their background in maintaining agricultural machinery ▪ Turbines with electro-mechanical parts, "*only fails at the beginning or never and easier to get spare parts - with new turbines that have a lot automation technic and software it could get more difficult*"
Less complexity in design	▪ Easier to operate and maintain
Pitch or stall-regulated control system	▪ Possibility to downregulate to be able to receive subsidies in Ireland for small power generation ▪ Stall-regulated turbines are often not compliant to the grid code
Operating voltage	▪ Turbines from Germany have 50 Hz, thus not compatible in the USA
Durability	▪ There are some turbine types that are known for being more durable ▪ Several older turbine types have significantly higher technical lifetimes after 20 years ▪ Turbines from 4 MW onwards, not known yet ▪ Robustness to extreme weather conditions

A highly relevant technical factor, mentioned for continued operation at the initial site and for a second-lifecycle operation of the turbine, is the availability of spare parts for the specific turbine type. A common assumption in the market expressed by several of the interviewed experts is that if you buy a turbine of a turbine type that has been commonly installed, then the likelihood of finding spare parts is high. This is due to the fact that new spare parts are usually no longer available for the old turbine types, as the OEMs typically have closed down production. To add to that, the existence of service infrastructure for the turbine type or more generally from the OEM is a crucial factor. One expert provides the example of Italian customers that mostly request Vestas turbines due to having access to their service. In this context, turbines from OEMs that are not anymore active (e.g. bankrupt) are less attractive. Also, the wind conditions at the new site are influencing which turbine type is suitable for the new site. For instance, a German expert mentioned that E40 turbines are particular suitable for the windy coast line in the UK. For the demand of a specific turbine, also the condition of the turbine and consequently the expected remaining lifetime and repair and maintenance expenses are of relevance. In this light, experts of both markets and all stakeholder groups stressed the point that the 20-year design lifetime is not a threshold at which demand would not occur anymore. Instead, they stated that the age of the turbine at the time of decommissioning did not play a role. However, two experts from Germany mentioned that, more recently, it has sometimes played a role when other turbines of the same type are available on the second-hand market. This is illustrated by the following:

> *“Age doesn’t really play a role – it is more about finding the spare parts”* (Denmark, stakeholder ‘decommissioning company wind turbines’)
>
> *“So, this German design life doesn't really play a role when exporting abroad. As I said at the beginning, it depends more on the type of tower, whether it is completely oversized or quite slim, so that there is not much left. However, for some projects, I can only say that age does play a role in sales, especially if there are models of the same type on the market at the same time and they are competing with each other. [...] The same type of turbine, but from different vintages, could have a completely different software version, and then suddenly one turbine is still worth something and the older vintage is not worth anything at all. And that competitive situation is kind of the deciding factor, so it's really a bit of a gamble. [...]. But basically, if you look at the components, a component from an older turbine might still be in better condition than one from a younger vintage; that can happen.”* (Germany, stakeholder ‘project developer & operator or service company’)

Legal and regulatory factors influencing the demand for second-lifecycle turbines



Legal/regulatory factors

- Import requirements
- Available grid connection at site
- Grid code of country
- Requirements for certification beyond design lifetime
- Permitting requirements (e.g. minimum distances to households, height restrictions, environmental standards)

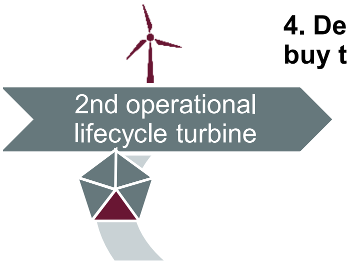
Figure 53. Legal and regulatory factors influencing the demand for second-lifecycle turbines. Based on conducted interviews.

As shown in Figure 53, various legal/regulatory factors exist that differ across countries and either hindered or promoted the demand for second-lifecycle turbines. An important influencing factor is a positive regulatory setting for importing, transporting, reinstalling and operating second-lifecycle turbines in a country, as it otherwise has led to significant barriers or the closure of the market. For instance, several experts from Denmark and Germany reported that Poland's second-hand market has been closed.

General legal requirements for installing new wind turbines – without differentiating between first-lifecycle and second-lifecycle turbines – exist that determine the eligibility of specific turbine types. In the case that the new-generation, larger turbines are not meeting the legal restrictions, only second-lifecycle and hence smaller turbines are an option. This might be defined by the available grid permit at the location or by strict permitting requirements for minimum distances of the turbine to households and height restrictions of the turbine. Exemplary, this was expressed by the experts for Italy and France. However, it was also added that in some countries (e.g. in Eastern Europe) the regulation has changed over time and as such opened up the market for bigger turbines, which consequently led to a reduced demand for smaller turbines. Moreover, local permitting requirements might require certifications on the safety of the turbine (e.g. stability assessment of turbine beyond the design lifetime) and the compliance with environmental standards. Moreover, the grid code in the respective country defines whether a turbine type is eligible or not, which can result in excluding old turbines that are for instance not pitch-regulated, but operate with stall-regulation. Again, some experts said that this has changed over time and that the requirements were low at the beginning when the first renewable energy projects were installed in a country and then increased over time as more flexible control of the grid became more important. Furthermore, some countries have set specific requirements for the import, reinstallation and operation of second-lifecycle turbines. For example, one German expert stated that Turkey only allows in accordance to import requirements the import of used turbines up to a maximum age.

In summary, specific turbine types, particularly of the first generation, are likely not suitable to be reinstalled again in several countries. The experts also reported that the reinstallation is not eligible in Denmark and Germany, which is also shown by the findings in 5.2.2 since none of the decommissioned turbines were reinstalled in Denmark and Germany.

Economic factors influencing the demand for second-lifecycle turbines



4. Decision to buy turbine

Economic factors

Economic feasibility of project:
- Initial investment
- Expected income
- Expected operational costs
- Expected decommissioning costs

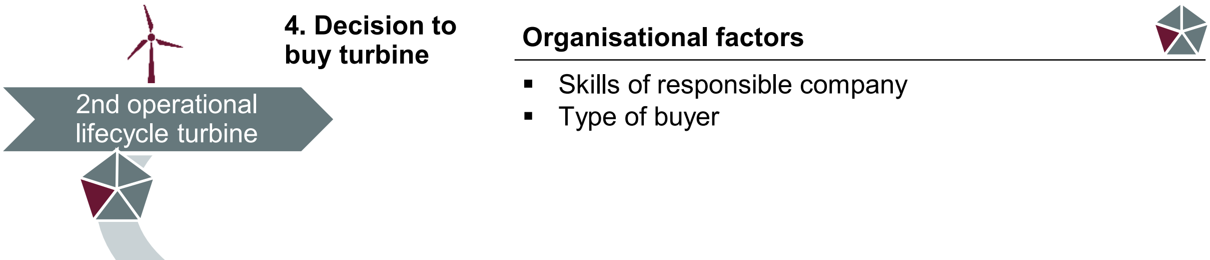
Economics of alternative turbines

Figure 54. Economic factors influencing the demand for second-lifecycle turbines. Based on conducted interviews.

In accordance to Figure 54, there are various economic factors that affect the potential buyer's financial calculations. These include the initial investment costs, the expected annual income and costs and the expected decommissioning costs. In addition, the valuation is influenced by the planned project term and the financing costs.

The initial investment consists of the purchase price for the turbine, eventually transportation costs (if not carried by the seller) and reinstallation costs (incl. permitting costs etc.). The transportation costs were already explained in the section on handling, and therefore it is just noted that the transport can also be organised by the buyer and as such its costs carried. The total initial investment is lower for second-hand turbines than for new turbines with a larger installed capacity, which is why some buyers preferred smaller turbines. The expected annual income for the planned power generation depends on market subsidies, and if not existing or eligible for second-hand turbines, then on the level of (expected) market power prices or negotiated PPA's. Ireland was reported by the experts to provide subsidies to small-scale wind turbines (i.e. small power output per turbine) that also led to demand for slightly larger pitch-regulated turbines that were then down-regulated (see Table 14). Experts also mentioned that in other countries only new turbines were eligible for the subsidy scheme. In addition, revenues could be generated through trading CO2 certificates. Moreover, the total expected revenues depend on the planned project term, that is dependent, amongst others, on the expected remaining lifetime of the turbine. Moreover, the expected operational costs are considered in the economic assessment, which are influenced by the turbine type, the turbine condition and expected maintenance plan. Furthermore, operational expenses are influenced by the service strategy and any economies of scales (e.g. through installing multiple turbines at a wind farm). If the overall expected return of the project is considered economic feasible by the buyer, then the project might be pursued. Experts of both countries state that the transportation costs of turbines above around 1 MW are often too high; but also, long-distance transportation could result in unattractive economics (see previous paragraph on handling). Despite, an expert from a decommissioning company from Germany recalls that the payback time of recent projects is still good; as the projects were expected to be rentable after roughly 4-5 years. On this note, another expert concludes that it is similar to the second-hand market for cars, hence a buyer can always be found depending on the offered price. Furthermore, the expected return of acquiring and reinstalling a specific second-hand turbine type might be compared to alternative new or second-hand turbine types. Due to the technological progress in the last decades, newer generations of turbines are more effective and as such more profitable as smaller used turbines. One expert gives an example by comparing the cost of a V80 on a certain location at around 4 cent per kWh to an V162, which would cost on the same location around 3 cent per kWh. This adds to the rationale that smaller turbines are likely only chosen when larger ones are not eligible at that project site or the buyer does not have access to the larger ones or the initial investment would otherwise exceed the available budget. This also justifies why the demand on the second-hand market changes towards larger turbines over time. One expert illustrated this with the example of demand for E40 turbines from Enercon. Initially these were in demand, then only the E40 spare parts, and finally more of the newer E66 turbine type.

Organisational factors influencing the demand for second-lifecycle turbines



Organisational factors

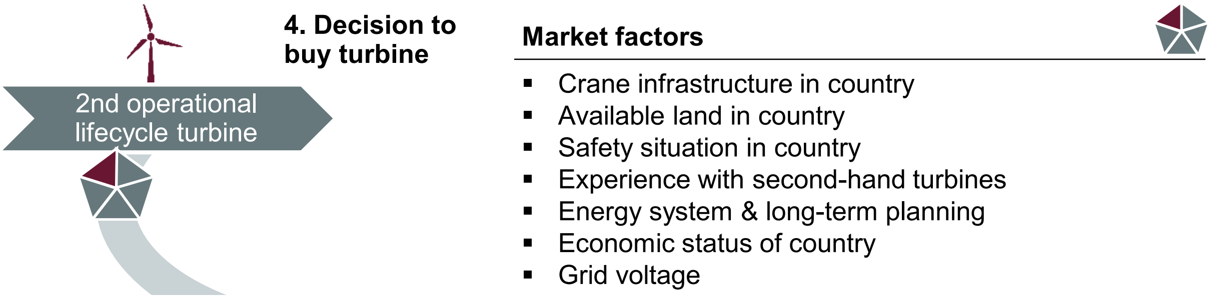
- Skills of responsible company
- Type of buyer

Figure 55. Organisational factors influencing the demand for second-lifecycle turbines. Based on conducted interviews.

Figure 55 illustrates that also organisational factors impact the decision to buy a second-hand turbine. On the one hand, the skills/knowhow of the buying company/person or its subcontractors to reinstall and operate the specific turbine type, and on the other hand, the demand varies according to the type of buyer.

Types of buyers identified as being likely to be interested in second-hand turbines were companies or individuals with a demand for their own energy consumption, demand for single turbines or for spare parts management of their serviced or operated wind turbine fleet. In contrast, large project developers were stated as typically only considering to develop wind parks with new and thus larger turbines. One stated reason for ownership and decentralisation of energy production is to ensure energy security, especially relevant for industrial companies and individuals in rural areas. An example given was that of manufacturing companies such as mining companies in Australia. Moreover, the private industrial and private sector likely demands single turbines, which are more difficult to procure from OEMs and as such promote demand on the second-hand market. Finally, demand occurs by operators and service providers of large wind turbine fleets, especially by large utilities and independent service providers. On the one hand, the to-be-decommissioned wind turbine might be kept for the spare parts management of the initial operator or on the other hand, is sold to independent service providers. In regard to the latter, one expert specified that the favoured models in Germany are currently E40, E66 and E70 is also demonstrating nascent growth.

Market factors influencing the demand for second-lifecycle turbines



Market factors

- Crane infrastructure in country
- Available land in country
- Safety situation in country
- Experience with second-hand turbines
- Energy system & long-term planning
- Economic status of country
- Grid voltage

Figure 56. Market factors influencing the demand for second-lifecycle turbines. Based on conducted interviews.

Shown in Figure 56, market factors identified throughout the interviews were when crane infrastructure for larger turbines were not existing in the country. Furthermore, countries with extensive land areas and no shortage of land are more conducive to second-hand turbines, as smaller turbines necessitate a greater number of turbines to achieve the same electricity generation output, consequently requiring more space. More generally, the demand for new power generation and the economic status of the country were mentioned. Wars are also likely to have triggered demand in regions, as new energy infrastructure was needed. In addition, energy markets with market risk exposure, i.e. without a feed-in system, are likely to stimulate demand from private industry and the private sector for their own electricity generation. Also, the grid voltage in a given country determines the compatibility of a decommissioned turbine from Denmark or Germany – which were designed for 50 Hz – for use in that country, thus explaining why the USA is not a market for such turbines. Finally, a further market factor identified were the existing experience in installing second-hand turbines and operating those in the country's energy system, e.g. implying (first) experiences by service providers (e.g. crane) and municipalities.

Finally, Table 15 provides an overview of the various countries mentioned that have demanded second-lifecycle turbines or have been identified as ineligible markets.

Table 15. Overview of countries in terms of demand for second-lifecycle turbines. Based on conducted interviews.

Country	**Did experts export?**	**Explanations given by interviewed experts**
Denmark	No	▪ Only as spare parts, never a turbine reinstalled
Germany	No	▪ Too costly to retrofit for grid compliance ▪ Did not remain in Germany due to requirement for lifetime extension certificate and not getting approval for grid connection
USA	No	▪ Different line voltage
Italy	Yes	▪ Prefer Vestas, access to Vestas service ▪ Strict height restrictions at project sites ▪ Nowadays a little less demand ▪ One expert stated that Italy and Ireland have nearly taken everything in the last 10 years ▪ Especially small turbines; became a remuneration for a while.
Canada	Yes	▪ Only turbines from certain OEMs
Australia	Yes	▪ Only turbines from certain OEMs ▪ During Covid-19, shipping costs increased significantly, making a planned second-lifecycle project uneconomical ▪ Demand by companies in rural areas (e.g. mining industry)
Poland	Yes	▪ Used to be a very attractive market; not allowed anymore
Moldavia	Yes	▪ Came as market after Poland closed. One expert expects that the market will close soon
UK	Yes	▪ Demand mostly small turbines ▪ Many of the E40 went to the UK, in particular at the windy coast line
Ireland	Yes	▪ Only pitch-regulated turbines, as otherwise not possible to down-regulate and hence qualify for subsidy scheme. Vestas started with pitch system relatively early ▪ One expert stated that Italy and Ireland have nearly taken everything in the last 10 years ▪ Demand smaller turbines
Turkey	Yes	▪ One expert mentioned to frequently export to Turkey ▪ Two other experts mentioned that they heard it is not allowed anymore, as Turkey has introduced import requirements in regard to a maximum turbine age
Ukraine	Yes	▪ Used to be a good market before the war, but stopped due to the war

Country	Did experts export?	Explanations given by interviewed experts
Kazakhstan	Yes	▪ Used to be a good market before the war in the Ukraine. Stopped as it would require transport through the Ukraine and Russia ▪ Prefer mechanical, less complex turbines over high-software/electronic-based turbines as it's less knowledge intensive to do maintenance and it is more robust for more extreme weather ▪ More or less closed due to logistics through Russia and the Chinese are very active in Kazakhstan as we speak
France	Yes	▪ Demand smaller turbines ▪ It's more like the countries like Ireland, Italy or even France with height restrictions or basically permit restrictions or grid restrictions or let's say logistic restrictions
Other countries mentioned with second-lifecycle turbines: Rumania, Bulgaria, Morocco, Czech Republic, Kirgizstan, Slovenia, Estonia, Sweden, South American countries, Spain, Belarus, etc.		

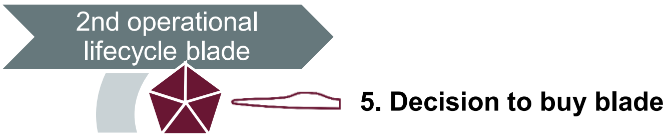
Conclusion

All in all, a buyer of a wind turbine evaluates the available turbine options for its intended site, depending in particular on national and local regulations. With the economics being a key evaluation criterion, the demand for second-hand turbines is particularly pronounced in instances where large turbines are not eligible for use. This is justified by the fact that second-hand turbines are less profitable than new and larger turbines. When intending the purchase of a second-hand turbine, there is a demand for certain turbine types that meet the legal/regulatory and market conditions, are the most economically viable, have sufficient remaining life, and have access to service and spare parts during operation.

Factors influencing the demand for second-lifecycle blades

The quantification of the pathways taken by the decommissioned turbines has revealed that blades as spare parts were only sold or kept in a few instances; for Denmark in the order of magnitude of 2 % and for Germany of 4 % (see Figure 25). As such, experts either did not sell any spare blades or only to a marginal extend. Therefore, not for every dimension influencing factors are identified and thus the following mostly outlines reasons for why the blades are not sold as spare parts and provides a brief overview of spare parts management. Figure 57 summarises the factors observed that influence the demand for a second lifecycle of blades as spare parts. In addition, the factors outlined in Figure 51 may also apply to the demand of second-lifecycle blades, e.g. the availability of adequate crane infrastructure.

5. Factors influencing the demand for second-lifecycle blades



Technical	Legal/regulatory	Economic	Organisational	Market
▪ Blade design ▪ Blade condition & expected remaining lifetime ▪ Blade compatibility to wind turbine types	*No factor mentioned.*	▪ Economic feasibility	▪ Spare parts management and current stock levels	▪ Total installed wind turbines with blade type

Figure 57. Factors influencing the demand for second-lifecycle blades. Based on conducted interviews.

Several experts stated that almost no demand for blades as spare parts exist, as blades usually do not fail during the planned operation period of at least 20 years. Also, beyond 20 years, blades still have a significant remaining lifetime and moreover, to some extend repairs during operation like leading edge protection are possible. An expert from an OEM stated that they prefer to repair the blade instead of recycling as long it is still repairable and economic feasible. A technical factor that has an impact on the demand for a second-lifecycle blade is the occasion of a lightning strike or another extreme weather event. In such cases the blade set can be replaced with a set of second-hand blades, if economically feasible and available. These kinds of events are rare and hence only a low quantity of spare blades is usually required. The demand of blades from a decommissioned turbine is also influenced by whether the blade type is compatible to various wind turbine types or only to a specific turbine type. Next to technical reasons for a lack in demand, also economic reasons were identified. With an increase in blade size, the transport and storage costs are high and as such, most of the interviewed decommissioner and recycler either sold the blade directly from the decommissioning site or it entered the other-waste handling pathway. This underpins that the window for finding a buyer is relatively narrow.

As a blade failure of an operating wind turbine would result in a stop of electricity production and thus a loss of revenues, operators and service providers do consider to store spare blades. A common rule of thumb that was stated by the operators and service providers of the interviews was to store one set per blade type, but only for the types which they were still operating in feasible quantities (e.g. E40). As such, also driven by the economics, it again underlines that only marginal quantities of blades as spare parts are demanded. Similar to wind turbine types, hence only specific blade types (e.g. from Vestas and LM) were demanded and of those only blades in good conditions or repairable ones. Usually, a full set of blades is demanded in order to avoid a rebalancing of the blades. Alternatives to second-hand blades are usually not available, as new blades of the older wind turbine types are no longer manufactured by the OEMs. One OEM expressed that for specific turbine types which were installed in large quantities, they might consider to reproduce. Another OEM stressed that it would be too costly to relaunch for small quantities and also the moulds for the old blade types would no longer exist.

Therefore, it is the standard procedure to acquire spare parts for older turbine types on the second-hand market by operators, OEMs and independent service providers. Another possibility is that the operator keeps spare parts during a decommissioning project from the operator’s own wind turbine fleet. Moreover, one expert that services wind turbines and offers decommissioning, also reported that they assess whether to keep spare parts. In this light, experts that service/operate wind turbines expressed that operators or service providers also collaborate and help each other with spare parts in the Danish and German market. Also, the OEMs purchase spare parts on the second-hand market for the turbine types in service, if they no longer have any new spare parts in stock. The interviewed experts from the OEMs reported that they usually aim to have a stock of spare parts for each wind turbine type of their turbines in service. One reported strategy is to initially produce new spare parts, but to stop at a certain point, even though the turbines are still in operation, in order to free up the production lines for new turbine types. Accordingly, one last large batch is produced before production is discontinued, after which spare parts are purchased on the secondary market. In addition, a further approach to ensure access to spare parts during the turbine’s service life is through the commonly applied service concept of swapping broken parts with fixed ones (so called swap concept). If a part fails in operation, it is taken back and replaced with a new/repaired/refurbished part, and then the failed part is repaired/refurbished by the service provider for use at a new site, if technically and economically feasible.

All in all, the demand for spare blades from decommissioned wind turbines is rare and only exists for blade types that are still in operation. In addition, as the blade size has increased over the years, the decision for a second lifecycle is increasingly being made at the decommissioning site to reduce handling costs. This shortens the decision window.

Conclusion

In summary, the findings of the analyses from chapter 5.2.3 allow to answer RQ4. Circular supply chain processes by multiple stakeholders are identified for decommissioned onshore wind turbines from Denmark and Germany. For a second lifecycle of the blades as part of a second-lifecycle turbine or as spare part, different possible process chains are identified. The development of those processes depends on several technical, legal/regulatory, economic, organisational and market factors, which influence the supply, demand and the supply-demand matching of decommissioned onshore wind turbines and their blades on the second-hand market.

Key factors identified include:

- The turbine’s condition and its remaining life at the time of decommissioning
- The design of the turbine type in terms of durability of the turbine, compliance with requirements of the demanding country (e.g. grid code, height restrictions) and a design that allows for appropriate decommissioning and disassembly
- The turbine manufacturer with its reputation and access in regard to spare parts and availability of service technicians
- Availability of spare parts
- Business practices of the decommissioning and handling company
- Regulatory requirements and subsidy schemes in the demanding country

In a nutshell, companies that considered a second-hand market, usually started their handling hierarchy at the turbine level and in the course of the process moved down to the component level, then to the parts level, and then considered scrapping the material, if there was no economically viable demand for any of the higher levels. History has also shown that a sufficient remaining life for turbines of different turbine types was usually not an obstacle to a second lifecycle. The key decisive factor was whether there was demand for the turbine existed at the time of decommissioning. Demand for specific turbine types depends on the economics of the project at the new site, which are pre-determined by regulatory and market conditions. If, for various reasons (e.g. height restrictions), the buyer wanted to acquire a particular turbine type on the second-hand market, the economics of that turbine and possible alternatives were assessed. This is summarised with the following two questions:

- Are the costs of purchasing this second-lifecycle turbine and the handling, particularly transport, economically feasible in relation to the expected revenues from operation at the new project site?
- And is this second-lifecycle turbine attractive compared to alternatives such as new turbines and other second-lifecycle turbines?

5.3 Discussion

The chapter provides an evaluation of Part A by comparing the empirical findings to the CSCM framework (5.3.1). It moreover discusses the main findings of Part B (5.3.2), followed by an assessment of the limitations in relation to RQ3 and RQ4 (5.3.3).

5.3.1 Comparison to theoretical understanding of Part A

Part A has introduced a literature-based CSCM framework for the wind industry that includes the forward supply chains and the supply chains that enable the circular flows in closed or open loops (see Figure 14). Building on this, Part B explored the circular supply chain processes and historical flows for decommissioned onshore wind turbines in Denmark and Germany. The following outlines the findings from the comparison of the empirical results with the conceptual understanding by discussing the two key elements of the CSCM framework, namely:

- Multi-level embedding of circular thinking in SCM with interconnections between and within CSCM levels
- Enabling circular flows in the value chain network in closed or open loops

The empirical investigations indicate that the multi-level structure of the CSCM framework and their interconnections is useful in practice. In regard to the organisational level, the experts interviewed identified factors that occur at the industry and market level and thus involve stakeholder management at the organisational level. For instance, the DIN Spec 4866 was a joint effort by supply chain actors in Germany to define a common standard for sustainable decommissioning practices. In addition, various organisational factors are mentioned in the interviews, e.g. the business strategy, business plan, business practices and available capacities. At the products level, the empirical study centred on turbines and blades and presents that the fulfilment of circular design criteria, such as durability or design for decommissioning, varies according to turbine type. Finally, on the processes level various circular supply chain processes (e.g. reinstallation of a decommissioned wind turbine) are identified, consisting of the main processes of the extended SCOR-model and sub-processes (e.g. inspection, storage) that emerged to be relevant for the flow of the turbine and blade along the pathways. In contrast, the conceptual design of the circular supply chain network is not as detailed for the second-lifecycle supply chain processes as the observations. This is due to the fact that the framework considers the main processes of the extended SCOR model, but does not further detail sub-processes.

The second key element of the CSCM framework is the objective to enable circular flows in the value chain network in closed or open loops. This is seen in practice in the decommissioning of wind turbines and their handling in Denmark and Germany, as a second lifecycle in another country is a common strategy. In theory, the product flows should follow the cascade of the R-ladder. Accordingly, there is an alignment, as observations in practice show that many experts first consider the upper strategies of reusing the turbine as a whole. However, this is not always the case due to the decisions of the stakeholders and the technical, economic, organisational, legal/regulatory and/or market feasibility.

Furthermore, Figure 58 is structured to show the 9R-ladder from theory and how they are aggregated into the three pathways used to study the turbine and blade flows in practice. It shows that the R-principles are being realized in practice, with only the R6-Remanufacturing of the turbine and the blade not being identified in the interviews. As outlined in the state of the art of second-lifecycle practices of blades, remanufacturing is technical not feasible for the current blade design (see 2.4.2). Therefore, it does not surprise that this R-principle is not observed in practice. Also, the remanufacturing of the entire turbine is not explicitly mentioned by the experts. Nevertheless, a few experts mentioned that they intend to work on a recertification process for decommissioned wind turbines that could indicate processes towards remanufacturing. In addition, experts approved that a high-value recycling solution for blade composites is not yet established and therefore listed repurposing, downcycling, energy recovery and landfill as strategies of the other-waste handling pathway.

	Theoretical understanding	**Observations for decommissioned onshore wind turbine in Denmark and Germany**		
	R-principles	*Second lifecycle as entire turbine*	*Second lifecycle as blade*	*Other-waste handling of blade*
R-PRINCIPLE LADDER	**R3 Reuse**	✓	✓	N/A
	R4 Repair	✓	✓	N/A
	R5 Refurbish	✓	✓	N/A
	R6 Remanufacture			N/A
	R7 Repurpose	N/A	N/A	✓
	R8 Recycle	N/A	N/A	(✓) downcycle
	R9 Recover	N/A	N/A	✓
Landfill				✓

Figure 58. Comparison of 9R-ladder by Potting et al. (2017, p. 15) and the observed circular strategies for decommissioned onshore wind turbines in Denmark and Germany.

When viewed in the context of the entire supply chain network, it is clear that circular flows are being considered, but not at every stage, as outlined below:

- Manufacturing new turbines:
    - Components and parts from decommissioned turbines are not used in the manufacture of new turbines due to rapid technological advances.
    - Recycled materials are used in the manufacturing process, however not for composites as a technical and economically viable solution is still in development.
- Refurbishment of decommissioned turbines: Use of new components or components from decommissioned turbines (with or without prior refurbishment or remanufacturing).
- Installation of turbines: Mostly new turbines due to the rapid technological progress, but also decommissioned turbines with or without prior refurbishment.
- Spare parts management of turbines in operation: Depending on the availability of spare parts of the turbine type, either spare parts from decommissioned turbines (with or without prior refurbishment or remanufacturing) or new spare parts. For older turbine type new spare parts are usually not manufactured anymore.

Furthermore, the observed circular flows occur in open or closed loops and are hence in accordance of the theoretical understanding. For example, blade reuse happens in closed loops when the operator of the site keeps the blade or when the original turbine manufacturer takes it back for its spare parts management. It is also observed in open loops, i.e. when another operator or service provider acquires the blades. Another example is the repurposing of blades, which is considered an open loop because it involves actors from different industries, such as the manufacturer of noise-cancelling walls. Also, for the recycling of materials closed and open loops are identified. For example, concrete from the foundation of a decommissioning project can be utilized in a repowering project (closed loop) or in other industries, such as the construction industry (open loop). This highlights the fact that repurposing and material recycling can also involve cross-industry flows.

In conclusion, even though the degree of detail varies between the conceptual CSCM framework and the observations in Denmark and Germany, the CSCM framework appears to be useful to guide practitioners in CSCM. It should be noted, however, that this empirical study is the first of its kind to focus on creating transparency into the historical turbine and blade flows, while also exploring the factors that influence the related decision-making of supply chain actors. To further evaluate the embedding of circular thinking in SCM (e.g. creating a paradigm shift), exploring the link between these findings and a target system would provide additional insights. Nevertheless, the empirical study has provided valuable insights, and in this respect, the operationalisation of the CSCM framework may be further improved by adding the perspectives of cross-country and cross-industry flows. In addition, the link between the circular strategies on turbine, component and material level could be further detailed with the empirical findings, resulting to an improved clarity of the product flows.

5.3.2 Discussion of results

The results chapters outlined and discussed the findings to answer RQ3 and RQ4. In accordance to the explorative research approach of Part B, this chapter triangulates the main findings with other sources, if available.

Discussion of answer to RQ3

RQ3 is addressed by showing that second lifecycle pathways of decommissioned onshore wind turbines were common in the markets Denmark (~60 %) and Germany (~50 %), at least for the pathway of exporting entire wind turbines. As noted above and also in Kramer et al. (2024, p. 180), this is the first study of its kind to systematically collect data and quantify the fraction of second lifecycle pathways taken, so the basis for comparison with other studies, and thus for evaluation, is limited. However, a comparison of the results for Denmark with Germany reveals that the historical flows of each circular economy pathway are comparable. This is further detailed in chapter 5.2.2, where the results for each country and stakeholder group are presented, and a sensitivity analysis is provided to further evaluate the results.

To further evaluate the findings, it is checked whether statistics exist or if other researchers have quantified the taken circular economy pathways of decommissioned turbines in Denmark, Germany or alternatively, in other countries and industries. Table 16 provides an overview of the identified studies.

Table 16. Overview of other available statistics on second lifecycle pathways on country level.

Scope	Reuse statistics	Other studies quantifying historical reuse	Studies with heuristics
Denmark	x *But access to landfill statistic*	x	✓ *Number of studies: 1*
Germany	x	x	✓ *Number of studies: 5*
Other countries	x	✓ *Number of studies: 1*	✓ *Number of studies: 1*
Other industries	x	✓ *Number of studies: 1*	- *Out of scope*

For Denmark, there is no study or data available on the pathway taken by the previous decommissioning. Ricard (2023) states that 50 % or more of the wind turbines received a second lifecycle, however without providing evidence. Furthermore, it is assessed in Kramer et al. (2024, p. 186) which quantities ended up at the two available landfills for blades in Denmark. As historically 7,130 tonnes of blade mass were decommissioned and approximately 1,325 tonnes of blade mass was landfilled, ~81 % remains that could have at least partially entered a second lifecycle (DEA, 2022; Energi Watch, 2020; From & Dohm, 2022). This could indicate that the quantified fraction is in a suitable order of magnitude.

For Germany, there is also no study or data available that has quantified the pathways taken by the decommissioned turbines. Five studies state heuristics for a reuse fraction, but none provide evidence:

- Kühne et al. (2022, pp. 404, 150): ‘relevant share’ of reuse for the decommissioned wind turbines. However, the study also argues that the second-hand market is only marginal, while noting a lack of data to assess this adequately.
- Volk et al. (2021, p. 10): A predecessor study of Kühne et al. (2022) take the same assumption.
- Zotz et al. (2019, pp. 88-89): A previous study of the above, recognises a relevant secondary market for decommissioned wind turbines in the past, but argues that the market has narrowed, although without providing any statistics.
- Bundesverband WindEnergie (2019, p. 6): Reports the reuse share of 10 % of the decommissioned turbines from one decommissioning company, although without disclosing the number of handled turbines (BWE, 2019, p. 6). The fraction was also reported by an expert of this study, nevertheless, other experts stated a fraction entering a second lifecycle of up to 100 % for their handled turbines (see Figure 24).
- Pehlken et al. (2017, p. 255): Assume that 60 % of the wind turbines below 1 MW will be decommissioned prior to the end of the design lifetime at an age of 15 years

and of those 90 % would then be exported for a second lifecycle. The reasons for the assumed threshold at 1 MW and 15 years are not explained.

In summary, these studies make different assumptions and no conclusions can be drawn. In addition, two studies from other regions are identified, that indicate that a significant share of wind turbines from Europe (Graulich et al., 2021, p. 52) and Norway (Andreassen, 2023, p. 14) were reused. Out of these two studies, only the Norwegian study provides empirical evidence by assessing the pathways taken of the historical decommissioning, resulting in a reuse fraction of around 20 %. However, only a few turbines from eight wind farms have been decommissioned so far. In addition, one study in regard to another industry is identified. Accordingly, Wang et al. show that 55 % of hybrid vehicles from Japan and 70 % of the associated batteries were exported for reuse (Wang et al., 2020, pp. 201-202). Further studies are difficult to find, as for instance for PV modules and electric vehicle batteries, similar to wind turbines, reuse statistics are currently lacking (Franco & Groesser, 2021, pp. 19, 23; Reinhardt et al., 2019, pp. 433, 442). In this light, Komoto et al. (2022, pp. 5, 14) outline for photovoltaic modules in Germany a lower than estimated actual waste volume, which could be due to a longer first lifetime, reselling on secondary markets or illegal exporting.

In conclusion, there is a lack of tracking data across multiple lifecycles in the wind industry and other industries, which underlines the importance of this study. As a result, the evaluation with other studies is limited, but this was counteracted by the research design of the study in two countries. In both countries, it is shown that a second lifecycle is common for wind turbines. Further research is needed to collect reuse statistics to further evaluate the results of this study.

Discussion of answer to RQ4

RQ4 is addressed by identifying factors influencing the decision-making to decommission an onshore wind turbine and in regard to the choice of subsequent handling pathway. The results of the study show that the observed circular supply chain processes in both countries are similar in design. Accordingly, several factors were identified in the expert interviews that could have influenced the development of second-lifecycle supply chains for decommissioned onshore wind turbines from Denmark and Germany. To the author's knowledge, there is no such study in the wind industry, which is in line with several researches calling for more empirical research (Graulich et al., 2021, p. 52; Kühne et al., 2022, pp. 122, 150; Volk et al., 2021, p. 10).

The only scientifically published study identified is the one from De Laurentis & Windemer, published in July 2024. De Laurentis & Windemer (2024, pp. 12-13) conducted 15 interviews with experts from wind farm developers, consultancies and policy in Italy, but do not disclose whether and how many turbines the experts have handled. The scope of the interviews is on the decision-making to decommission operating wind projects. Nevertheless, the authors also express an initial idea about the handling pathway of the decommissioned wind turbines. Accordingly, they state that a second lifecycle would be “*the most economically viable approach*” (p. 10) and that operators that repower younger sites, certainly might have an incentive “*to consider and explore second market opportunities*” (p. 13).

The four further identified studies are whitepapers, some are assigned by governmental bodies of the addressed county/region of the study (e.g. Andreassen, 2023; Zotz et al., 2019). It should be noted that only Andreassen (2023, pp. 12-15) collected empirical data on the taken pathways of ~55 decommissioned onshore wind turbines in Norway, but provides only limited information on the reasons for the taken pathways. The other whitepapers briefly discuss potential influencing factors in Germany (Zotz et al., 2019, pp. 61, 88-89), EU (Graulich et al., 2021, pp. 45-56) and the UK (Butler et al., 2023). They base their findings on their own experience, existing literature and the involvement of experts, either through expert interviews, surveys or workshops, but without specifying whether and how many decommissioned wind turbines the experts have handled.

The five studies are used to evaluate parts of the results of this study, hence Table 17 provides an overview of their influencing factors in comparison with this study.

Table 17. Overview of influencing factors for second-lifecycle turbines from this study in comparison to other literature.

	This study	De Laurentis et al. (2024)	Zotz et al. (2019)	Andreassen (2023)	Graulich et al. (2021)	Butler et al. (2023)	Σ
Study’s geographical scope	*DNK & GER*	*Italy*	*Germany*	*Norway*	*EU*	*UK*	
Age	x	x	x			x	4
Repowering	x	x	x			x	4
Economics	x	x			x	x	4
Turbine type	x		x			x	3
OEM of turbine	x		x	(x)			3
Turbine condition	x	(x)				x	3
Availability of spare parts	x	(x)				x	3
Storage at site	x	x	x				3
Turbine size	x		x				2
Country’s regulation on installation of reused turbines	x		x				2
Eligibility of reused turbines for market subsidies	x		x				2
Transport distances	x		x				2
Number of to-be decom. turbines per wind farm	x		x				2
Requirement of new project site	x		x				2
Expected overall market supply vs. demand for reused turbines	x		x				2
Available refurbishment	x			(x)			2
Delivery time of turbine	x				x		2
Company’s commitment not to landfill in other countries	(x)				x		2
Further factors	x						

It shows that a wide variety of factors is mentioned in the studies, but most often only by one of them. All the factors mentioned in one of the studies were identified in this study for Denmark and Germany. It is not surprising that this study identified the largest variety, as the other studies are not dedicated to exploring factors influencing a second lifecycle. In addition, there are several other factors that are found in this study for the handling of the Danish and German decommissioned wind turbines, e.g. the grid codes of the countries, transportation route and import requirements (see Table 39 in Appendix B2). Furthermore, the following section discusses key factors in relation to the choice of decommissioning and handling pathway.

Decision and timing of decommissioning

Zotz et al. (2019, p. 88) express that wind turbines that are decommissioned as part of a repowering project tend to be decommissioned prior to reaching 20 years. This study finds that repowering is one of the factors that could trigger the decision to decommission in Denmark and Germany, with experts reporting that this could happen before, during or after the end of design life. Experts from Germany did mention a tendency for an earlier decommissioning due to repowering at very good wind locations, which is also stated in existing literature (Laurentis & Windemer, 2024, p. 9; Ziegler et al., 2018, p. 1267). Furthermore, researchers who have looked closely at decommissioning decisions in Italy (Laurentis & Windemer, 2024), Denmark, Germany, the UK and Spain (Ziegler et al., 2018) emphasise that there is a complex decision-making process. They demonstrate that assumptions based on only one influencing factor are not suitable for determining the time of decommissioning. This is in line with the results of this study for the decommissioned onshore wind turbines in Denmark and Germany.

Decision to take pathway of second-lifecycle turbine

The predominately mentioned factors by the publications and this study are discussed below (see Table 17). The ‘age of the turbine’ is seen by the other studies as a dominant factor for the potential resale of the turbine at the second-hand market. For instance, De Laurentis & Windemer (2024, pp. 12-13) conclude that the turbine’s age influences the subsequent handling pathways, as they state that decommissioning prior to the end of the turbine’s design lifetime would likely higher the potential of reselling on the second-hand market. Zotz et al. (2019, p. 88) express that wind turbines that are decommissioned before reaching 20 years would have a longer operating life in a potential second lifecycle. This rationale has been explicitly checked during the interviews (see question 15 of the interview guide in Appendix A1). Across all interviews, the experts stated that the likelihood of reselling on the second-hand market was not influenced by surpassing the threshold of the turbine’s design lifetime of 20 years. In addition, they state that the turbine age at the time of decommissioning has not been a key factor so far. However, the age could emerge as a more prominent influencing factor in the case several turbines of the same type are offered on the second-hand market. Furthermore, it is noted that the influencing factor ‘remaining technical life’ of the wind turbine at time of decommissioning would be more accurate than the ‘turbine age’. However, it remains to be seen whether a different threshold will emerge, as there is limited data available on the condition of turbines beyond their design life of 20 years.

A prominent factor found in this study to influence the likelihood of a second lifecycle is the ‘turbine type’ of the decommissioned wind turbine. This was also confirmed by Zotz et al. (2019, pp. 88-89) and Butler et al. (2023, p. 12). Another prominent factor identified in this study is the ‘availability of spare parts’, but this is only mentioned in literature by Butler et al. (2023, p. 12). De Laurentis, however, cite it in relation to enabling continued operation at the initial site (2024, p. 12). In addition, the study shows that the economic feasibility and legal/regulatory requirements of the potentially demanding country determine whether a turbine type is in demand. This is also for some aspects addressed by existing literature (Graulich et al., 2021, p. 52; Ortegon et al., 2012, p. 156; Zotz et al., 2019, pp. 88-89). For example, Zotz et al. (2019, pp. 88-89) also mentions the legal requirements in regard to the turbine’s hub height or the turbine’s compliance with the country’s grid codes.

In summary, the comparison with the other studies confirms the existence of various factors, however this study has presented additional factors. For example, organisational factors of each supply chain actor involved are relevant, such as whether the operator of the turbine and the decommissioning company consider a second-hand market in their business practices. Furthermore, in contrast to this study, the other studies lack a comprehensive discussion of the interconnections in regard to the choice of pathway of the decommissioned wind turbine. Nevertheless, the results of Denmark and Germany both show that the choice of circular economy pathways involves a complex decision-making process.

Decision to take pathway of second-lifecycle blade

Next to the most common pathway of exporting the entire turbine, this study moreover investigated factors influencing a second lifecycle as spare parts by focusing on wind turbine blades. The available set of mentioned influencing factors by the other studies is limited. Only Butler et al. (2023, pp. 4-5) provide a quite comprehensive list, but address those for recirculating components and parts and do not mention blades explicitly. Furthermore, Andreassen (2023, p. 13) mention in regard to a second lifecycle, that some of the decommissioned blades in Norway could not be repaired or directly reused due to the condition of the blade at decommissioning. In this regard, Graulich (2021, p. 52) add that a sufficient remaining technical life of the blade is beneficial for reuse and moreover, mention that the blade type is of relevance to assess the compatibility to a wind turbine. Finally, Zotz et al. (2019, p. 89) outline that the demand for spare parts depends on the number of turbines per turbine type that are still in operation. These outlined aspects are also identified in this study for Denmark and Germany.

All in all, comparing the study’s findings from two countries and multiple stakeholder groups with each other and with the existing literature, allows for concluding that the second lifecycle of turbines and blades as spare parts are influenced by several factors and in this light, prominent factors were discussed. For further evaluation of the findings and transferability to other countries, further dedicated studies on the decision-making for handling decommissioned wind turbines are required, as this study is the first of its kind in the wind industry.

5.3.3 Discussion of methodology and limitations

The research design of Part B ensures that trustworthy findings are found, thanks to applying mixed methods to two countries and collecting data from multiple stakeholders. Accordingly, two countries with the longest and comprehensive decommissioning history in the onshore wind industry were chosen. 18 interviews were conducted with experts that cover a significant share of the markets to explore the circular supply chains and taken pathways of the decommissioned onshore wind turbines from Denmark and Germany. The collected data was quantitatively and qualitatively analysed. Even with this comprehensive and rigorous research design, the below limitations to the methodology and findings are noted.

The method of semi-structured interviews is not following strict rules, hence findings could vary if a different interviewer or setting is chosen (Gläser & Laudel, 2010, p. 115; Saunders et al., 2019, p. 447). However, as empirical and theoretical studies on second-lifecycle supply chains for the wind industry were missing beforehand, the chosen method seems most suitable to fulfil the research objective of exploring second lifecycle pathways. Moreover, the data collection was comprehensively documented to empower other researchers to repeat the study.

It should be pointed out that experts were asked for their knowledge of the entire company's history. This may lead to uncertainty as to whether the experts remembered and reported this fully during the interviews (Kramer et al., 2024, p. 186). That is particularly relevant for Denmark, as experts had to remember a history of up to 25 years and the majority of the decommissioned onshore wind turbine fleet was decommissioned in 2002 (see 6.2.1). However, this uncertainty has to be accepted, as due to a lack of data systems in the companies, more structured data collection methods are not applicable. This risk is seen manageable for the quantification of pathways, as only the total numbers of aggregated pathways were requested and for both markets a significant share of the market was covered. Also, for the identification of circular supply chain processes and associated influencing factors this is tolerable, as the research is explorative in nature and aims at investigating the status quo by outlining the perspectives of the interviewed experts from the different stakeholder groups. In addition, the results of the paths taken by the decommissioned turbines from Denmark and Germany could be further evaluated by conducting studies in the demanding countries. To add to this, also in other countries empirical data seems to be widely missing, underlining the need for further empirical studies.

5.4 Interim conclusions

Part B of the thesis provides empirical insights into second lifecycle pathways of decommissioned onshore wind turbines in Denmark and Germany from a multi-stakeholder perspective. Accordingly, interviews with 18 experts, covering more than 50 % of each market and representing four stakeholder groups, are conducted (see 5.1.1). This collected data is quantitively (see 5.1.2) and qualitatively analysed (see 5.1.3) to answer RQ3 and RQ4, and resulting to four key contributions:

- Quantification of the historical flows of decommissioned onshore wind turbines and their blades along circular economy pathways (see 5.2.2)
- Gaining an understanding of existing circular supply chain processes (see 5.2.3.1)
- Providing an exploration of the factors influencing the choice for a second lifecycle (see 5.2.3.2)
- Evaluation of conceptual CSCM framework for the wind industry (see 5.3.1)

Contribution 1: Second-lifecycle supply chains for reinstallation of decommissioned turbines are common in Denmark and Germany

The findings of the quantitative analysis show that second lifecycle pathways of decommissioned onshore wind turbines are common, at least for exporting entire wind turbines (see Figure 25). In Denmark, ~60 % of the decommissioned onshore wind turbines and their blades have a second lifecycle, and in Germany the fraction accounts to ~50 %. In the case of a second lifecycle of the entire turbine, the decommissioned turbines are always exported, mainly to European countries. If not sold as an entire turbine, then the likelihood that the blades are reused as spare parts is marginal. The outlined findings therefore comprehensively answered RQ3.

RQ3 Which paths are taken for onshore wind turbines and their blades after decommissioning in Denmark and Germany? Is a second lifecycle common or not? ✓

Contribution 2: Provision of a comprehensive understanding of second-lifecycle supply chains

The findings of the qualitative analysis present the observed circular supply chain processes of decommissioned onshore wind turbines in Denmark and Germany (Figure 27). In this regard, the following second-lifecycle supply chains exist.

- **Turbine level:**
    - The observed supply chain processes are storage, refurbishment, transport, export and reinstallation at new site.
    - A decommissioned wind turbine is mostly directly exported for reinstallation at a new site.

  - Alternatively, prior to export, the decommissioned turbine is stored and/or refurbished. This is, however, only considered by a small number of experts.
  - None of the decommissioned turbines remained in the domestic country for reinstallation.
- **Component level:**
  - The observed supply chain processes are storage, refurbishment, repair, transport, export and reinstallation in a wind turbine.
  - Components are mostly reused as spare parts to repair a wind turbine in operation, either with or without prior storage and/or refurbishment and repair of the component.
  - Components from decommissioned wind turbines in Denmark and Germany either remain in the country or are exported.
  - Spare parts are either for the repair of wind turbines in their first or second lifecycle, or for the refurbishment of decommissioned wind turbines.

Contribution 3: Identification of factors influencing the decision-making for second lifecycle pathways

The qualitative analysis reveals that various technical, legal/regulatory, economic, organisational and market factors influence the development of second-lifecycle supply chains for onshore wind turbines from Denmark and Germany (Figure 32). The identified factors impact various decisions by different actors along the supply chains for the decommissioned wind turbine and the subsequent handling. It is found, for both markets, that the threshold of surpassing the design life of 20 years does not determine the likelihood of a second lifecycle. Instead, the demand for second-lifecycle turbines is mainly linked to the availability of spare parts and certain design criteria of the turbines. This makes the turbine type of the decommissioned turbine a decisive factor. In addition, it is critical that the demand occurs in the time window associated with the handling of the turbine, which is usually capped at the time of decommissioning, as additional transport and storage is usually not economically viable. In summary, in light of the aforementioned contributions, a comprehensive response to RQ4 is provided.

RQ4 What is influencing the development of second-lifecycle supply chains for onshore wind turbines from Denmark and Germany ✓

Contribution 4: Evaluation of conceptual CSCM framework for the wind industry

The results of Part B also evaluate the conceptual understanding of Part A and indicate that the CSCM framework is feasible for CSCM in the wind industry. It moreover shows that not all circular supply chain processes have yet been observed in practice (see Figure 58). In the light of the empirical findings, the operationalisation of the CSCM framework for the wind industry can be further improved by adding the perspectives of cross-country and cross-industry flows.

In summary, Part B fulfils the second research objective of the thesis, as it comprehensively answers RQ3 and RQ4.

RO2 Explore second lifecycle pathways in the wind industry from a multi-stakeholder perspective. ✓

The newly collected empirical data on historical turbine, component and material flows shows that circular supply chains for further lifecycles and end-of-life pathways are existing. This leads to the question to which extend the findings will continue in the future. Therefore, Part C of the thesis proposes scenarios to quantify expected turbine, component and material flows for stakeholders in the circular supply chains.

6 Part C: Turbine, Component and Material Flow Forecasts of Circular Economy Pathways

Part C of this thesis has the objective to quantify expected turbine, component and material flows to establish circular supply chains for further lifecycles (e.g. refurbishment) and end-of-life practices (e.g. recycling) (research objective 3) by answering RQ5. That said, turbines, components and materials flow models are developed and results presented for multiple stakeholders that handle decommissioned onshore wind turbines and blades from Denmark and Germany.

The chapter comprises of four subchapters and begins by outlining the methodology in 6.1. Subsequently, the results of the turbine, components and material flow forecasts for decommissioning companies, second-lifecycle companies and recycler are presented in 6.2. Finally, the findings and methodology are discussed in 6.3.

6.1 Methodology

The methodology of Part C is quantitative in nature and is based on the new findings of Part A and Part B. As illustrated in Figure 59, the methodology consists of four parts.

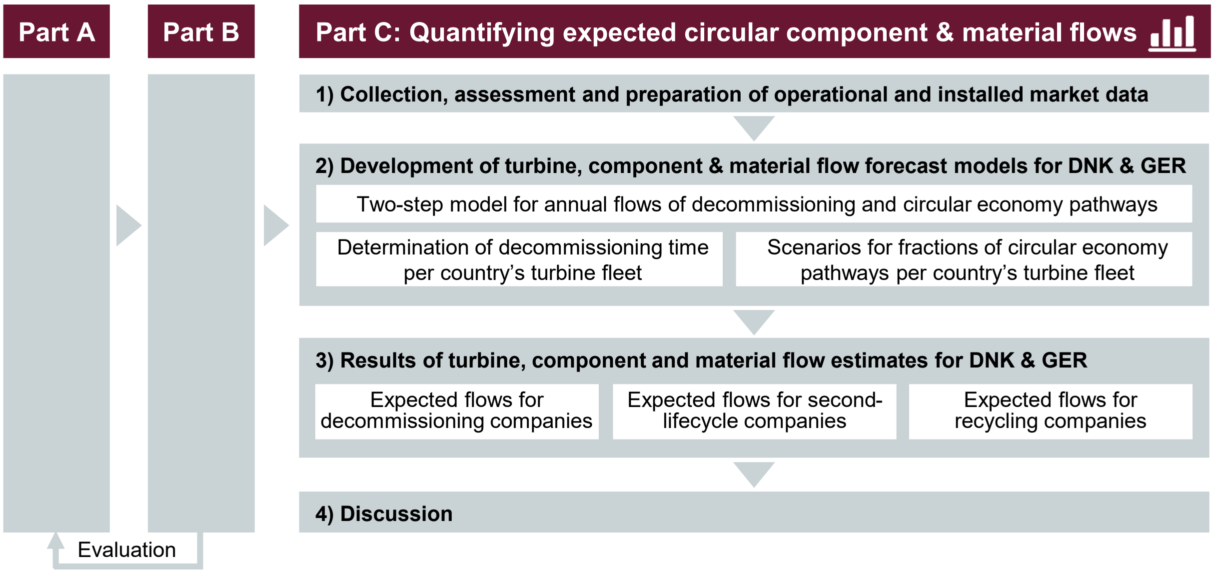


Figure 59. Part C's methodology of quantifying expected turbine, component and material flows.

Expected turbine, component and material flows after the first lifecycle of the installed onshore wind turbines from Denmark and Germany are to be estimated (Kramer et al., 2024). Hence, first, market data of the currently installed onshore wind turbines in these countries are collected, assessed and prepared. The second step of the methodology foresees the development of new models for the estimation of turbine, component and material flows to support the capacity planning of stakeholders in decommissioning, second-lifecycle practices and recycling. Hence, a forecasting method is selected and appropriate modelling assumptions are made for the time of decommissioning and the cascading circular flow. The assumptions are determined by the state of the art, and the derived findings from Part B of this thesis. In order to account for the fact that historical developments and current observations cannot necessarily be extrapolated to the future, various scenarios are employed (Saunders et al., 2019, p. 451). The use of scenarios is considered suitable because it enables to reflect quantitative and qualitative data and to illustrate a range of different possible future paths in the complex circular supply chain (Hyndman & Athanasopoulos, 2021, 6.5). The third and fourth part of the methodology is to present and discuss the results of the estimated circular flows of the installed onshore wind turbines from Denmark and Germany for supporting the stakeholders' capacity planning.

In the following, the data collection, analysis and modelling is further detailed. As such, 6.1.1 presents the current state of the art on component and material flow models for onshore wind turbines, followed by 6.1.2, the selection and preparation of market data. In 6.1.3, a forecast method is selected and the component and material flow models for the application to the Danish and German onshore wind turbine fleet are developed.

6.1.1 State of the art on component and material flow models

This chapter provides an overview of the state of the art on component and material flow models for onshore wind turbines by presenting the used models and core assumptions of relevant publications.

In general, common methods for forecasting resource flows are heuristics, statistical methods, simulation and machine learning methods. Depending on the available data, the subject of prediction and the requirements for modelling time and accuracy, different methods are suitable (Hyndman & Athanasopoulos, 2021, 1.4). Heuristics, also called rule-of-thumb, are commonly used in practice, as they require no empirical data and are fast to derive (Hyndman & Athanasopoulos, 2021, 6.). However, they often lack in accuracy, especially in more complex and dynamic environments. Statistical methods are for instance moving averages, exponential smoothing, linear regression, and multivariate regression (Schmidt & Nyhuis, 2021, p. 96; Schuh & Schmidt, 2014, pp. 70-78). The order of this list starts with the simplest method that requires only a limited set of data and ends with multivariate regression, which models various influencing factors for the prediction. In this context, where data availability is limited, it is possible to fill data gaps with simulation data or use what-if analysis to simulate different possible strategic directions (Kurbel, 2016, pp. 361, 433). Simulations are therefore particularly useful when the object of prediction has a relatively high degree of uncertainty, as in such cases different simulations can be carried out. Moreover, machine learning methods are particularly suitable for identifying patterns in complex environments, but require high-quality datasets with a wide-range of data features over a long-time horizon to be able to model resource flows in complex and uncertain environments (Cerqueira et al., 2019; Kramer et al., 2022; Kramer & Schmidt, 2022).

Regarding the forecasting of resource flows within the onshore wind industry, 18 studies were identified that are presented in Table 18.

Table 18. Overview of state of the art on component and material flow models, inspired by Kramer et al. (2024, p. 182), Abrahamsen et al. (2023, p. 167).

Study	Objective of prediction	Method for the time of decommissioning	Method for the fraction of a second lifecycle	Region
Abrahamsen et al. (2023)	Blade mass at decommissioning	Weibull function (ratio decom/installed p.a.)	N/A	DNK
Andersen et al. (2016)	Waste mass of wind turbines	Heuristic (20 years)	Heuristic (three scenarios)	SWE
Chen et al. (2021)	Waste mass of wind turbines	Distribution t0 = 14, 18 and 21 years	Not considered	Guangdong province, CHN
Cooperman et al. (2021)	Waste mass and volume of blades	Heuristic (15, 20, 25, 30 years); distribution t0 = 20 years	Not considered	USA
Delaney et al. (2021)	Blade mass at decommissioning	Distribution t0 = 20 years	N/A	IRL
Heng et al. (2021)	Waste mass of blades	Heuristic (20, 25, 30 years)	Not considered	CAN
Kühne et al. (2022)	GFRP & CFRP waste mass of blades	Heuristic (20 years)	Not considered	GER
Lahuerta et al. (2023)	Waste mass of blades	Normal distribution of 20-30 years	Not considered	Europe
Lefeuvre et al. (2019)	CFRP waste mass of blades	Heuristic (25 years)	Not considered	World
Lichtenegger et al. (2020)	Waste mass of blades	Distribution t0 = 18 years	Not considered	Europe
Liu and Barlow (2017)	Waste mass of blades	Heuristic (18, 21, 26 years)	Not considered	World
Pehlken et al. (2017)	Waste mass of blades	Heuristic (20 years)	Heuristic (one scenario)	GER
Sommer et al. (2020)	GFRP & CFRP waste mass of blades	Stochastic distribution	Not considered	Europe
Sultan et al. (2018)	Composite waste mass of blades	Distribution t0 = 25 years	Not considered	GBR
Tazi et al. (2019)	Waste mass of wind turbines	Heuristic (15 years)	Not considered	Champagne-Ardenne, FRA
Tota-Maharaj et al. (2021)	Waste mass of wind turbines	Heuristic (20 years)	Heuristic (two scenarios)	GBR
Volk et al. (2021)	GFRP & CFRP waste mass of blades	Heuristic (20 years)	Not considered	GER
Zotz et al. (2019)	Waste mass of wind turbines	Heuristic (20 years)	Not considered	GER

The studies address different countries (e.g. Canada, Sweden) or broader regions (e.g. Europe), while 13 out of the 18 studies cover Europe and European countries. The thesis's regional scope of Denmark and Germany is addressed by Abrahamsen et al. (2023) for Denmark and four studies focus on Germany's wind turbine fleet (Kühne et al., 2022; Pehlken et al., 2017; Volk et al., 2021; Zotz et al., 2019). Moreover, the majority of the studies address installed onshore (and offshore) wind turbines in a country and forecasts the expected waste of the blades in tonnes, i.e. end-of-life volumes (e.g. Kühne et al., 2022). However, two studies provide the expected blade mass at decommissioning (Abrahamsen et al., 2023; Delaney et al., 2021). The blade mass is calculated with approximating through the installed capacity (e.g. Lefeuvre et al., 2019, p. 33) or a regression function based on the diameter of the rotor blade (e.g. Abrahamsen et al., 2023, pp. 8-9; Volk et al., 2021, pp. 4-5). The applied assumptions for the time of decommissioning and the second-lifecycle fraction are further detailed in the following.

Time of decommissioning

As Table 18 outlines, the studies either use heuristics or statistical methods for the determination of the time of decommissioning (Kramer et al., 2024, p. 182). None of the researchers applies multi-variate regression models, simulation or machine learning methods.

Eleven out of the 18 studies apply static heuristics, hence approximating the time of decommissioning with assuming a specific year. Eight studies expect that onshore wind turbines are decommissioned after 20 years, which the studies' authors justify by the turbine's design lifetime of 20 years or, in the case of Germany, by the expiry of the subsidy scheme (IEC, 2019; Volk et al., 2021). All existing studies on Germany follow this assumption (e.g. Volk et al., 2021, p. 4). Otherwise, one study on globally expected resource flows assumes 25 years (Lefeuvre et al., 2019, p. 33) and one study regarding a French region anticipates decommissioning after 15 years (Tazi et al., 2019, p. 202). In addition, three studies work with 3-4 scenarios of varying ages between 15-30 years (e.g. Heng et al., 2021, p. 62).

The other seven studies use a distribution function that are either backed with a heuristic (Delaney et al., 2021, p. 3) or through applying data-based statistical methods. One of the data-based approaches is to use the historical average age of decommissioned turbines of the respective region (Lichtenegger et al., 2020, p. 122) and another one is to derive a depletion curve that additionally takes the age of the operating fleet into account (Abrahamsen et al., 2023, p. 14). The latter method is used for expected decommissioning flows from the onshore and offshore wind turbine fleet in Denmark. The authors apply an accumulated Weibull function with parameters based on the historical ratios of decommissioned over installed onshore wind turbines per installation year. It shows that their model is more accurate than to base a model purely on historical decommissioning, as it is more akin to the actual Danish decommissioning data (Abrahamsen et al., 2023, p. 15).

Second lifecycle fraction and consideration for recycling flows

16 out of the 18 studies forecast the annual expected mass for waste handling, while 13 neglect a second lifecycle for wind turbines and their blades and three consider a second-lifecycle fraction with a heuristic (Kramer et al., 2024, p. 182). No justification is given for the magnitude of the static heuristics, and furthermore, no data-driven method is yet applied.

The studies that do not consider a second lifecycle therefore assume that the mass of the blades at decommissioning is equivalent to the blade mass for waste treatment (e.g. Kühne et al., 2022, p. 150; Volk et al., 2021, p. 5). The three heuristic studies that consider a second lifecycle relate to Germany, UK and Sweden; Denmark is therefore not included: Pehlken et al. (2017, p. 255) assume that 60 % of small-scale turbines (0-1 MW) in Germany are decommissioned after 15 years and out of those, 90 % are exported for a second lifecycle. Tota-Maharaj et al. (2021, p. 134) present different scenarios for onshore and offshore wind turbines in the UK, of which two include an assumption on a second lifecycle. One scenario states a second lifecycle for 10 % of the wind turbines for an additional 10 years, half in the UK and half overseas. The other reuse scenario expects that 10 % of the total decommissioned mass of components is applicable for remanufacturing and reuse, 5 % within the industry (excl. blades) and 5 % outside of the wind industry (excl. blades and towers). Andersen et al. (2016, p. 12) predict the blade mass for onshore wind turbines in Sweden and apply three different scenarios for a second lifecycle. The first scenario estimates that 50 % of the decommissioned turbines are reused domestically for 15 years. The second scenario also assumes a split of 50/50 between a second lifecycle and waste handling but calculates with a second lifecycle abroad. The last scenario differentiates between small (< 1 MW), medium (larger than 1 MW and smaller than 3 MW) and large-scale onshore wind turbines (< 3 MW). 100 % small, 50 % medium and 75 % of large-scale turbines are sold to be reused abroad.

Conclusion

In summary, most studies cover forecasts of expected annual flows of blade mass for waste handling. So far, mostly static heuristics and only a few data-based methods for determining the time of decommissioning are used, of which the study by Abrahamsen et al. (2023) consider the most comprehensive data available to date. This approach has yet to be applied to the German turbine fleet, where the sole consideration has been the rigid assumption of decommissioning after a period of 20 years. In addition, this would enable an assessment of the transferability of the method by Abrahamsen et al. (2023) to other countries.

Moreover, a second lifecycle was widely neglected and no evidence-based and data-based method is yet applied in any region. However, the results of Part B show that it is crucial to consider the second-lifecycle flows when estimating recycling flows, as this changes the regional distribution and timing of recycling. Consequently, this affects the long-term capacity planning of recycling companies.

Therefore, this study aims to overcome the current shortcomings by developing a new model for the expected decommissioning, second-lifecycle and recycling flows of the Danish and German onshore wind turbine fleet. In this light, it strives for providing expected annual flows of onshore wind turbines and blades as a central basis to different stakeholders for their long-term capacity planning.

As a benchmark to the newly to-be developed flow model, the most commonly applied method of assuming a decommissioning after 20 years and neglecting second-lifecycle flows is taken (hereafter referred to '20-year heuristic').

6.1.2 Market data for installed onshore wind turbines in Denmark and Germany

This chapter describes the selection, assessment and preparation of the market dataset of onshore wind turbines installed in Denmark and Germany in order to be able to forecast their subsequent flows after decommissioning, as partially presented in Kramer et al. (2024). For an easier repeatability of the study, publicly and freely available data is to be chosen and as such official market registers are of preference. Moreover, it is assessed whether the datasets represent the entire market history. This is done by cross-checking with other sources such as other databases and publications.

Selection and assessment of comprehensive market data

Denmark has a master data register of wind turbines, which is published on the website of the Danish Energy Agency (DEA), with the latest available data as of 31/01/2022 (DEA, 2022). The dataset provides data on decommissioned and operational offshore and onshore wind turbines, of which onshore turbines are in the scope of this study. Each turbine is represented with a data entry and attributes such as the date of commissioning, the rotor diameter and the installed capacity (see Table 40 in the Appendix C1 for a full overview).

The DEA states that their data fully covers the market of wind turbines larger than 6 kW in Denmark (Danish Energy Agency). Moreover, it is noted by Abrahamsen et al. (2023, p. 5), who used the data for material flow forecasting, that the register was already established in 1977. This suggests that the data has been gathered in a comprehensive and systematic manner. Furthermore, an alternative data source is available by GWEC, who provide data as of 31/12/2022 (GWEC, 2023b). A comparison of the data from GWEC with the data extract from DEA reveals minimal discrepancies, which suggests a high degree of consistency. It can thus be concluded that the data on decommissioned and operating onshore wind turbines from DEA is comprehensive and representative, and therefore fulfils the requisite criteria for further analysis.

Germany has a market master data register (Marktstammdatenregister, MaStR), which is provided by the Federal Network Agency on a publicly-available website and is updated on a daily basis (Bundesnetzagentur, 2023). The register provides data on decommissioned, operational and planned onshore and offshore wind turbines and it is obligatory for operators to enter data into the market register. A data extract of the decommissioned and operational onshore turbines was compiled as of 30/06/2023. Each turbine is represented with a data entry with various attributes, e.g. turbine type, rotor diameter, location of turbine (see Table 41 in the Appendix C2 for a full overview).

It should be noted that the register was only launched on 31/01/2019, with the previously collected market data also migrated at that time and requesting retroactive reporting obligations to the operators. Despite, Deutsche WindGuard (2023, p. 2) note that wind turbines that were not existing at that time anymore, as already decommissioned, could be missing in the dataset. They therefore added not-captured decommissioning to the MaStR data. Two alternative data sources are therefore identified, the one mentioned above from GWEC as of 31/12/2022 and moreover by Deutsche WindGuard as of 30/06/2023 (Deutsche WindGuard, 2023, p. 4; GWEC, 2023b). A comparison of the MaStR data with that from GWEC and Deutsche WindGuard shows that the operational turbine fleet is similarly represented by the aforementioned sources. This finding is supported by the studies conducted by Volk et al. (2021, p. 5) and Kuehne et al. (2022, pp. 108-110). Hence, it can be concluded that the data extract as of 30/06/2023 from the market register is comprehensively representing the operating wind turbines in Germany and can be used for further analysis (Kramer et al., 2024).

Moreover, the comparison of the decommissioning data reveals, as argued above, that data is missing in the national market register. The decommissioning that took place from 2019 onwards are consistent in the various sources, but the sources differ for the period before that. In total, Deutsche WindGuard has recorded ~3.6 GW of decommissioning, while the market registry has only captured 1.2 GW due to incomplete retrospective data collection from 2019 onwards. Therefore, the market data does not sufficiently represent Germany’s decommissioning and as such the data from Deutsche WindGuard is selected. However, the data per each turbine is not publicly available and instead different reports are accessible. These are timeseries on annual decommissioning capacity per decommissioning year since 2000 as of 30/06/2023 (Deutsche WindGuard, 2023, p. 4) and annual decommissioning capacity per installation year since 1995 as of 31/03/2023 (Lüers et al., 2023, p. 46). Consequently, further descriptive analyses (e.g. distribution across turbine manufacturers) are not feasible. Any analysis based on the market register would yield misleading findings, as only a fraction of the overall decommissioned turbines is recorded in the register.

With regard to the representation of the overall installed onshore wind turbine fleet, i.e. decommissioned and operating turbines, the national market register could approximate it, if decommissioning volumes are marginal in comparison to the operational capacity (Kramer et al., 2024). As the operational capacity equals to ~59 GW (Bundesnetzagentur, 2023) and the decommissioned capacity to ~3.6 GW (Deutsche WindGuard, 2023, p. 4), it results to a fraction of 6.1 % decommissioned capacity over in-operation capacity. On this basis, the assumption is made that the fraction is small enough and hence the operational fleet can be used to approximate the installed turbine fleet. This approximation is accepted, as the market register provides a more detailed dataset and if required throughout the further analysis, also the comprehensive timeseries on annual installations from Deutsche WindGuard can be used (Lüers et al., 2023, p. 46).

Finally, Table 19 offers an overview of the selected datasets, along with their respective attributes and reference dates, to facilitate better orientation for the remainder of the thesis.

Table 19. Overview of selected datasets.

Source	Date of data	Description of selected data
DEA (2022)	31/01/2022	▪ Operational and decommissioned onshore wind turbines from Denmark ▪ Data extract of each turbine with several attributes, e.g. commissioning date, rotor diameter, installed capacity
Bundesnetzagentur (2023)	30/06/2023	▪ Operational onshore wind turbines from Germany ▪ Data extract of each turbine with several attributes, e.g. commissioning date, rotor diameter, installed capacity
Deutsche Wind-Guard (2023)	30/06/2023	▪ Timeseries on annual decommissioned capacity per decommissioning year
Lüers et al. (2023)	31/03/2023	▪ Timeseries on annual decommissioned and installed capacity per installation year

Preparation of the selected market data

Offshore wind turbines and small-scale turbines are excluded from the data extracts, as those are household turbines and hence a different technology (see 2.1). In Denmark, the regulation commonly uses a threshold of 25 kW (e.g. BEK nr 73 af 25/01/2013, 2013, § 18) and in Germany of 50 kW (EEG 2023, 2014/2023, § 46, No 3). In addition, the German dataset included vertical-axis wind turbines, that are mostly excluded through filtering out the small-scale turbines. A further filter was therefore not applied, especially as an assessment of the turbines with a capacity exceeding 50 kW, classified as ‘vertical axis’, revealed that the majority were in fact horizontal-axis turbines.

In accordance to the research objective of Part C, the following data attributes are necessary. As concluded in the state of the art on component and material flow models (see 6.1.1), the annual decommissioning and installation volumes per installation year are required. The benchmark to the expected decommissioning flows is the actual decommissioning, hence the annual decommissioning volumes per decommissioning year. In addition, the expected component and material flows are to be quantified for several stakeholders, which leads to different units of measurement being required. Decommissioning companies and companies involved in second-lifecycle practices need the expected annual number of turbines and recycling companies are interested in the annual blade masses. Furthermore, the identified influencing factors have yielded evidence that only specific turbine types are in demand on the second-hand market (see Figure 51). As such, the expected flows are ideally also expressed in the annual number of turbines per turbine type. In order to comply with these data requirements, the selected data extracts (Table 19) are prepared in accordance.

Calculation of blade mass

The blade mass per turbine is not part of any of the selected data extracts and needs to be added. In accordance to the state of the art (see 6.1.1), the blade mass can either be calculated with a regression function that bases on the blade length per turbine (e.g. Abrahamsen et al., 2023, pp. 8-9; Liu & Barlow, 2017, p. 233) or by approximating in relation to the installed capacity (e.g. Lefeuvre et al., 2019, p. 33). It should be noted that a few existing studies further differentiate the blade mass into the mass of glass fibre composites and carbon fibre composites (Sommer et al., 2020, pp. 86-87; Volk et al., 2021, p. 4). However, most decommissioning in the next ten years is likely to only consist GFRP (Volk et al., 2021, p. 7), and it is thus not deemed necessary to provide a further breakdown at this time.

For the market registers, the rotor diameter per turbine (D_{rotor}) is available in the data extracts and thus the regression function for the mass of a wind turbine with three rotor blades (m_{blades}) by Abrahamsen et al. (2023, p. 8) is used as shown in Eq. (1):

$$m_{blades} = 3 \cdot a \cdot \left(\frac{D_{rotor}/2}{R_0}\right)^{b} \tag{1}$$

Where the blade length is represented by $D_{rotor}/2$ in the unit of meters [m] and R_0 equals 1 m. The scaling factor a and exponent b of Eq. (1) are determined through the process of fitting a function along data points of known blade masses per turbine type, hence per blade length (Abrahamsen et al., 2023, p. 9). Accordingly, Abrahamsen et al. derive values of a = 0.00129 tonnes and b = 2.32, as presented in Eq. (2).

$$m_{blades} = 3 \cdot 0.00129 \cdot \left(\frac{D_{rotor}/2}{R_0}\right)^{2.32} \tag{2}$$

For the timeseries of annual decommissioning in Germany, an approximation has to be used since the rotor diameter is not part of the data extract. Existing assumptions are 9.9 tonnes per MW by Sultan et al. (2018, p. 939), who average previously applied approximations, and 10 tonnes per MW (Lefeuvre et al., 2019, p. 33; Pehlken et al., 2017, p. 255). In the light of this study, the rule of 9 tonnes per MW seems sufficient, as the average blade mass of the decommissioned turbines from the market register (Bundesnetzagentur, 2023) corresponds to ~9 tonnes per MW. Moreover, when looking at the time period of 1983-2003 – the timeframe to which most non-captured decommissioning belongs – the average of onshore turbines in operation equals to ~9 tonnes per MW in these installation years. Furthermore, the number of turbines is approximated with 0.8 MW per turbine, which corresponds to the average capacity of the decommissioned turbines from the market register (Bundesnetzagentur, 2023).

Improvement of data quality of attribute ‘turbine type’

When assessing the data quality of the attribute ‘turbine type’ in both datasets from the market registers, the data quality is not sufficient. In reference to Table 40, it can be observed that within the Danish dataset, 7.8 % of entries corresponding to operational turbines and 22.6 % of entries on decommissioned turbines lack information regarding the turbine type. A significant proportion of the remaining entries are disclosed in a cryptic manner. However, the combination of the attributes ‘turbine type’, ‘turbine manufacturer’ and ‘installed capacity’ suggest a probable turbine type. This approach is therefore applied, however, it should be noted that it is not feasible for the entries that completely lack the turbine type, as those also lack information on the turbine manufacturer. For Germany, the majority of data entries include information on the turbine type, as illustrated in Table 41. However, as it is a free-text entry in the register, numerous typographical errors exist, resulting in a greater number of distinct turbine types than actually exist. In order to enhance the uniformity of the attribute, the aforementioned errors are aimed to be corrected through the manual compilation of a list of expressions that correspond to the same turbine type. This is then followed by the execution of a Python script for the purpose of correcting the dataset (see Appendix C3 for an excerpt from the script). For example, the expressions ‘E-40/ 6.44’, ‘E 40 6.44’, ‘Enercon E-40/6.44’, etc. are likely to be references to the turbine type E-40/6.44 from the manufacturer Enercon. The aforementioned measures enhanced the data quality of the attribute, thereby making it suitable for further analyses. However, it should be noted that the dataset may still include data entries that have been incorrectly registered.

6.1.3 Turbine, component and material flow forecasting

The aim is to develop a new model in order to forecast annual flows of decommissioned onshore wind turbines for supporting long-term capacity planning of companies involved in decommissioning, second lifecycle pathways and recycling in Denmark and Germany.

In this light, it is important to recognise that the stakeholder groups have different information requirements for their capacity planning. For planning the capacity requirements of companies engaged in decommissioning, it is essential to have accurate data on the quantities of decommissioned turbines. Further information, e.g. on the expected number of turbines per turbine type or more generally on the expected turbine sizes and weights, improves the basis for planning the necessary resources, such as the required crane types. Moreover, as outlined in Part B, the companies responsible for the decommissioning of the onshore wind turbine are usually also responsible for the subsequent handling on the second-hand market or via the waste-handling industry. For planning the various processes that are foreseen for handling and reinstalling an entire turbine for a second lifecycle, it is crucial to have information on the annual quantities of to-be-decommissioned turbines with likely demand on the second-hand market. Hence, companies involved in the secondary market require annual expected quantities expressed in the unit of number of turbines and ideally also distinguished by turbine type or more broadly by turbine size and weights. This information supports the planning of companies involved in the logistics, refurbishment, reinstallation and operation of the second-lifecycle turbine. In contrast, domestic recycling companies are interested in the fraction of to-be-decommissioned wind turbines that is not exported for a second lifecycle but rather remains in the country and as such would enter domestic waste handling at one point. Forecasts of annual quantities for blade recycling are expressed in blade mass, usually in tonnes, and ideally with additional information on the materials composition of the blades.

Therefore, two-step forecasting models are developed for estimating the annual turbine, component and material flows from the Danish and German onshore wind turbine fleets for the multiple stakeholders. The scope of this study is on the installed onshore fleet in the respective countries and thus planned installations are out of scope. As displayed on the left side of Figure 60, the first step is to determine the time of decommissioning in order to forecast the annual number of to-be-decommissioned turbines ($n_{decom}(t)$) and the corresponding blade mass ($m_{decom}(t)$). Secondly, the right side of Figure 60, the fractions of decommissioned onshore wind turbines from Denmark and Germany entering a second lifecycle pathway ($f_{reuse}(t)$) and recycling ($f_{recycle}(t)$) are defined. With this information, the annual number of turbines entering a second lifecycle ($n_{reuse}(t)$) and the annual recycling blade mass ($m_{recycle}(t)$) can be estimated.

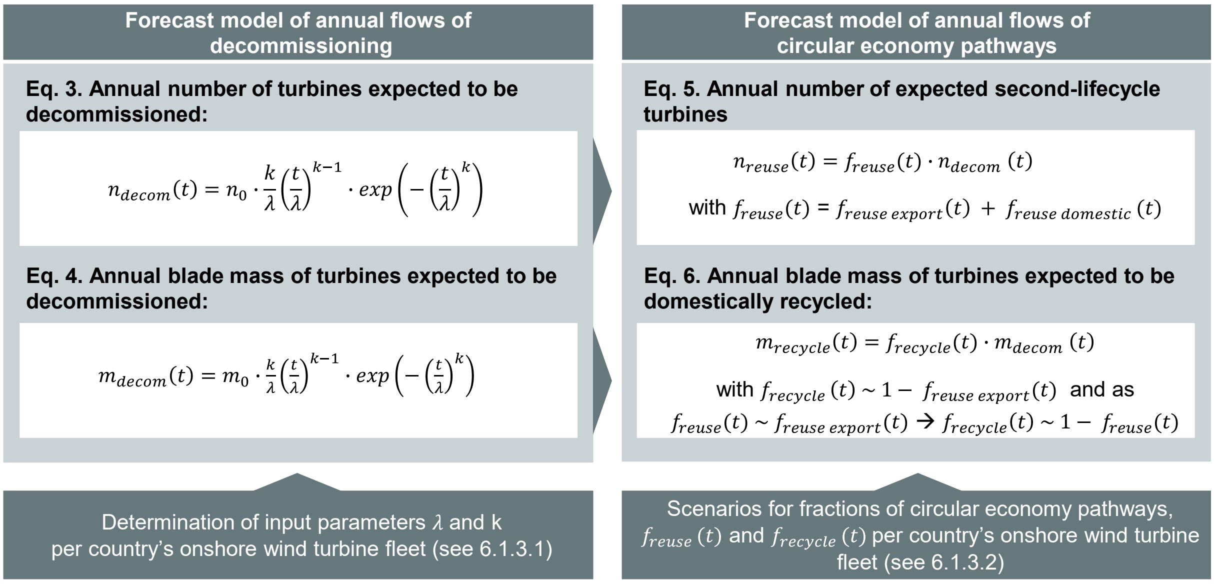


Figure 60. Model for forecasting decommissioning, second-lifecycle and recycling flows. Inspired by Kramer et al. (2024), Abrahamsen et al. (2023).

Forecast model of annual flows of decommissioning

In contrast to most of the studies outlined in 6.1.1, the model in this thesis to forecast annual flows of decommissioning applies a data-based method to determine the time of decommissioning. The approach by Abrahamsen et al. (2023) is applied, which uses a Weibull distribution to estimate the depletion of the Danish turbine fleet. The Weibull function is commonly applied in wind energy research, amongst others for the modelling of the turbines' lifetime distribution (Abrahamsen et al., 2023, p. 3; Burton et al., 2011, p. 205; Manwell et al., 2009, p. 58). It is therefore applicable for the prediction of the depletion of a turbine fleet (Abrahamsen et al., 2023, p. 3; Chen et al., 2021, p. 2).

Multivariate regression, simulation and machine learning methods are not yet applied in existing studies (see Table 18). More advanced methods would require a dataset with multiple features and sufficient history. On that note, Denmark has a comprehensive market dataset on historical decommissioning and currently operating wind turbines, and also captures several data features (e.g. installed capacity, rotor diameter) (DEA, 2022). Also, Germany provides a market dataset with several data features, however only comprehensively on the operational fleet and not of the historical decommissioning (Bundesnetzagentur, 2023). The latter, is only available as a timeseries expressed in the unit of installed capacity (Deutsche WindGuard, 2023; Lüers et al., 2023). Nevertheless, Part B outlines factors that influence the time of decommissioning, which currently are mostly not captured in the Danish or German market registers. In addition, datasets for annual second-lifecycle and recycling quantities do not exit. Consequently, advanced data analytics are not applied in this study either.

As it is a proven method for Denmark, as outlined above, this thesis uses the approach of a Weibull function by Abrahamsen et al. (2023, pp. 5-10) and applies it to the Danish and German onshore wind turbine fleet (Kramer et al., 2024, p. 184). It defines Eq. (3) to estimate the annual number of to-be-decommissioned turbines, $n_{decom}(t)$. Moreover, the annual blade mass estimated to be decommissioned, $m_{decom}(t)$, is calculated with Eq. (4), and is thus in accordance to Kramer et al. (2024, p. 184) and Abrahamsen et al. (2023, pp. 5-10). The equations reflect that the initial number of turbines (n_0) and blade mass (m_0) is removed over time.

$$n_{decom}(t) = n_0 \cdot \frac{k}{\lambda}\left(\frac{t}{\lambda}\right)^{k-1} \cdot exp\left(-\left(\frac{t}{\lambda}\right)^{k}\right) \tag{3}$$

$$m_{decom}(t) = m_0 \cdot \frac{k}{\lambda}\left(\frac{t}{\lambda}\right)^{k-1} \cdot exp\left(-\left(\frac{t}{\lambda}\right)^{k}\right) \tag{4}$$

Where n_0 is the initial number of turbines and m_0 the initial blade mass at t = 0, t is the time after the initial installation year, and k and λ are the shape and scale parameters of the accumulated Weibull function. The accumulated Weibull function and the data-based method for determining the parameters k and λ is detailed in the subsequent chapter 6.1.3.1.

Forecast model of annual flows of circular economy pathways

The model for the expected annual flows of circular economy pathways is the first of its kind that systematically introduces second-lifecycle considerations (Kramer et al., 2024, p. 184). So far research has widely neglected second lifecycle flows in their annual flow models. Therefore, Eq. (5) is introduced to estimate the annual number of decommissioned turbines entering a second lifecycle.

$$\begin{gathered} n_{reuse}(t) = f_{reuse}(t) \cdot n_{decom}(t) \\ \text{with } f_{reuse} = f_{reuse\ export}(t) + f_{reuse\ domestic}(t) \\ \text{and } f_{reuse}(t) \sim f_{reuse\ export}(t) \end{gathered} \tag{5}$$

For the calculation of $n_{reuse}(t)$, $n_{decom}(t)$ from Eq. (3) is multiplied with the fraction of turbines entering a second lifecycle per time unit, $f_{reuse}(t)$. The equation thus considers that not necessarily every decommissioned onshore wind turbine enters a second lifecycle, i.e. $f_{reuse}(t) \leq 1$. Moreover, $f_{reuse}(t)$ can be split up into the fraction of decommissioned turbines and their blades being exported for a second lifecycle ($f_{reuse\ export}(t)$) and the fraction that remains for a second lifecycle in the country ($f_{reuse\ domestic}(t)$). As the quantification of taken pathways of the decommissioned turbines (see Figure 25 in Part B) revealed, none of the turbines from Denmark or Germany remained in the country and also only a marginal share of blades remained as spare parts. Therefore $f_{reuse}(t)$ of Denmark and Germany is approximated by $f_{reuse\ export}(t)$.

Eq. (6) is applied to estimate the annual mass of blades potentially entering domestic recycling and reads as follows.

$$\begin{gathered} m_{recycle}(t) = f_{recycle}(t) \cdot m_{decom}(t) \\ \text{with } f_{recycle}(t) \sim 1 - f_{reuse\ export}(t) \\ \text{and } f_{recycle}(t) \sim 1 - f_{reuse}(t) \end{gathered} \tag{6}$$

For the estimation of $m_{recycle}(t)$, the expected blade mass to be decommissioned derived from Eq. (4) is multiplied with the fraction that remains in the domestic country for recycling per time unit, $f_{recycle}(t)$. The fraction $f_{recycle}(t)$ is approximated through subtracting the reuse fraction $f_{reuse}(t)$. As outlined in Kramer et al. (2024, p. 184), the equation therefore reflects that the potential blade mass for recycling in a country ($m_{recycle}(t)$) is reduced by the fraction of decommissioned blade mass that is exported for a second lifecycle. This assumption is suitable for Denmark and Germany as none of the decommissioned turbines and only a marginal share of blades remained for a second lifecycle in the country.

In case the turbines would remain in Denmark and Germany, the flows for recycling would be postponed by the duration of the turbine's second lifecycle and any lifecycle beyond that. Then also a tracing system of multiple lifecycles of turbines and blades would have to be established. However, the magnitude and feasibility of multiple lifecycles has not been explored yet and moreover, any second-lifecycle turbine is likely still in operation and hence only a limited data history would exist. Furthermore, it is unlikely that turbines and blades will be re-imported after a second lifecycle with the intention of recycling them in Denmark or Germany. The exclusion of this from Eq. (6) is assumed appropriate as waste movements across borders currently involves complex regulation and is expensive to carry out (Regulation (EC) No 1013/2006, 2006).

The approach of deducting a reuse fraction from the expected annual decommissioning quantities in order to derive estimates on domestic recycling flows is acknowledged by three existing studies (see 6.1.1). One study on Germany also assumes that none of the decommissioned turbines remains in Germany for a second-lifecycle and instead a share is exported (Pehlken et al., 2017, p. 255). The studies on the UK and Sweden expect the occurrence of a second lifecycle abroad and domestically. For the domestic share, the annual quantities for domestic recycling are delayed by 10 years in one study and by 15 years in the other study; both studies assume decommissioning after 20 years (Andersen et al., 2016, p. 12; Tota-Maharaj & McMahon, 2021, p. 134).

In principle, the resulting share from decommissioning could also follow other circular economy pathways at end of life of the blade (R7-R9), as shown in the CSCM framework (see Figure 17). In the light of current research (see 2.4.2), energy recovery (R9) is currently the only economically viable option, as industry has called for a ban on long-term landfilling in Europe from 2025 (Beauson et al., 2022, p. 9; WindEurope, 2020). The industry is therefore aiming to establish a recycling loop for blades (R8), which is backed by targets of fully recyclability across supply chain actors (Kramer & Beauson, 2023, p. 9). Consequently, assuming $f_{recycle}(t) \sim 1 - f_{reuse}(t)$ for estimating future recycling quantities seems feasible at this stage.

For forecasting the fraction of turbines entering a second lifecycle, four scenarios are determined, which is detailed in the subsequent chapter 6.1.3.2.

6.1.3.1 Determination of decommissioning time

As outlined, the time of decommissioning is determined according to the method by Abrahamsen et al. (2023, pp. 5-10). They foresee "*to describe the decommissioning as a depletion process of the different installation years with one general distribution as function of time*" (p. 5). As such, parameters k and λ for an accumulated Weibull function are fitted according to the ratios of decommissioned over installed wind turbines per installation year in the respective country. The method for determining the decommissioning time consists of five steps, which are outlined below.

Identify historical market data

The first step is to identify historical market data on the total installed onshore wind turbines and their decommissioning rate per installation year. It should be noted that the data obtained must be checked to ensure that it is comprehensive for the market under consideration (e.g. Germany). If the data do not fully represent the market history, or if the market history is not long enough, there is a risk to determine imprecise values for the parameters k and λ. For example, Abrahamsen et al. (2023, p. 5) outline that sufficient data on the Danish onshore wind turbine fleet is available, while for the offshore fleet the history is not yet long enough. Another case would be, if only fragmented decommissioning data were selected, as this would result in inaccurate ratios of decommissioned to installed turbines per year of installation. Therefore, if comprehensive market data is not available, a heuristic could be used until the data gaps are adequately filled. Another approach could be to check whether the market under observation is comparable to markets for which sufficient data are available (e.g. onshore wind in Denmark), so that these parameters, if met, could eventually be transferred. In contrast, if comprehensive data of the market under observation is available, the data can be selected for further analysis. For the case of onshore wind turbines in Denmark and Germany, timeseries of the historical decommissioning and overall installations per installation year are available for further analysis. The results of the assessment are detailed in the chapter 6.2.2.

Determine the ratios of decommissioning over installation per installation year

The second step is to calculate for each installation year the quantities of decommissioning and overall installations and to determine the ratios of decommissioning over installations. Again, the quality of the data (e.g. presence of outliers) must be assessed before proceeding with the next step, the Weibull fit.

Fit the accumulated Weibull function

The third step is to fit the accumulated Weibull function to the ratio of decommissioned to installed onshore wind turbines of the respective country as function of time. In the study of reference, the fitting is conducted on the ratios of decommissioned blade mass over installed blade mass. Moreover, they describe the accumulated Weibull function F(t) as follows (Abrahamsen et al., 2023, p. 6):

$$F(t) = 1 - exp\left(-\left(\frac{t}{\lambda}\right)^{k}\right) \tag{7}$$

In Eq. (7), λ is the scale parameter and k the shape parameter of the Weibull distribution in relation to t, the time variable. For example, the parameters for the Danish onshore turbine fleet are λ = 30 years and k = 10 and a 20-year lifetime is expressed with λ = 20 years and k = 70 (Abrahamsen et al., 2023, p. 11). Building upon this, the determined parameters can be used to describe how long the depletion of half of the turbine fleet ($t_{½} = \lambda(ln2)^{\frac{1}{k}} = \lambda\,(0.6931)^{\frac{1}{k}}$) and the decommissioning of 10 % to 90 % of the fleet ($\Delta t = \lambda\left(2.303^{\frac{1}{k}} - 0.105^{\frac{1}{k}}\right)$) takes (Abrahamsen et al., 2023, p. 7).

Definition of scenarios

In addition, to account for the possibility that the historical depletion does not continue in the future, two further scenarios are considered. One scenario adjusts the scale parameter λ in order to account for a faster depletion and the other one considers a slower decommissioning of the turbine fleet. The shape parameter k is kept constant in both scenarios.

Evaluation

Finally, the accuracy of the prediction model is evaluated in relation to the historical annual decommissioning in Denmark and Germany, and also in relation to predictions from other studies. Moreover, the research design of providing multiple scenarios for determining the time of decommissioning enables to envision different effect on annual decommissioning quantities. In this context, the likelihood of the different scenarios is discussed on the basis of the findings from Part B and existing studies. Finally, the implications for capacity planning of decommissioning companies in Denmark and Germany are also discussed.

The results of the determination of λ and k, together with their implementation in equations (3) and (4), are presented and discussed in chapters 6.2 and 6.3.

6.1.3.2 Scenarios for fractions of circular economy pathways

The rationale of using different scenarios for the fractions of the circular economy pathways of the to-be-decommissioned turbines is to enable the exploration of different future settings (Kurbel, 2016, p. 433; Schoemaker, 1993, pp. 193-194). This approach therefore recognises that there are still many uncertainties in determining the future proportions of circular economy pathways, as second-lifecycle supply chains and the link to recycling supply chains have rarely been researched from a systemic perspective. The scenarios are defined on the basis of the findings from Part A and B. Figure 61 provides an overview of the scenarios for the fraction of the installed onshore wind turbine fleet from Denmark and Germany that will enter a second lifecycle ($f_{reuse}(t)$). Consequently, also the fraction of domestic recycling ($f_{recycle}(t)$) can be derived. In total four scenarios are defined which is in line with a recommended number of scenarios of 3 to 6 (Amer et al., 2013, p. 33).

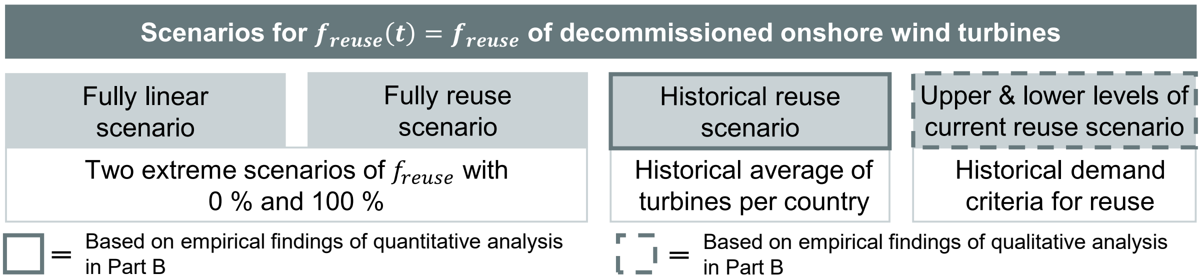


Figure 61. Overview of the scenarios for the reuse fraction of the installed onshore wind turbine fleet from Denmark and Germany.

The fractions $f_{reuse}(t)$ and $f_{recycle}(t)$ are kept static in these scenarios and as such are the same at each given time. Accordingly, the fractions can be simplified in the Eq. (5) to f_{reuse} and in Eq. (6) to $f_{recycle}$.

The 'fully linear' scenario ($f_{reuse} = 0\ \%$, $f_{recycle} = 100\ \%$) is chosen to visualise the worst case from a circular economy perspective and the 'fully reuse' scenario ($f_{reuse} = 100\ \%$, $f_{recycle} = 0\ \%$) to envision the full impact of circular strategies that foresee a second lifecycle of the entire turbine and blade abroad. It hence follows the recommendation by Schoemaker (1991, p. 556) to consider two extreme cases when developing scenarios. The 'historical reuse' scenario uses the average reuse and recycling fractions from historical decommissioning in Denmark and Germany, and as such considers the newly collected data from Part B of this thesis. Finally, the 'upper level' and 'lower level' of current reuse flows are defined on the basis of the qualitative analysis in Part B. In this context, an analysis is carried out to assess the extent to which the identified requirements for a second lifecycle are met by the currently operating wind turbine fleet, and thus to define upper and lower levels of f_{reuse}. Accordingly, the corresponding share of the country's turbine fleet in operation is determined for measurable factors with available data and for non-measurable factors qualitatively discussed. In light of this, factors can either be a definitive barrier to the initiation of a second lifecycle or can negatively/positively influence the decision to consider a second lifecycle for the turbine and its blades. For instance, the occurrence of a lightning strike on the turbine was cited by the interviewed experts as resulting to the rejection of a second lifecycle. Another example is the turbine size, which can have a positive impact – if below specific threshold values (e.g. height restrictions in a country) – and a negative impact – if above specific threshold values (e.g. exponentially increasing transport costs).

The findings are evaluated through the research design of providing multiple scenarios for the time of decommissioning and the fractions of circular economy pathways in two countries. This enables to assess the impact on second-lifecycle and recycling flows. Additionally, sensitivity analyses on the impacts of different values for f_{reuse} and $f_{recycle}$ to annual second-lifecycle and recycling quantities are provided. Furthermore, the results are discussed in comparison to existing studies and in context with required capacities of second-lifecycle and recycling companies in Denmark and Germany, if available.

The results of the determination of f_{reuse} and $f_{recycle}$, along with the application of the different scenarios to equations (5) and (6), are presented and evaluated in the chapters 6.2 and 6.3.

6.2 Results

This chapter presents the results of Part C, beginning with an overview of the decommissioned and installed onshore wind turbines in Denmark and Germany (6.2.1). Subsequently, the input factors for the annual flow models are determined, namely the parameters of the accumulated Weibull functions (6.2.2) and the fractions of the circular economy pathways (6.2.3). In the following chapters, the forecasts of annual decommissioning (6.2.4), second-lifecycle (6.2.5), and recycling quantities (6.2.6) are presented as a core information basis for long-term capacity planning of supply chain actors.

6.2.1 Onshore wind turbines in Denmark and Germany

This chapter provides an overview of the selected and prepared market data on the onshore wind turbine fleets from Denmark and Germany. Hence, it outlines the historical development of installations and decommissioning, with a particular focus on the characteristics of onshore turbines in operation to provide insights into the future decommissioning. Moreover, an investigation of the ways in which the characteristics of future decommissioning will differ from those of the past provides further insights. However, Germany does not have such detailed data (see 6.1.2), whereas Denmark does and is therefore considered.

Historical development of onshore wind installations

The development of the annually installed onshore wind turbines in Denmark and Germany was introduced in chapter 2.2 (see Figure 5), which is why reference is made to this chapter at this point. The subsequent Figure 62 moreover presents the historical development expressed in blade mass (tonnes). It becomes evident that the annual blade mass is strongly linked to the installed capacity, which is not surprisingly as the turbines have increased in size and consequently also the length of the rotor blades. In Denmark a total blade mass of 51,016.2 tonnes is in operation and in Germany this accounts for 738,718.6 tonnes, as described in Kramer et al. (2024, p. 185).

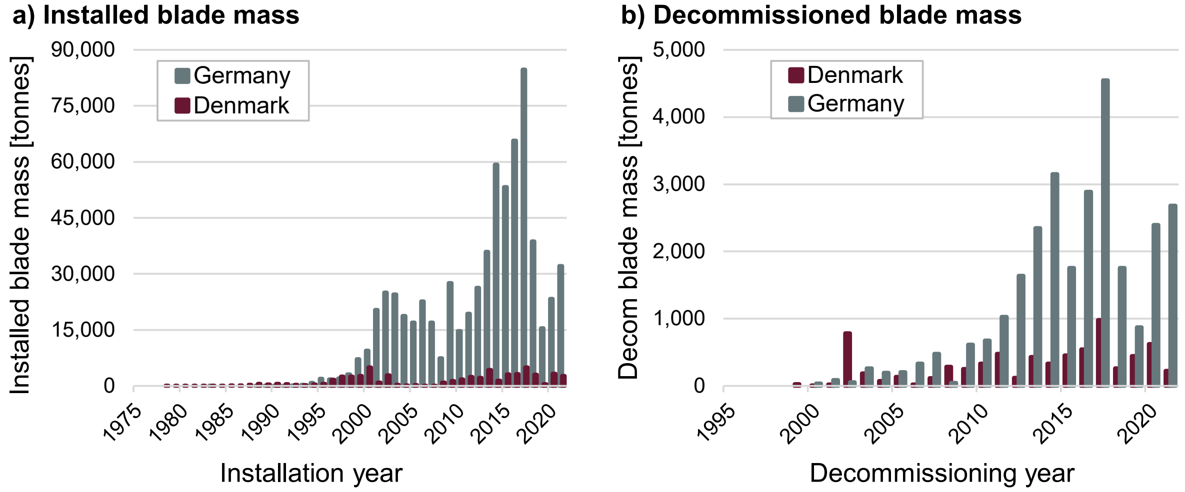


Figure 62. Historical development of a) installed and b) decommissioned blade mass from onshore wind turbines in Denmark and Germany. The decommissioned blade mass in Germany is based on 9 tonnes/MW. Inspired by Kramer et al. (2024). Based on data from DEA (2022), Deutsche WindGuard (2023), Bundesnetzagentur (2023).

Historical development of onshore wind decommissioning

The historical decommissioning is shown in the right side of Figure 62 by presenting the annual decommissioned blade mass in Denmark (red bars) and Germany (grey bars). Moreover, Figure 63 presents the historical development expressed in number of turbines and installed capacity (in MW). It is to be noted that for Germany only a timeseries on annual decommissioning capacity is available and thus the blade mass is approximated through 9 tonnes per MW and the number of turbines with 0.8 per MW (see 6.1.2). Decommissioning has started slightly earlier in Denmark (1998) than in Germany, where it started around 2000.

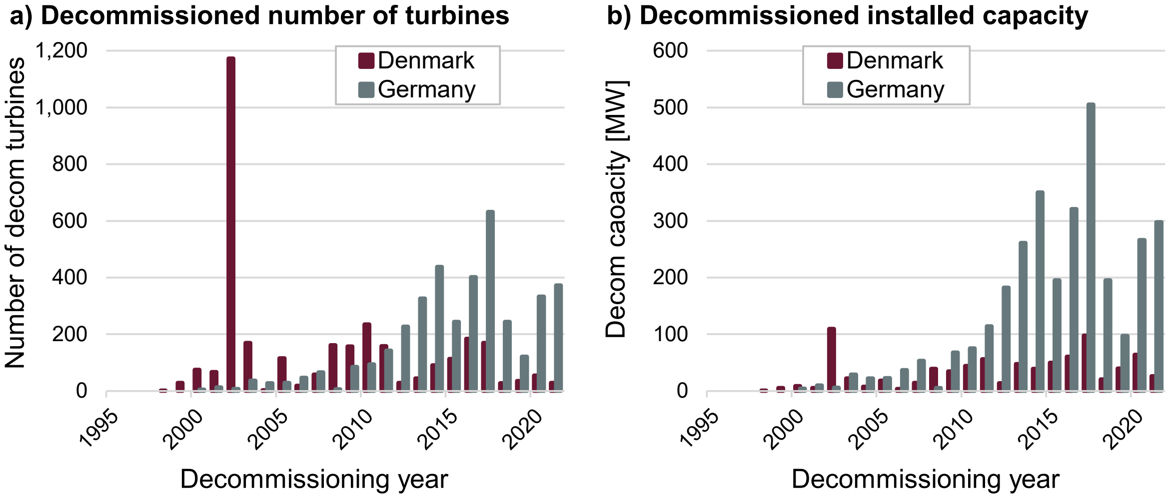


Figure 63. Historical development of a) number of turbines and b) installed capacity of decommissioned onshore wind turbines in Denmark and Germany. The number of turbines in Germany is based on 0.8 MW/turbine. Based on data from DEA (2022), Deutsche WindGuard (2023).

Decommissioning in Denmark

In Denmark, 3,195 onshore wind turbines with an installed capacity of 826.4 MW and a blade mass of 7,130.8 tonnes were decommissioned in total. The onshore wind turbines have an average age of 18.0 years at decommissioning with ranging from less than a year to 39 years (see Figure 64). The decommissioning mainly stems from Vestas turbines, which were also the most frequently installed. Annual decommissioning has greatly fluctuated. Noticeable is the peak in 2002, which is in a greater magnitude when looking at the number of turbines: 36.7 % of the total number of decommissioned turbines and 13.3 % of the total decommissioned capacity. One potential explanation for this peak is the financial incentive ('skrotpræmie'), which was granted by the government between 1999 and 2003 for the decommissioning of wind turbines with a capacity of up to 150 kW (BEK nr 187 af 16/03/2001, 2001). When comparing the left side to the right side of Figure 63, it becomes visible that the turbine size has increased over time. For example, in the time period 1998-2002 mostly turbines below 150 kW were decommissioned and in 2016-2020 at an average of ~600 kW. This is also why the marginal decommissioning of 117 turbines in the last three years (2019-2021) still corresponds to 15.7 % of the total decommissioned capacity.

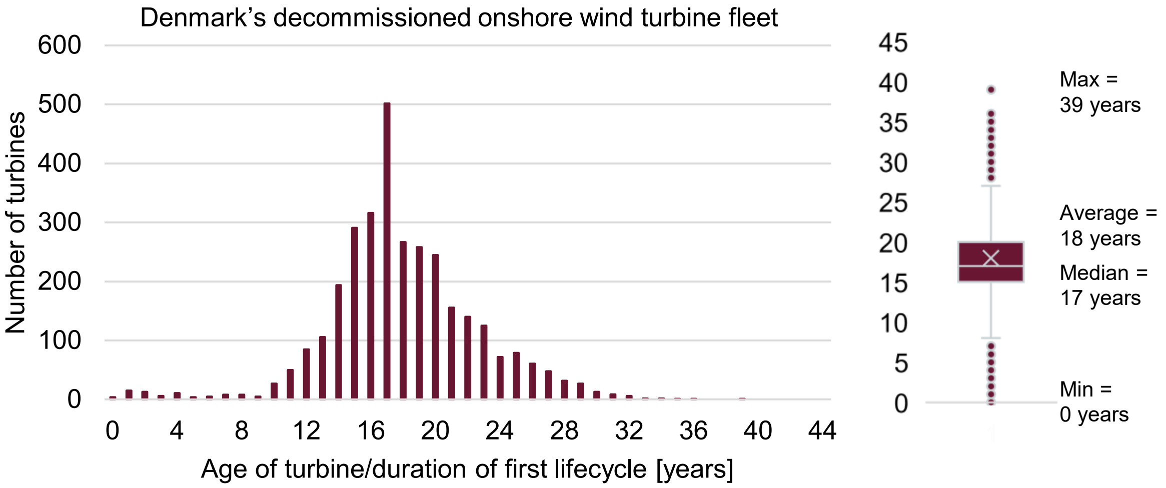


Figure 64. Age distribution of the decommissioned onshore wind turbines in Denmark as of 31/01/2022. Based on data from DEA (2022).

Decommissioning in Germany

In Germany, decommissioning totals around 4,500 turbines with an installed capacity of ~3,600 MW and 32,400 tonnes of blade mass (Deutsche WindGuard, 2023). Figure 63 illustrates that the decommissioning years 2014 (350 MW) and 2017 (505 MW) record the highest decommissioning to date. Moreover, the statistics from Deutsche WindGuard state decommissioning levels of 266 MW in 2020, 298 MW in 2021 and 292 MW in 2022. A recent report also signalled that with 500 MW of decommissioning in 2023, the annual dismantling volumes have gradually increased in recent years (Deutsche WindGuard, 2024, p. 3). In general, annual rates are greatly fluctuating, with an annual average of 148.2 MW decommissioned capacity and a standard deviation of 140.9 MW in the timespan of 2000 to 2022. Initially, the Federal Environment Agency had anticipated an exponential increase in 2021, which was justified by the fact that the expiry of the fixed feed-in tariff would expose onshore plants to market prices for the first time and their assumption that this would therefore favour decommissioning (Volk et al., 2021; Zotz et al., 2019). However, this did not materialise, assumingly due to significantly increased market electricity prices (Netztransparenz, 2023).

Characteristics of the onshore turbine fleets in operation

The following describes the operational onshore fleets in Denmark and Germany according to the distribution by turbine age, turbine manufacturer, turbine type, installed capacity and rotor diameter.

Age distribution

The following two figures present the age distribution of the operational onshore wind turbines in Denmark (Figure 65) and Germany (Figure 66). In Denmark, the age of the operational turbines is ranging from 5 days to 44 years with an average at 21 years and median at 23 years. Figure 65 illustrates that some age groups are more strongly represented than others, which is related to the varying installations in the individual years. As of 31/01/2022,

- 7.0 % of the turbines are 0-5 years,
- 8.8 % between 6-10 years,
- 3.7 % between 11-15 years,
- 8.4 % between 16-20 years,
- 51.4 % between 21-25 years and
- 20.7 % older than 25 years.

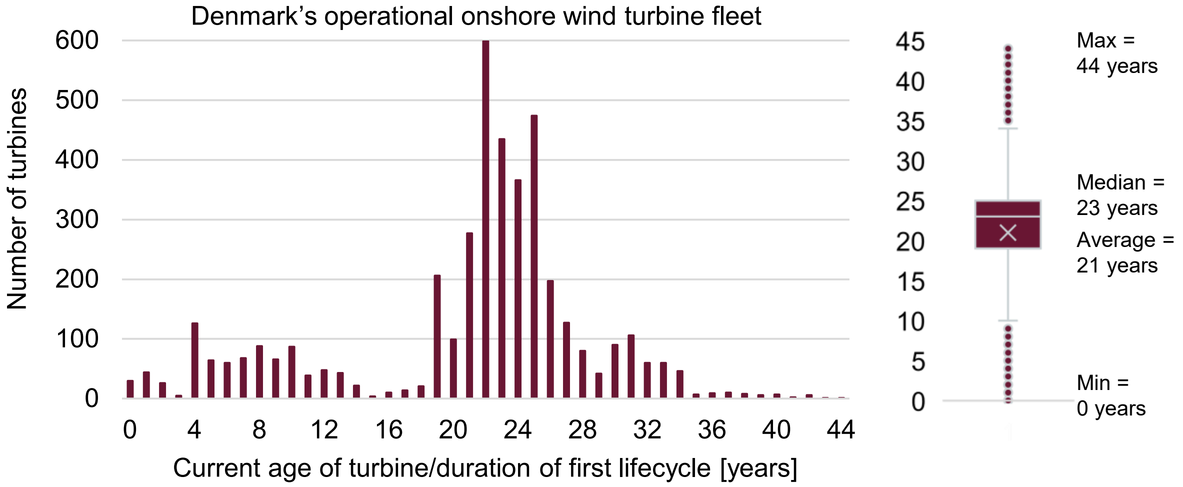


Figure 65. Age distribution of the onshore wind turbines in operation in Denmark as of 31/01/2022. Based on data from DEA (2022).

In Germany, the distribution of the turbine age is varying from 2 days to 40 years with an average at 14.6 years and median at 14 years.

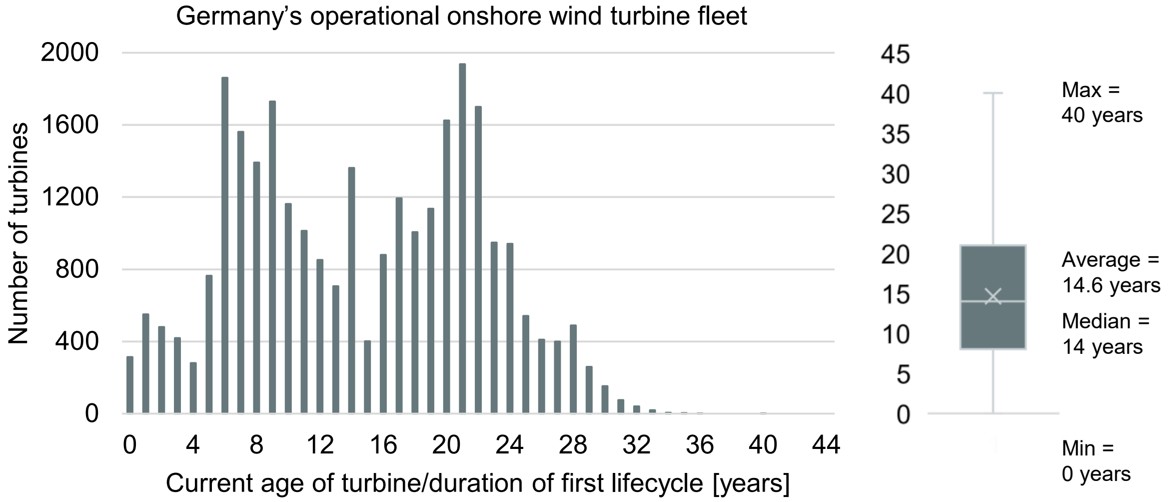


Figure 66. Age distribution of the onshore wind turbines in operation in Germany as of 30/06/2023. Based on data from Bundesnetzagentur (2023).

The left side of the diagram illustrates that some age groups are more strongly represented than others, which is related to the varying installations in the individual years.

As of 30/06/2023,

- 9.8 % of the turbines are 0-5 years,
- 26.9 % between 6-10 years,
- 15.2 % between 11-15 years,
- 20.4 % between 16-20 years,
- 21.2 % between 21-25 years and
- 6.5 % older than 25 years.

Distribution by turbine manufacturer

Furthermore, Figure 67 outlines the distribution of operational onshore wind turbines in Denmark (left side) and Germany (right side) by turbine manufacturer.

In Denmark, mainly Vestas turbines (37.7 %) are in operation, followed by NEG Micon (29.2 %) and Bonus (9.9 %). The remaining turbines were manufactured by Siemens (5.9 %), Nordex (3.3 %), other manufactures (6.3 %) or, in 7.8 % of the register entries, the name of the manufacturer was not given. In Germany, the majority of operational onshore wind turbines is from Enercon (42.6 %), followed by Vestas (20.1 %) and Nordex (8.5 %). The six manufacturers that have installed the most turbines cover 85.1 %, of which the first two, Enercon and Vestas, represent the majority. The remaining turbines (14.9 %) were installed by other manufacturers like Repower Systems, Siemens Gamesa, AN Windenergie, Tacke or Fuhrländer.

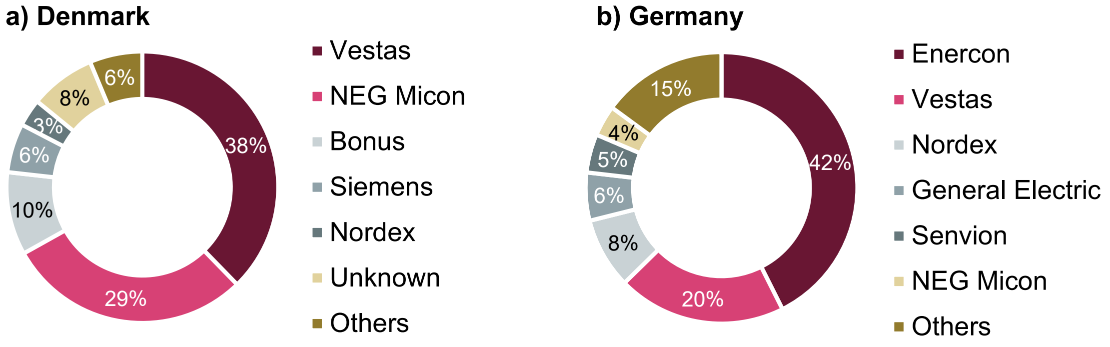


Figure 67. Distribution of the onshore wind turbines in operation in a) Denmark and b) Germany by turbine manufacturer. Based on data from DEA (2022), Bundesnetzagentur (2023).

Both markets are characterised by the fact that the majority of the market is represented by a few manufacturers, with one manufacturer covering around 40 % of the market. Vestas is active in both markets with large market shares, while Enercon has a strong presence in Germany but only plays a marginal role in Denmark. In addition, it should be noted that some manufacturers no longer exist or are now part of another company, e.g. NEG Micon became part of Vestas and AN Windenergie, Bonus, Senvion's service business, and Siemens belong to Siemens Gamesa.

Distribution by turbine type

Building upon this, Figure 68 and Figure 69 show the distribution of operational wind turbines in Denmark and Germany per turbine type.

Figure 68 presents the number of turbines per turbine type in Denmark, but in order to provide a clearer overview, the turbine types with less than 50 turbines in operation have been aggregated (grey bars). Accordingly, 22 turbine types with at least 50 operational turbines each (red bars) represent 68.9 % of the total number of operational turbines. Turbine types with a minimum of 10 operational turbines account to 51 turbine types and equate to 86.5 % of the operational fleet. In line with Vestas's large market share, also most of the frequently installed turbine types belong to Vestas. The turbine type with most operational turbines is the NM 447/750 from NEG Micon, a manufacturer that today belongs to Vestas. This is followed by a V47-660 and V44-600 from Vestas, illustrating that the three most common operational turbines are below 1 MW of installed capacity.

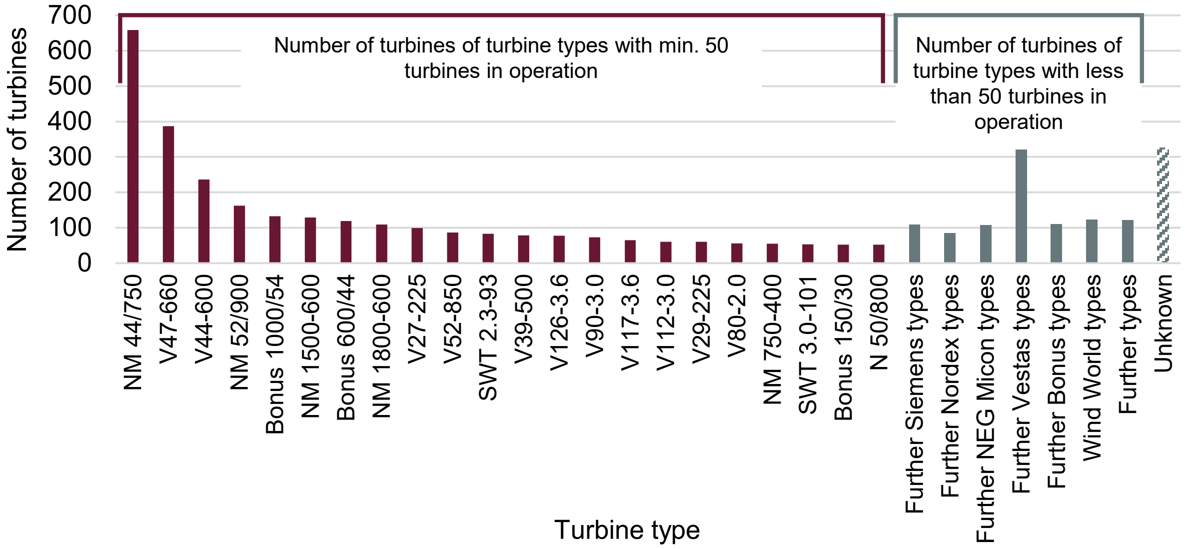


Figure 68. Number of operational onshore wind turbines in Denmark per turbine type. Based on data from DEA (2022).

Figure 69 shows the number of turbines per turbine type in Germany, but again, aggregation of less installed turbines is necessary for a clearer overview.

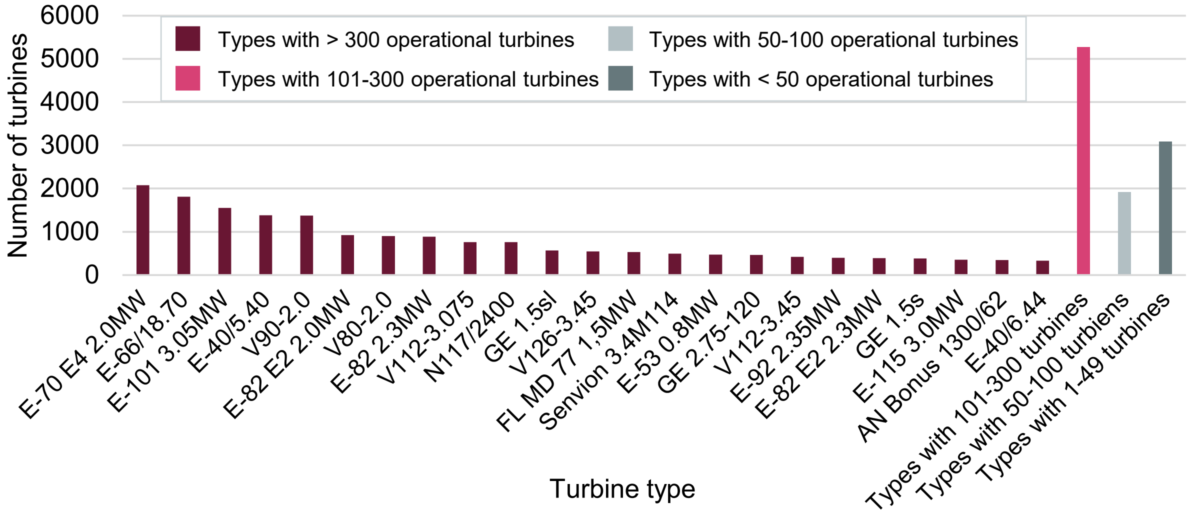


Figure 69. Number of operational onshore wind turbines in Germany per turbine type. Based on data from Bundesnetzagentur (2023).

Accordingly, only types with a minimum of 300 operational turbines are displayed (red bars) and the types with 101-300 operational turbines (pink bar), with 50-100 operational turbines (light grey bar) and less than 50 operational turbines (grey bar) have been aggregated. There are 23 turbine types installed in Germany with more than 300 turbines in operation, representing a market coverage of 63.8 %. In addition to that, further 33 turbine types operate more than 100 turbines and again additionally, 27 turbine types operate more than 50 turbines. Hence, in total 83 different turbine types represent at least 50 operational turbines that correspond to 89.1 % of the market. As Enercon has the largest market share in Germany, it is not surprisingly that various turbine types from Enercon are frequently installed. According to the market register, the Enercon models E-70 E4 2.0 MW, E-66/18.70 and E-101 3.05 MW are the types with most operational turbines.

Distribution by installed capacity

Moreover, Figure 70 shows the distribution of installed capacity from decommissioning (left side) and operation (middle) in Denmark and operation in Germany (right side).[4]

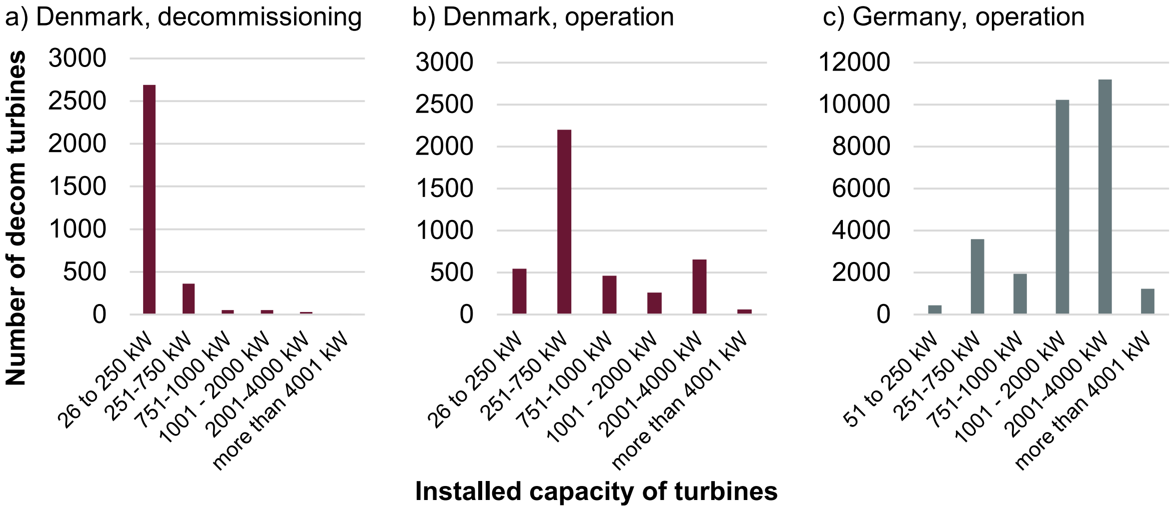


Figure 70. Number of turbines per installed capacity of the onshore wind turbines from a) decommissioning in Denmark, b) operation in Denmark and c) operation in Germany. Based on data from DEA (2022), Bundesnetzagentur (2023).

The installed capacity per turbine is clustered into ‘up to 250 kW’, ‘251-750 kW’, ‘751-1,000 kW’, ‘1,001-2,000 kW’, ‘2,001-4,000 kW’ and ‘more than 4 MW’. It becomes apparent that the Danish decommissioning mostly accounts to turbines below 750 kW and particularly of turbines below 250 kW. This is in line with the significant number of decommissioned turbines outlined in Figure 63. Turbines that are in operation in Denmark vary between the different capacity clusters, with 251-750 kW being the most

---

[4] The distribution by installed capacity of decommissioned wind turbines in Germany is not shown as this information is not comprehensively available (see 6.1.2).

common and followed by 2-4 MW turbines. In Germany, most turbines in operation range between 251 kW and 4 MW, with 1-4 MW being the most prominent.

Distribution by rotor diameter

Finally, Figure 71 presents the distrubution of turbines' rotor diameters.[5] Herefore, the rotor diamters are clustered to 'up to 44 meters', '45-72 meters', '73-99 meters', '100-150 meters', and 'more than 150 meters'. Since the rotor diameter also increases with increasing installed capacity, the distribution is relatively similar to that shown in Figure 70. The majority of turbines installed in Denmark have a rotor diameter of less than 44 meters, while in Germany there is a relatively even distribution between the different clusters. Only turbines with a rotor diameter of more than 150 meters are marginally represented, which is consistent with Figure 70 and the modest number of operational turbines with an installed capacity of more than 4 MW.

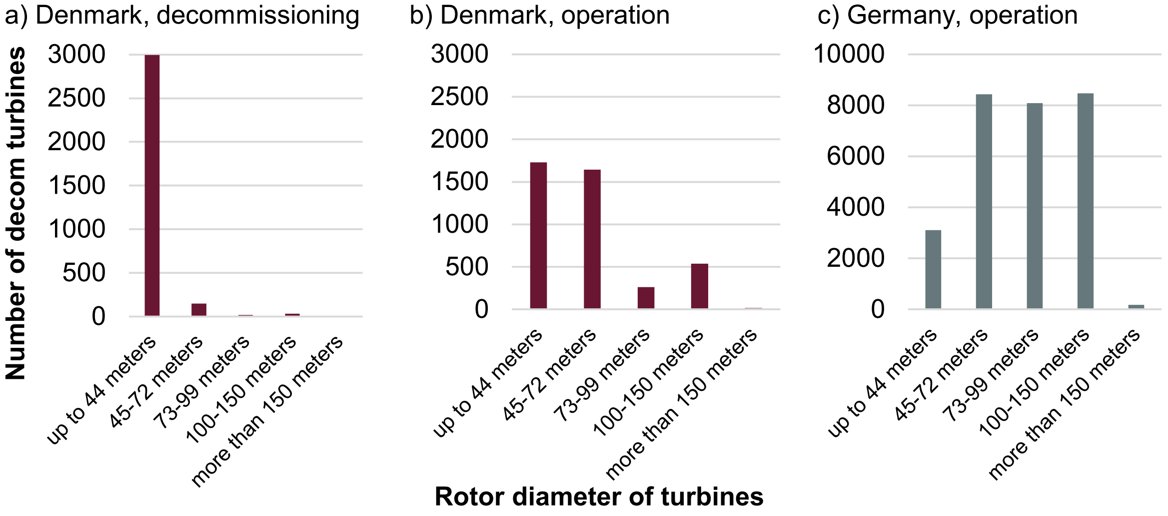


Figure 71. Number of turbines per rotor diameter of the onshore wind turbines from a) decommissioning in Denmark, b) operation in Denmark and c) operation in Germany. Based on data from DEA (2022), Bundesnetzagentur (2023).

In summary, the development of the decommissioned and operational fleets in Denmark and Germany demonstrate that the annual quantities fluctuate considerably over the years, and that the age of the operational turbines also varies significantly. Furthermore, the analysis reveales that in Denmark mostly Vestas turbines with less than 750 kW and a rotor diameter of up to 48 meters are installed. In Germany, decommissioning could not be characterised due to a lack of comprehensive data, while the operating fleet consists mainly of Enercon turbines with an installed capacity of 1-4 MW and a rotor diameter of up to 150 meters.

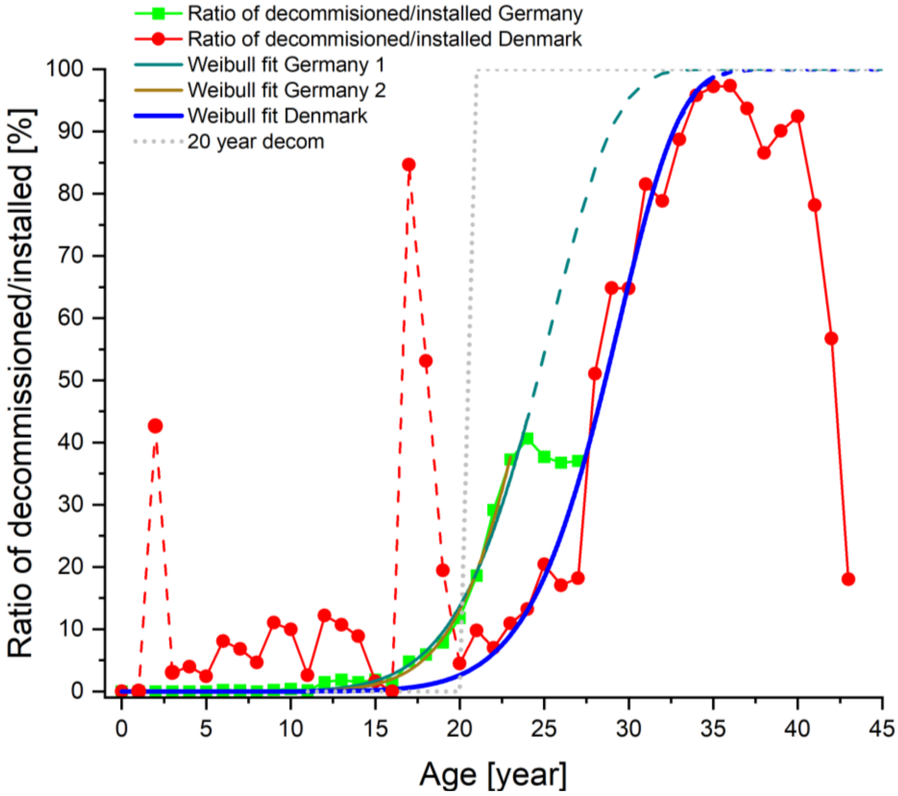
---

[5] The distribution by rotor diameter of decommissioned wind turbines in Germany is not shown as this information is not comprehensively available (see 6.1.2).

6.2.2 Determination of the time of decommissioning

Following the methodology outlined in 6.1.3.1, first it is assessed whether for Denmark and Germany comprehensive market history of their decommissioned and overall installed onshore wind turbines are present. As outlined in section 6.2.1, this is indeed the case, even if the use of multiple sources is therefore required for Germany.

Figure 72 illustrates the ratios of decommissioned wind turbines over installed onshore wind turbines per installation year for the respective markets, together with the corresponding fit of the accumulated Weibull function.



Model	Weibull DNK
Lambda	29.79 0.25
k	9.11 0.88
R-Square	0.96

Model	Weibull GER 1
Lambda	25.83 0.18
k	7.49 0.34
R-Square	0.99

Model	Weibull GER 2
Lambda	25.06 0.12
k	8.71 0.29
R-Square	0.99

Figure 72. Accumulated Weibull functions representing the ratio between decommissioned and installed blade mass from Denmark's and Germany's onshore wind turbine fleet, in comparison to a 20-year lifetime. Based on Kramer et al. (2024, p. 187) and inspired by Abrahamsen et al. (2023); data from DEA (2022) and Lüers et al. (2023).

Fitted accumulated Weibull function for the Danish onshore turbine fleet

In evaluating whether certain key figures for the Danish onshore fleet (red-marked points) should be regarded as outliers and thus excluded from the Weibull fit, it becomes evident that some outliers exist when examining the data (Abrahamsen et al., 2023; Kramer et al., 2024). Namely, those are at the age of 2 years and 17-19 years as well as beyond the age of 35 years. It is argued that the data points marked with a dashed red line (2, 17-19 years) should be disregarded due to the marginal number of installed turbines in these years. Consequently, the ratios are deemed to be highly sensitive, resulting in a significant depletion. In addition, according to Abrahamsen et al. (2023, p. 11), turbines over 35 years old do not meet the design standards for wind turbines, as the turbines were erected earlier. It is therefore concluded that these ratios should be disregarded, as the continued operation of museums and similar institutions may result in low depletion ratios. In addition, it was tested whether the ratios would change greatly, if the ratios are expressed in terms of the number of turbines or the installed capacity instead of blade mass. This cannot be confirmed, only the already excluded outliers with low installation values change significantly.

After excluding the outliers, the remaining ratios of decommissioned over installed turbines are fit with the scale parameter λ = 29.79 years ± 0.25 and the shape parameter k = 9.11 ± 0.88 of the Weibull function (blue line) (Kramer et al., 2024, p. 187). This is in line with the initial study by Abrahamsen et al. (2023, p. 11) who state λ = 30 years and k = 10.

Fitted accumulated Weibull function for the German onshore turbine fleet

For the German onshore turbine fleet, the green-marked points in Figure 72 represent the ratios of decommissioned over installed. It becomes evident that Germany's history is shorter than compared to Denmark, and additionally, the available ratios only date back to 1995 (Lüers et al., 2023, p. 46). In other words, ratios for the installation years of 1983 to 1994 are missing in the dataset. It is therefore not surprising that none of the ratios have been fully depleted yet. Currently, the ratios rather level at around 37-38 % in the years 1995-1997, which would indicate that approximately 62-63 % of the turbines, which are currently aged 25-27 years, are still operational (Kramer et al., 2024, p. 187).

At this point in time, it is not possible to make an accurate determination as to whether these data points should be classified as an outlier in the context of the Weibull fit or retained. For instance, it could indicate a flattening trend resulting from the pursuit of multiple-year lifetime extensions following the expiration of the original 20-year design lifetime. Hence, it could be possible that the German market will behave differently than the Danish onshore market. In fact, Germany regulates continued operation beyond the planned design life more strictly, which could imply that this is only financially viable if the turbine can be operated for several more years (see Figure 33 and Ziegler et al., 2018, p. 1265). An alternative explanation is that the data history is not yet sufficiently extensive, and thus the ratios would increase with the availability of a longer historical record. In the present analysis, the data points prior to 1998 have been excluded, resulting in the fit of the Weibull function being based on the ratios for the installation years 1998 to 2022. Given the absence of extreme outliers in the data set from the early installation years, no further data points are excluded. It is noticeable that the German data has a lower level of noise in recent installation years than the Danish data, which is to be expected given the larger absolute numbers of installations.

The fit of the Weibull function (turquoise line in Figure 72) to the kept data points equals to the parameters of λ = 25.83 years ± 0.18 and k = 7.49 ± 0.34 (Kramer et al., 2024, p. 187). Moreover, a further Weibull function (No. 2, brown line in Figure 72) is fit to assess the sensitivity of also including the ratio of 1997 and hence fitting to ratios of

1997 to 2022. In this instance, the parameters are represented by λ = 25.10 years ± 0.12 and k = 8.71 ± 0.29, indicating a somewhat lower scale parameter and slightly increased shape parameter (Kramer et al., 2024, p. 187).

In conclusion, if the decommissioning of the onshore wind turbine fleet were to adhere to the derived accumulated Weibull functions of the respective countries, half of the Danish fleet would be decommissioned after approximately 29 years, and in Germany, after approximately 25 years (Kramer et al., 2024). Moreover, in Denmark 10 % of the fleet would be expected to be decommission after 23.3 years and 90 % after 32.7 years, corresponding to a time span of 9.4 years. For Germany, this time span would equal to 9.8 years, with a depletion of 10 % of the fleet after 19.1 years and 90 % after 28.9 years. It should be noted that the depletion of the fleets in both countries would take significantly longer than the commonly applied assumption of decommissioning after 20 years of operation (see 6.1.1).

Definition of scenarios for the adjusted accumulated Weibull functions

In addition, to take account of possible changes in the depletion function in the future, two further scenarios are formulated to help visualise potential impacts. Therefore, as shown in Figure 73, the scale parameter λ of the determined Weibull functions is adjusted to reflect a faster decommissioning in one scenario and a slower depletion in the other.

The findings from Part B on the factors influencing the decision to decommission have not signalled any major changes in Denmark. Experts have commented that the number of decommissioning projects has been low in recent years, partly because there have been few new onshore installations. When new installations have taken place, they have mostly been on greenfield sites, so no operating turbine had to be decommissioned. In light of the aforementioned considerations, the current depletion curve (see Figure 72), which anticipates the continued operation of a significant portion of the fleet beyond the design life of 20 years, appears to be a realistic projection for the future. However, in the future the depletion could further slowdown, for example to be represented by a scale parameter of λ = 32 years. For instance, an expert from an OEM highlighted the widely untapped potential for a long technical lifespan of the turbine, which lies in the utilisation of the turbine's sensor data to improve the operation and establish predictive maintenance (see 5.2.3.2).

In contrast, countervailing factors could lead to an overall shorter depletion, for instance expressed with λ = 26 years. For example, some interviewed experts and studies (e.g. Beauson et al., 2022, p. 7) tend towards a lower expected technical lifetime by arguing that manufacturer got closer to design limits. Moreover, could a decommissioning or repowering incentive be introduced by the government, which could promote decommissioning instead of continued operation. It is still to be explored to which extend and direction the various influencing factors will impact the aggregated depletion curve.

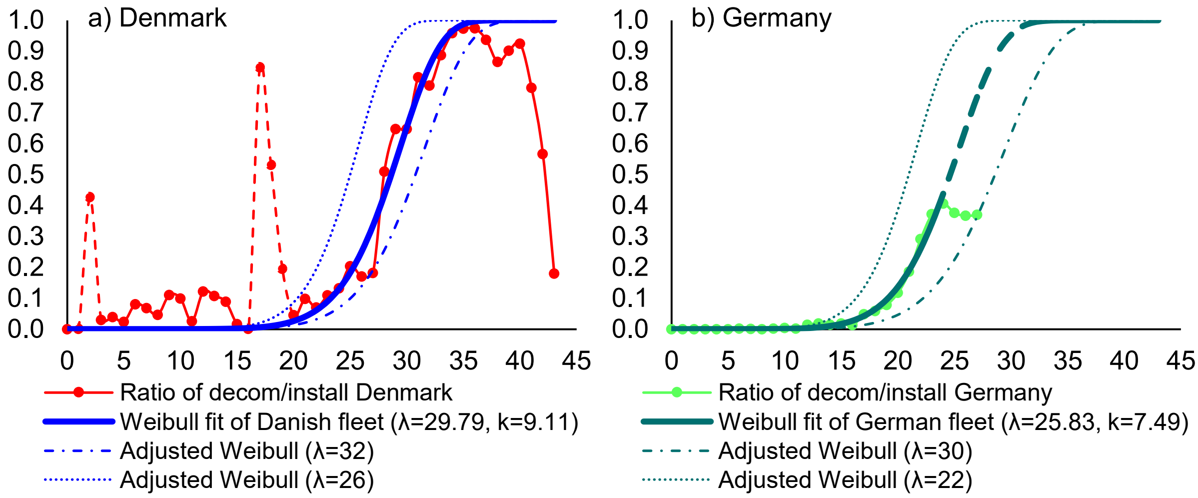


Figure 73. Weibull functions with different scale parameters for a) the Danish onshore fleet and b) the German onshore fleet in comparison to the ratios of decommissioned over installed. Data from DEA (2022) and Lüers et al. (2023).

These two outlined trends could also influence the fleet's depletion curve in Germany in one direction or the other. For Germany, limited data history is available and it is not yet reflecting installations years that have been fully decommissioned. This leads to higher uncertainties for the determination of the Weibull parameters (see Figure 72). In particular, as the share of the fleet that considers a lifetime extension is likely not fully represented in the data. Therefore, the scenarios reflect a wider spread, one scenario assuming λ = 30 years and the other λ = 22 years. The value of 30 years is chosen, as it roughly corresponds to the Danish fleet, where the data and experts indicate a large proportion of continued operation. Examples of factors that could encourage continued operation include attractive spot market prices or power purchase agreements, and regulatory relief for life extension (e.g. allowing remote sensor-based assessment) (see Figure 33).

The value of 22 years is chosen to envision the effect of further promotion of repowering. The interviewed experts have indicated that, in general, the planned project lifetime is fulfilled prior to repowering and only in instances of very good wind conditions an earlier repowering may be considered. Moreover, it is assumed that authorities allow a transitional period of a few years before an approval for continued operation would otherwise have to be in place. Consequently, the value of 22 could be suitable for illustrating the promotion of repowering. However, it should be noted that the value depends in particular on the level of the financial incentive for repowering. A financial subsidy has not been promised by the German government, but a simplification of the permitting processes (e.g. BImSchG, 1974/2024, § 16b). Moreover, the findings from Part B also show that some operators do not consider repowering or the project site is not feasible for repowering (e.g. due to legal, technical or economic reasons). For this reason, the selected scenario should rather be understood as an extreme scenario in order to understand potential impacts.

Summary of input parameters for the accumulated Weibull functions

A summary of the input parameters for calculating the decommissioning quantities, expressed in terms of the number of turbines ($n_{decom}(t)$) and blade mass ($m_{decom}(t)$) is given in Table 20.

Table 20. Overview of input parameters for forecasting annual decommissioning flows.

	Denmark	**Germany**
Heuristic	20 years	20 years
Weibull function	λ = 29.79 years; k = 9.11	λ = 25.83 years; k= 7.49
Adjusted Weibull functions		
a) Earlier decommissioning	λ = 26 years; k = 9.11	λ = 22 years; k = 7.49
b) Continued operation	λ = 32 years; k = 9.11	λ = 30 years; k = 7.49

6.2.3 Determination of the fractions of circular economy pathways

The fractions of circular economy pathways are defined by four scenarios, the 'fully linear', 'fully reuse', 'historical reuse' and 'current reuse'. These are presented below.

The 'fully linear', 'fully reuse' and 'historical reuse' scenarios

The 'fully linear' and 'fully reuse' scenarios are defined as two extreme scenarios. Accordingly, the 'fully linear' scenario disregards the second-hand market and assumes $f_{reuse} = 0\ \%$ and consequently $f_{recycle} = 100\ \%$. Such an extreme case is unlikely, as historically a significant reuse was observed in Denmark and Germany and none of the experts has expressed that they believe that the market would fully disappear going forward. However, this scenario has been widely assumed by existing scientific literature (see 6.1.1). In contrast to the 'fully linear' scenario, the 'fully reuse' scenario assumes that each wind turbine or blade enters a second lifecycle and therefore sets $f_{reuse} = 100\ \%$ and $f_{recycle} = 0\ \%$. It therefore slows down the use of resources and changes the geographical destination of the blade mass in the recycling stream. This assumption is also unlikely to materialise in the next few years, as it would require a more circular turbine design and is therefore not applicable to the already installed turbine fleet. However, this scenario is considered to show the potential impact of a transition towards a circular economy. Furthermore, the 'historical reuse' scenario estimates business as usual and therefore applies the historical reuse fractions and corresponding export ratios collected in Part B.

Upper limit for the 'current reuse' scenario

In accordance to the methodology outlined in 6.1.3.2, upper and lower limits for the 'current reuse' scenario are defined. Accordingly, the identified influencing factors of Part B are compared to the operational wind turbine fleets in Denmark and Germany (see 6.2.1). The results for the upper limit are presented in a funnel diagram consisting of four steps to filter the turbine fleet to the fraction that could be in principle feasible for a second lifecycle. Figure 74 presents the results for the operational onshore wind turbine fleet in Denmark.

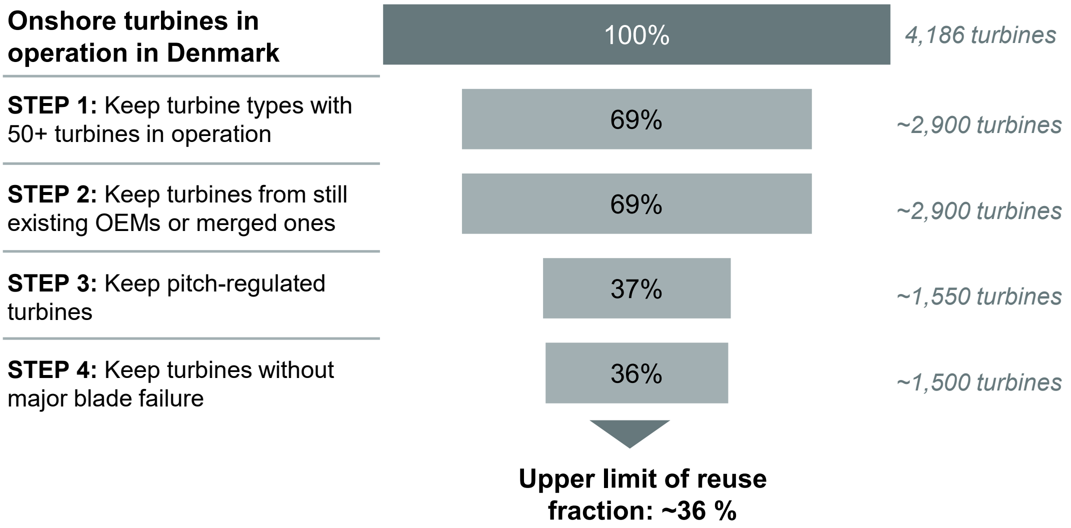


Figure 74. Funnel diagram for the upper limit of the reuse fraction of onshore wind turbines in operation in Denmark.

Furthermore, Figure 75 shows the results for the fleet of onshore wind turbines that are currently in operation in Germany.

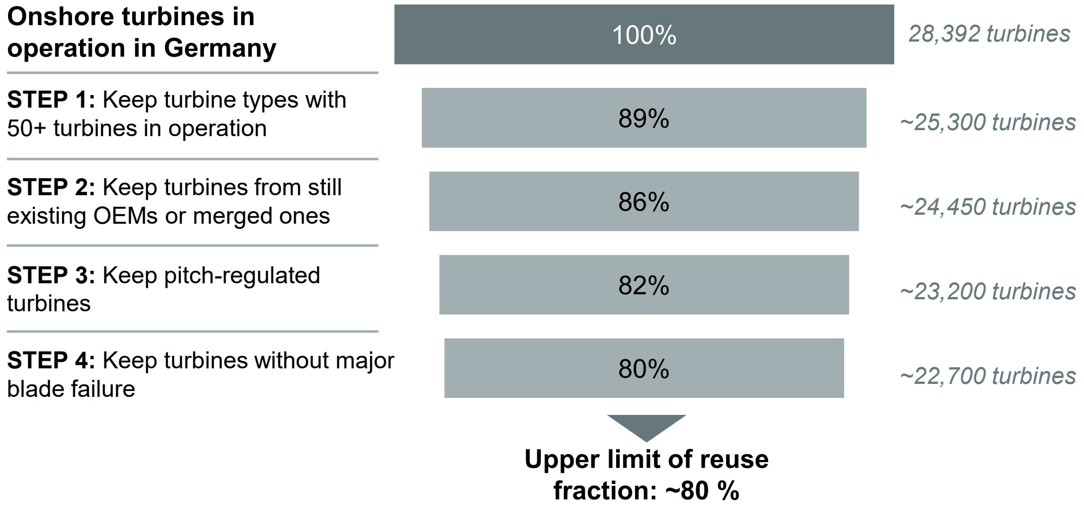


Figure 75. Funnel diagram for the upper limit of the reuse fraction of onshore wind turbines in operation in Germany.

The following section provides a detailed explanation of each step represented in the funnel diagrams.

First condition: Access to spare parts

First of all, a common factor that is expressed by all stakeholder groups and countries is the necessity to access spare parts and service technicians for the operation of second-hand turbines. In this context, several experts have mentioned that the most commonly installed turbine types are in demand, as there is still the possibility of locating spare parts for them. Moreover, there is broader industry knowledge in terms of operation and maintenance. Consequently, turbine types that have only a few turbines in operation are rarely in demand on the second-hand market. Therefore, the assumption is taken that turbine types with less than 50 operational turbines are likely not demanded, accounting for the first step of the funnel diagrams. This also leads to disregarding some of the newer turbine models, as those have not yet surpassed the threshold of 50 installations, but will likely do in the next years. This methodology is nevertheless deemed acceptable, given that the objective of the analysis is to determine a reuse fraction, in particular to estimate the annual flows for the next ten years. This is a time period in which the newer turbine types are likely to remain operational. The results of the filter for Denmark show that 2,882 of the 4,186 turbines (~69 %) are kept and ~31 % neglected. This neglected fraction includes the data entries with an unknown turbine type (7.8 %, see Figure 68). For Germany, the application of this criterium results to a remaining fleet of ~89 %, hence ~25,306 turbines. If the threshold of still existing turbines per turbine type would be lowered to 10 turbines per turbine type, the remaining share would account to 87 % for Denmark (see Figure 93 in the Appendix D1) and 98 % for Germany.

Second condition: Access to MRO service

Secondly, a further measurable influencing factor that was expressed by all stakeholder groups in both countries is the manufacturer of the turbine. Experts have pointed out that OEMs with a long company history, a global service business and from the premium segment are particularly favoured. For instance, one expert mentioned that Vestas has a service network in Italy and therefore customers from Italy would prefer their turbines. In contrast, the experts argue that OEMs that no longer exist or have been merged into small OEMs without an internationally known brand are unlikely to be in demand, as it is likely to be more difficult for them to find access to qualified service technicians. Therefore, in the second step, the funnel assumes that turbines from OEMs that have been closed or merged with a small OEM are not in demand on the second-hand market. For Denmark, this results to the same order of magnitude of remaining turbines (~69 %) and for Germany to ~86 %, also see Figure 67 in 6.2.1.

Third condition: Grid compliance

Thirdly, a common influencing factor that emerged from the interviews is the turbine's compliance with grid code requirements of the respective country. Accordingly, passive stall-regulated turbines (see 2.1) are in most countries not allowed to install and are therefore neglected for the second-hand market. The type of control system seems to be particularly relevant for the export of second-hand turbines to Ireland, as it is technically not possible to downregulate stall-regulated turbines. However, this appears to be a common approach for pitch-regulated turbines in order to qualify for the Irish subsidies that apply to small-scale wind energy production. Despite the taken assumption to neglect stall-regulated turbines, it should be noted that the grid code requirements vary across countries. Countries which have a minor share of variable renewables in their energy system might still allow the reinstallation of stall-regulated turbines. On that note, stall-regulated turbines are known for being robust, relatively cheap and easy to operate (Garcia-Sanz et al., 2011, p. 164). As a result, experts have reported that they were exporting some of these turbines at the start of the second-hand market. In addition, one expert mentioned that buyers from Kazakhstan, for example, are interested in low-maintenance and robust turbines. Nevertheless, it seems still suitable to neglect stall-regulated turbines as those were usually the ones from the first generations and are likely also not meeting environmental standards anymore.

For the calculation of the share of stall-regulated turbines from Denmark and Germany, it was necessary to add the relevant data, as the market registers lack this information. Consequently, publicly accessible data on the technical specifications of the remaining turbine types were investigated and added. The application of the third filter results in a remainder, comprising ~37 % of the Danish turbine fleet and ~82 % of the German fleet. For comparison, the analysis of Denmark's fleet with a threshold of at least 10 turbines per turbine type would result to ~45 %.

Forth condition: No lightning strike

The last step of the funnel acknowledges that turbines and their blades that are hit by a lightning strike and burnt are not going to enter any second lifecycle and are therefore disregarded. No actual market data for Denmark, nor for Germany is available, however a common used assumption in scientific literature is a failure rate of blades in operation of ~2 % (Heng et al., 2021, p. 61; Lichtenegger et al., 2020, p. 122; Liu & Barlow, 2017, p. 237). This is in line with the track record of I10, who reported the decommissioning of ~2-3 % of burnt turbines in Germany.

Conclusion

In conclusion, for Denmark ~40 % of the turbines in operation are deemed to be potentially eligible for the second-hand market and for Germany ~80 %. This is understood as an order of magnitude for the upper limit of current reuse flows, as a second lifecycle of a turbine and its blades depends on several further factors.

Lower limit for the 'current reuse' scenario

The lower limit for the 'current reuse' scenario therefore takes additional factors into consideration that impact the technical and economic feasibility of a second lifecycle pathway. Accordingly, the remaining technical life and the transport costs, as two prominent influencing factors, are discussed to set a lower level of the reuse fraction in Denmark and Germany (see 5.2.3.2). It should be noted, however, that for many factors, data is not available for Denmark and Germany, and further research is therefore needed to collect the data systematically. For example, the market registers do not provide any information on the type of tower, i.e. concrete, hybrid or steel, but this was identified as a factor that could influence the likelihood of a second lifecycle.

Remaining technical life

The remaining technical life at the time of decommissioning is a key factor in assessing the technical and economic feasibility of a second lifecycle. As 6.2.2 outlined, the time of decommissioning varies and consequently the age of the turbine at the time of decommissioning. Based on historical data, the depletion of the Danish turbine fleet is characterised by 10 % of the fleet being decommissioned after 23.3 years, 50 % after 29 years and 90 % after 32.2 years. For Germany, the current data results to a depletion of 10 % after 19.1 years, 50 % after 25 years and 90 % after 28.9 years. Consequently, a major proportion of the fleets is estimated to be decommissioned beyond surpassing the design life of 20 years, in particular for Denmark. The experts commonly agreed that the threshold of 20 years does not impact the likelihood of selling a second-hand turbine. To date, comprehensive data on the remaining technical life at the time of decommissioning is only rarely available for some turbines, ranging at an overall technical life of 22.6-40 years for different turbine types (8.2 Group, 2021). However, this data does not include data on the newer turbine generations, as these turbines do not yet have a long enough history. Moreover, the technical life is not only impacted by the turbine design, but amongst others depends on the wind conditions at the site, the maintenance strategy or latest replacements of components (see Figure 33). In addition, research on refurbishment and remanufacturing of turbines is rare (see 2.4) and it is to be seen how the refurbishment and remanufacturing of turbines can increase the overall technical life of the turbine. This demonstrates that defining a limit value for the reuse fraction is only feasible to a limited extent on the basis of currently available information.

Transport costs

Furthermore, experts frequently highlighted the rising transportation costs associated with the growing size and weight of the turbines, which could impede the possibility of a second lifecycle. In this light, it seems useful to cluster whether the blade length surpassed 20.75 meters or 35 meters. The threshold of 20.75 meter is chosen because transport up to this length is not classified as special transport (in German called "*Langtransporte*") (StVO, 2013/2024, § 22 (4)).[6] The expert I2 adds to this, by stating that up to a length of 12 meters, thus at turbines with an installed capacity of approximately 200 kW, transport is possible with standard trucks and does not involve any transport permissions. For blade length of over 20.75 m, special transport is required, which includes transport permits and a restriction of the permissible times (StVO, 2013/2024, § 29 (3); BWE). Furthermore, transport costs increase significantly if a component exceeds the structure gauge (in German called "*Lichtraumprofil*"), which defines the standard dimensions of roads (including bridges and tunnels) in most European countries such as Germany (StVZO, 2012/2024, § 32). Accordingly, on roads a maximum width of 2.55 m (in special circumstances 2.6 m) and a height of 4.00 m (or 4.50 m in some areas) is given. A turbine blade of approximately over 35 m exceeds the

---

[6] The current law is used as a reference. However, some company websites mention the possibility to extend the 20.75 meters by additional 2 meters (Arnold Schwerlast).

maximum height, which leads to a restriction of the possible transport routes and possibly requires the use of special lifting devices for passing under bridges (BWE).

With reference to the outcome of the upper limits of ~36 % of turbines in Denmark (see Figure 74) and ~82 % of turbines in Germany (see Figure 75), the fractions can be reduced, depending on what length of blade is assumed to still be economically transportable. This can therefore support the determination of a lower limit of the current reuse fraction in the respective countries. In this light, Table 21 shows the reduction of the upper reuse levels for the Danish and German turbine fleets in accordance to certain thresholds of rotor blades lengths.[7] Accordingly, the application of this filter has a particular impact on the German operational fleet, which is characterised by greater blade lengths than the Danish fleet (see Figure 71).

Table 21. Determination of lower limits for the ‘current reuse’ scenario.

Rotor blade length	Reduction of Denmark’s upper limit of ~36 %	Reduction of Germany’s upper limit of ~82 %
Up to 20.75 m	~11 %	~7 %
Up to 35 m	~25 %	~32 %
Up to 45 m	~28 %	~56 %

A possible assumption for the determination of the lower limit for the ‘current reuse’ scenario could be to only consider turbines up to a blade length of 35 meters. Hence, transportation remains within the structural gauge. In this case, the upper limit of the expected reuse shares is reduced in Denmark to ~25 % and in Germany to ~32 %. Nevertheless, further research on a suitable threshold value is required. For instance, an expert has reported that enquiries have already been received for turbines with larger blade lengths (e.g. V89, V90), although these are currently only rarely being decommissioned. It is therefore important to note, that to date mostly turbines below 2 MW of installed capacity and blades below 35 meters have been decommissioned and hence it is still to be seen how the market evolves.

Conclusion

Based on the discussion of remaining technical life and transport costs, it shows that further research about the various influencing factors is required. However, it does provide a first insight on the potential impact of identified influencing factors such as transport costs. The feasibility of a second lifecycle defined on the above thresholds of blade lengths has a larger impact on the operational fleet of Germany. In addition, the fitted Weibull function for Denmark reveals a longer depletion that may indicate a larger impact for the technical feasibility of second lifecycle. As an initial order of magnitude, the lower limit of the ‘current reuse’ scenario is set to ~20 % for Denmark and to ~30 %

---

[7] In the case the threshold of 10 turbines per turbine types is applied, then the values change slightly to ~12 % for up to 20.75 m, ~28 % for up to 35 m, and ~31 % for up to 45 m.

for Germany. This leads to a wider spread for the upper and lower level of current reuse flows and therefore acknowledges the current uncertainties.

Summary

A summary of the scenarios for $f_{reuse}(t)$ for calculating the expected annual number of decommissioned onshore turbines for a second lifecycle ($n_{reuse}(t)$) is provided in Table 22. Moreover, the resulting $f_{recycle}(t)$ is shown in Table 22, which is the basis for calculating the expected annual recycling flows ($m_{recycle}(t)$).

Table 22. Overview of input parameters for forecasting annual second-lifecycle and recycling flows.

Scenario	**Denmark**		**Germany**	
	$\boldsymbol{f_{reuse}(t)}$	$\boldsymbol{f_{recycle}(t)}$	$\boldsymbol{f_{reuse}(t)}$	$\boldsymbol{f_{recycle}(t)}$
Fully linear scenario	0 %	100 %	0 %	100 %
Fully reuse scenario	100 %	0 %	100 %	0 %
Historical reuse scenario	60 %	40 %	50 %	50 %
Upper limit of current reuse	40 %	60 %	80 %	20 %
Lower limit of current reuse	20 %	80 %	30 %	70 %

6.2.4 Forecasts of annual decommissioning quantities

This chapter presents the results of the expected annual decommissioning from onshore wind turbines in Denmark and Germany and thus provides a key basis for the long-term capacity planning of companies involved in the decommissioning and disassembly at the project site. The annual decommissioning quantities are calculated through the application of the derived input parameters (Table 20) to the Eq. (3) and Eq. (4) (see 6.1.3). The results for the overall depletion are presented, first for Denmark and then for Germany, with a particular focus on the next ten years. This time horizon is appropriate for long-term planning as predictions with a longer time horizon are subject to greater uncertainty. It is important to note that only current installations are included in the analysis, and not additional turbines that are planned for installation. This also explains the reduction of the decommissioning flows to zero by 2065 the latest.

Annual decommissioning quantities in Denmark

Figure 76 shows the annual expected decommissioning flows from the installed onshore fleet in Denmark in the unit of blade mass ($m_{decom}(t)$) and as such the depletion of in total 57,915.7 tonnes. Moreover, the annual expected number of decommissioned turbines ($n_{decom}(t)$) of in total 7,381 turbines is displayed in Figure 77. The results of the decommissioning flows according to the Weibull function ($\lambda = 29.79$, $k = 9.11$, blue line), which considers the historical ratios of decommissioning to installed, are compared with the two adjusted Weibull functions. One adjusted Weibull function assumes an earlier decommissioning of the installed turbines (λ = 26, blue-dotted line) and the other a later decommissioning (λ = 32, blue-dashed line). These results are compared to actual decommissioning numbers (dark blue line), the 20-year heuristic (pink-dashed line) and to the one existing Danish study by Abrahamsen et al. (2023, orange-dashed line). The aforementioned study shows the decommissioned blade mass and is thus only considered in Figure 76.

Estimated annual decommissioning blade mass in Denmark

The developed decommissioning model forecasts that the annual blade mass from the depletion of the installed onshore wind turbine fleet from Denmark is expected to range between ~950 and ~1,900 tonnes in the next ten years (see Figure 76, Kramer et al., 2024, p. 188). From 2022 onwards, blade mass is expected to increase gradually to peal at an annual rate of ~1,900 tonnes in 2028 and 2029. This is expected to be followed by a decline in the annual decommissioning mass until 2035 to ~1,050 tonnes and a further increase in blade mass until 2044. In the case of the Weibull function, which was adjusted to represent a shorter timespan for decommissioning the turbine fleet, the annual rate is expected to vary between ~900 and ~2,000 tonnes. In contrast, the function that assumes a longer timespan forecasts ~700 to ~1,900 tonnes over the next ten years. Moreover, it is observed that none of the decommissioning flows based on a Weibull function fluctuate as much as the ’20-year heuristic’, which is unsurprising given that the heuristic follows the highly fluctuating installation rates, only shifted by 20 years. Furthermore, Abrahamsen et al. (2023) employed similar parameters in their accumulated Weibull function, resulting in comparable annual decommissioning flows.

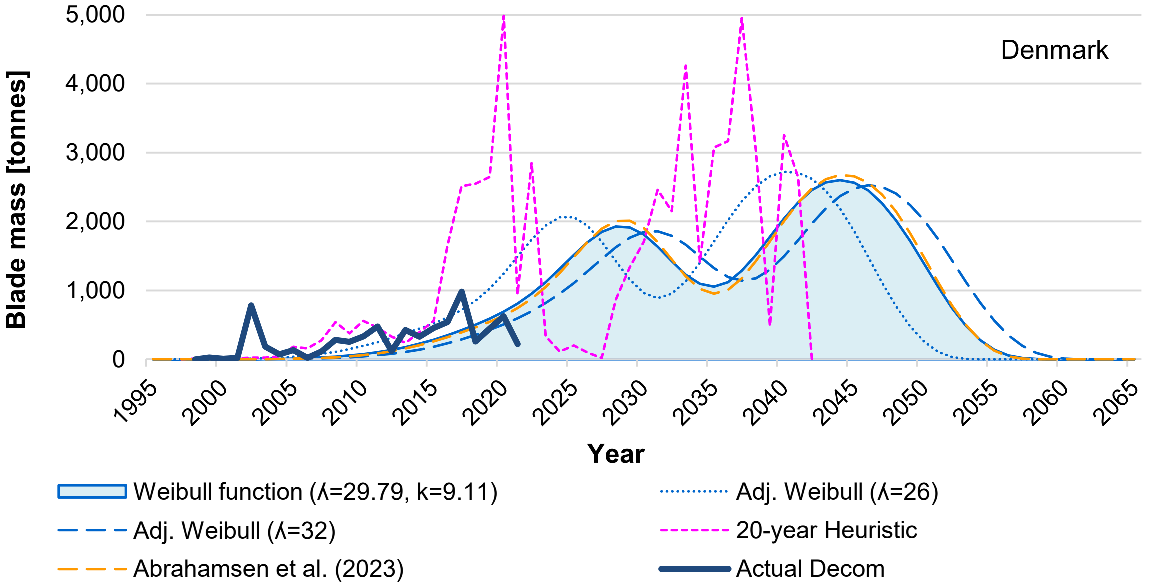


Figure 76. Expected annual decommissioning blade mass of installed onshore wind turbines in Denmark, in comparison to a 20-year heuristic, Abrahamsen et al. (2023) and actual decommissioning. Data based on DEA (2022).

Estimated annual number of decommissioned turbines in Denmark

For the decommissioning volumes expressed in number of turbines, Figure 77 presents the results of the application of the accumulated Weibull functions to the Danish fleet. As with the annual blade masses, the volumes of the Weibull functions are not fluctuating as greatly as the 20-year heuristic. The blue line in the chart indicates that the annual rate of decommissioning is expected to oscillate between 215 and 326 turbines over the next ten years. The volumes slightly shift into earlier years for the adjusted blue-dotted Weibull function (λ = 26) and hence forecast a range of 285-350 turbines annually in the next five years, followed by a gradual decline to 54 turbines in 2031. Finally, the blue-dashed Weibull function that assumes a longer timespan for the depletion of the fleet (λ = 32), estimates that annual decommissioning accounts to 290-315 turbines per year in the next ten years.

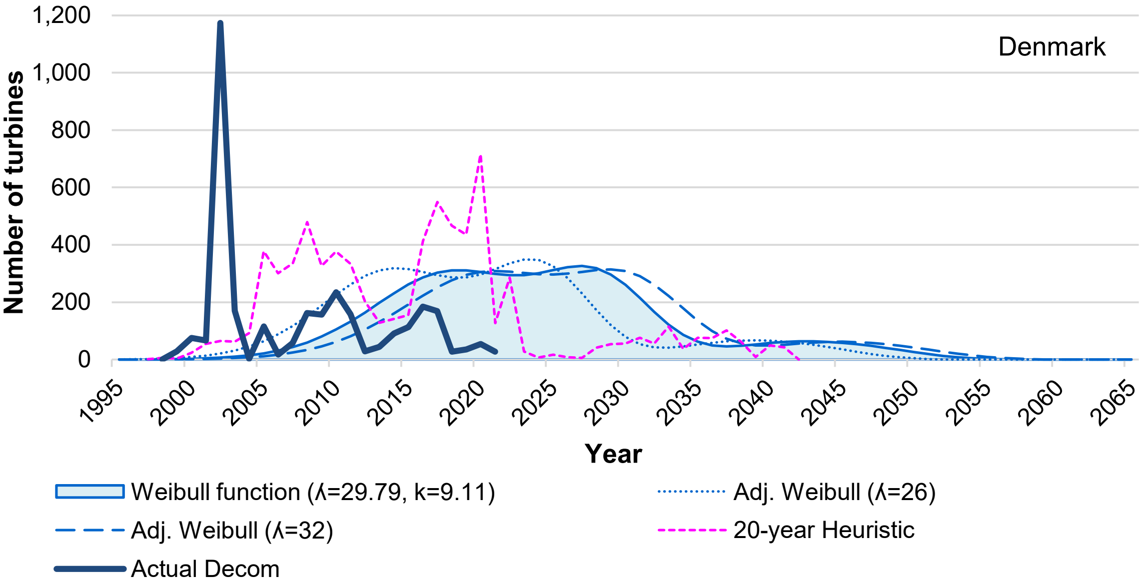


Figure 77. Expected annual decommissioning of installed onshore wind turbines in Denmark, in comparison to a 20-year heuristic and actual decommissioning. Data based on DEA (2022).

Evaluation

In regard to the accuracy of the models, the mean absolute error (MAE) of each prediction model is calculated for the time period of 1999-2021, as actual decommissioning values are available for these years. The MAE for each prediction model is shown in Figure 78. A comparison of the metrics reveals that the commonly applied '20-year heuristic' is the most unfavourable method for estimating annual blade mass and the number of decommissioned turbines. The MAE of the '20-year heuristic' is three times as high as that of the other methods. Accordingly, the average prediction error of the '20-year heuristic' is 641 tonnes. In contrast, the predictions from the fitted Weibull functions (i.e. the dark grey bar and the white-grey striped bar) are, on average, 203-204 tonnes off, while the adjusted Weibull functions are, on average, 215 tonnes (for a longer depletion) and 246 tonnes (for a shorter depletion) off.

With regard to the projection of the annual number of decommissioning, the MAEs of the methods are more closely aligned with one another. However, the ’20-year heuristic’ remains to show a notable inaccuracy, with an average prediction error of 243 turbines, approximately 1.5 times greater than the other methods. It is unsurprising that the models' performance still exhibits relatively large discrepancies compared to the actual values, particularly with regard to the number of turbines, given that an exceptionally high number of turbines were decommissioned in 2002 (see Figure 77).

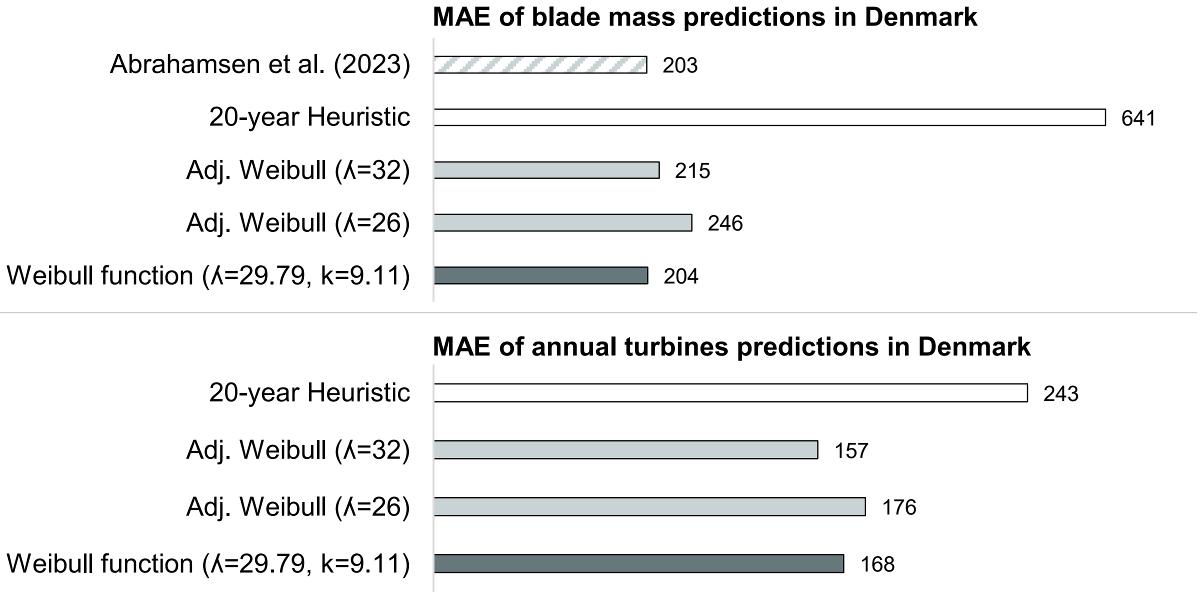


Figure 78. Overview of the MAE of each prediction model estimating annual decommissioning in blade mass (above) and number of turbines (below) for the Danish onshore wind turbine fleet.

Furthermore, comparing the historical development of the different predictions of Figure 76 and Figure 77 to the development of the actual decommissioning (dark blue line), it again shows that the Weibull functions predict the historical values more accurately than the heuristic. For example, it can be observed that the annual blade masses of the heuristics deviate significantly from 2016 onwards, which also the findings from Abrahamsen et al. (2023, p. 15, see Figure 76) confirm. It demonstrates that a significant proportion of the Danish onshore fleet is operated beyond the turbine’s design lifetime of 20 years.

Annual decommissioning quantities in Germany

The results of the annual decommissioning flows from the German onshore fleet are shown for the estimated blade mass in Figure 79 and for the number of turbines in Figure 80. The figures present the results according to the Weibull function (λ = 25.83, k = 7.49, green line), which considers the historical ratios of decommissioning to installed, and moreover of two adjusted Weibull functions. One adjusted Weibull function assumes an earlier decommissioning of the turbine fleet (λ = 22, green-dotted line) and the other a later decommissioning (λ = 30, green-dashed line). These results are compared to actual decommissioning numbers (dark blue line), the 20-year heuristic (pink-dashed line) and to the studies by Pehlken et al. (2017, orange-dashed line) and Kühne et al. (2022, purple-dotted line). Existing literature shows estimated blade waste, but as they neglect a second lifecycle, it is equivalent to the decommissioned blade mass and is thus employed for comparison. These studies are based on blade mass and are therefore only considered in Figure 79.

Estimated annual decommissioning blade mass in Germany

The annual expected blade mass (Figure 79), which totals to 738,718.6 tonnes, fluctuates less annually for the Weibull-function-based predictions than it does for the '20-year heuristic' and the models by Pehlken et al. (2017) and Kuehne et al. (2022) (Kramer et al., 2024, p. 188). Moreover, the flows of the Weibull functions range over a wider period of time than the aforementioned studies. A gradually increasing annual rate is forecasted, that would peak for the Weibull function in 2041 with ~42,100 tonnes of blade mass. When focusing on the subsequent ten-year period (2024-2033), it is observed that the annual decommissioning rate rises from 10,770 tonnes to 23,970 tonnes. The peak in the forecasts of the adjusted Weibull functions would be reached 4 years earlier in 2037 (~45,400 tonnes) and 4 years later in 2045 (~39,000 tonnes). In contrast, the '20-year heuristic' and the models proposed by Pehlken et al. (2017) and Kuehne et al. (2022) represent the highly fluctuating annual installation rates with a 20-year delay. With the exception of the Kuehne et al. (2022) model as it shows a significant peak in 2021. They assume that all turbines exceeding 20 years of age are decommissioned at the inception of the prediction period.

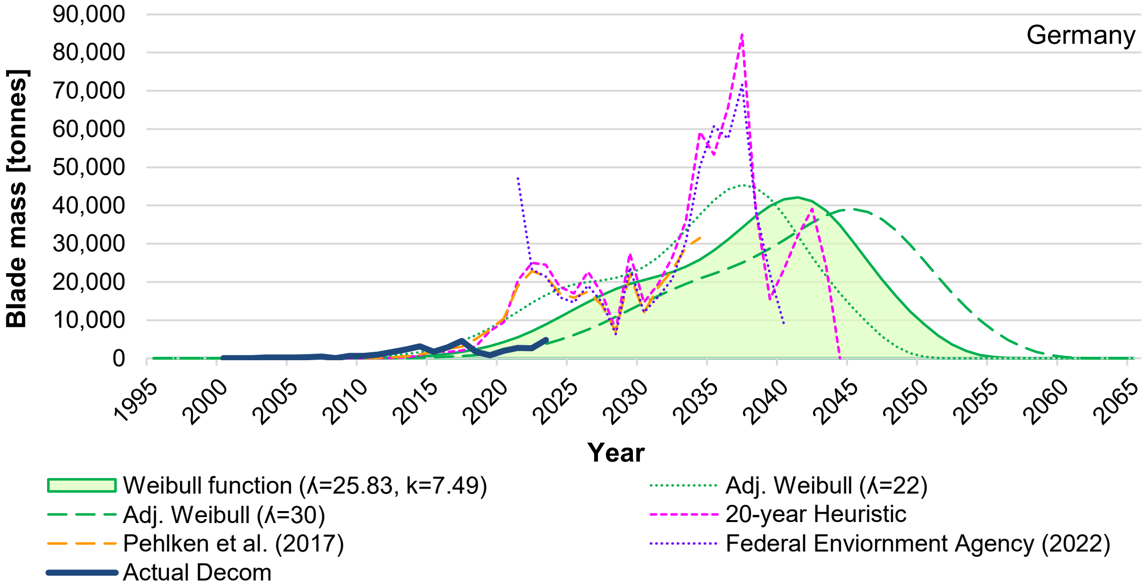


Figure 79. Expected annual decommissioning blade mass of installed onshore wind turbines in Germany, in comparison to a 20-year heuristic, existing studies (Kühne et al., 2022; Pehlken et al., 2017) and actual decommissioning (Deutsche WindGuard, 2023; 2024). Data based on Bundesnetzagentur (2023).

Estimated annual number of decommissioned turbines in Germany

Furthermore, Figure 80 illustrated the annual depletion of the 28,611 turbines. As with the annual blade masses, the annual number of turbines derived from the Weibull functions are less volatile than the ‘20-year heuristic’. The Weibull function (green line) expresses that the annual decommissioning is expected to range between 929 and 1,198 turbines. The volumes slightly shift into earlier years for the adjusted green-dotted Weibull function (λ = 22) and thus forecast a range of 1,005 to 1,250 turbines for the next ten years. Finally, the green-dashed Weibull function that assumes a longer timespan for the fleet’s depletion (λ = 30), estimates a range of 517 to 1,162 turbines. In particular, in the next three years of the forecast, 2024-2026, the three Weibull functions predict differently to a scale of 500-700 turbines. This difference then gradually decreases to 100-200 turbines in the remaining years of the 10-year planning period. To further illustrate this point, the annual rate from 2024-2028 ranges between 520-1,250 turbines for all three Weibull functions, and from 2029-2033 they level off at 1,000-1,200 turbines.

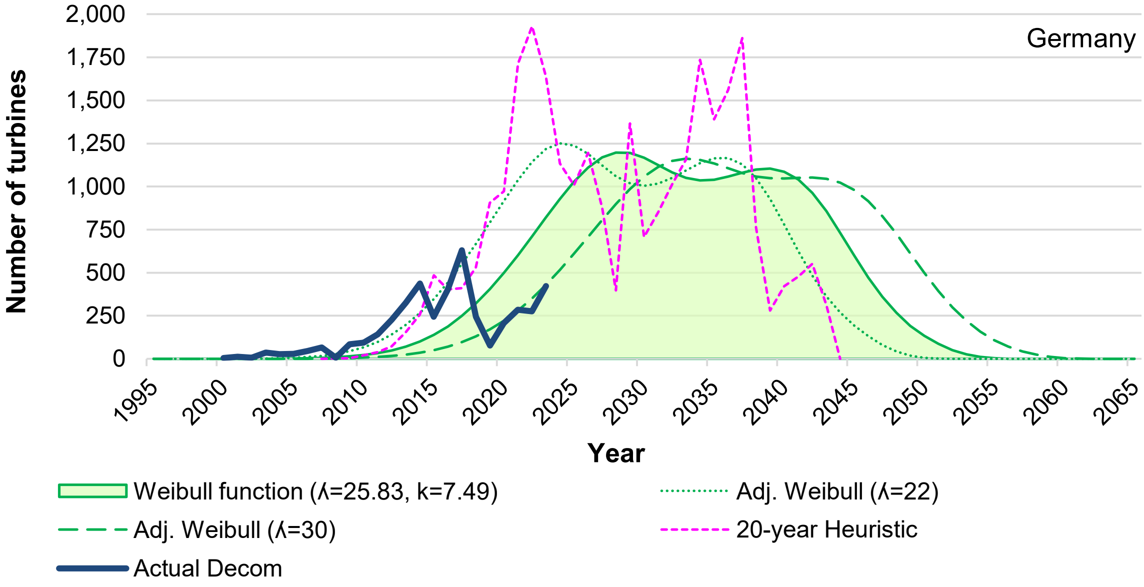


Figure 80. Expected annual decommissioning of installed onshore wind turbines in Germany, in comparison to a 20-year heuristic and actual decommissioning (Deutsche WindGuard, 2023; 2024). Data based on Bundesnetzagentur (2023).

Evaluation

The accuracy of the models is evaluated through the calculation of MAE on the basis of the years from 2000 to 2023, as the actual decommissioning values for those years are available. An overview of the MAEs is given in Figure 81. A comparison of the metrics reveals that the commonly applied ‘20-year heuristic’ and, correspondingly, the predictions by the Federal Environmental Agency (Kühne et al., 2022) and Pehlken et al. (2017) are the least favourable methods for estimating annual blade mass and the number of decommissioned turbines. The MAEs of these methods (3,441-3,686 tonnes) are almost three times as high for estimating annual decommissioning mass as that of the fitted Weibull function (1,323 tonnes). The most accurate model performance is achieved by utilising an adjusted Weibull function (λ = 30), which incorporates a longer time span for depletion, comparable to that observed in the Danish data. This model hence has an average prediction error of 917 tonnes. In contrast, assuming a shorter depletion with a scale parameter of 22 in the Weibull function, results to almost doubling the MAE in contrast to the original Weibull function. The observed increase in MAE may indicate that this scenario can more be treated as an extreme case to envision potential market changes, as stated in 6.2.2. In this respect, it is not accurately reflecting the historical dynamics of the market.

With regard to the projection of the annual number of decommissioning, the ranking according to the MAEs of the methods does not change. The '20-year heuristic' remains the method with the highest MAE (319 turbines) and the adjusted Weibull function (λ = 30), the most accurate (117 turbines). The prediction from the fitted Weibull functions (i.e. the dark grey bar) is, on average, by 158 turbines off, while the adjusted Weibull function (λ = 22) is, on average, 216 turbines off.

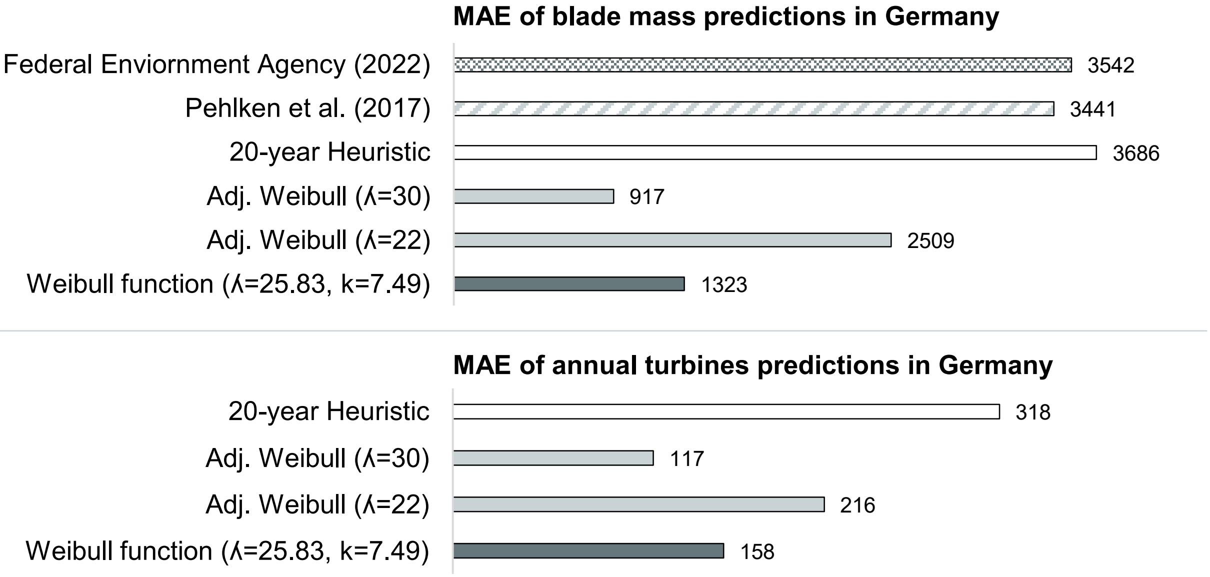


Figure 81. Overview of the MAE of each prediction model estimating annual decommissioning in blade mass (above) and number of turbines (below) for the German onshore wind turbine fleet.

A visual comparison of the forecast models to the actual values (Figure 79 and Figure 80) confirms that a large fraction of the onshore fleet in Germany is not decommissioned after 20 years, as the actual values significantly deviate since 2017 in terms of absolute number of turbines and since 2019 in terms of blade mass. This finding is in line with the results for the Danish onshore fleet. Moreover, it is notable that in the last five years (2019-2023), the adjusted Weibull function (λ = 30) closely corresponds to the actual historical development. This could indeed hint towards a large fraction of the fleet pursuing a continued operation beyond the design lifetime of the turbine, amongst others due an increased spot market prices since 2021 (Netztransparenz, 2023). Furthermore, the results suggest for the Danish models a more sensitive response to changes than for the German models, due to the smaller number of turbines installed in Denmark. Therefore, single wind farms have a larger impact than it is the case for the German market.

Long-term capacity planning by decommissioning companies

The results presented can be used as an input for the long-term capacity planning by decommissioning companies and their subcontractors. Since no data on currently available capacities are available for either Denmark or Germany, it is not possible to assess whether the currently available market capacity will be sufficient in the future. Nevertheless, the experts interviewed did provide brief information on their company's capacity and of the overall market.

In the peak years of decommissioning around 2002 in Denmark, experts reported that they had to turn down projects due to a lack of capacity. This is not surprisingly given the exponential jump in the number of projects (see Figure 77). In this context, a close monitoring of the current regulatory and market environment can be used to supplement the provided forecasts accordingly. In the case of no extraordinary event (e.g. introduction of a decommissioning incentive), the annual flow models show that no extreme outliers are expected, neither for Denmark, nor for Germany.

However, when looking at the annual blade mass in Denmark, two peaks exist and in the next 20-year timespan annual quantities increase to almost 2,000 tonnes, followed by a decline to 1,000 tonnes and again an increase to more than 2,000 tonnes. As the turbine sizes and the blade mass per turbine continuously increase, this fluctuation is not estimated for the annual number of turbines, but instead a continuous decline from 2031. In recent years annual decommissioning quantities were low in Denmark and the Danish experts confirmed that their companies still had available capacity. Moreover, larger recycling companies have entered the decommissioning market in the last years, which indicates that sufficient capacity is available. In conclusion, as no sharp increase in annual decommissioning for onshore wind turbines is expected in the next years in Denmark, the current market situation for decommissioning companies is not expected to significantly change.

For Germany, experts reported that decommissioning quantities were relatively low in the past but increased notably in 2023. When looking at the estimated annual flows, the sharp increase as originally forecasted by the 20-year heuristic did not materialise. However, also in the Weibull models a significant increase to more than 1,000 turbines annually is estimated over the next ten years. Hence, more than twice as much as the highest historical value of 423 turbines in 2023 (Deutsche WindGuard, 2024). One of the experts reported that they had to turn down projects in the beginning of 2024, but partially also due to the fact that some operators demanded on relative short notice. In addition, some of the experts who subcontract crane companies reported that securing access to crane capacities is becoming increasingly important. In this context, chapter 6.3.1 discusses the scaling of decommissioning services and infrastructure. On that note, the developed annual flow models could be further detailed for more specific capacity planning, e.g. with regard to the required crane sizes and corresponding threshold values for economic feasibility.

6.2.5 Forecasts of annual second-lifecycle quantities

This chapter presents the results of the expected annual flows for a second lifecycle from the decommissioned onshore wind turbines from Denmark and Germany and thus provides a key basis for the long-term capacity planning of involved supply chain actors (e.g. logistic companies, refurbishment companies). The annual second-lifecycle quantities are derived in accordance to the application of the input parameters from Table 22 to the Eq. (5) (see 6.1.3). The annual results for each country's turbine fleet are presented below, with a focus on a ten-year planning horizon, recognising that forecasting uncertainties increase with time.

Annual second-lifecycle quantities in Denmark

Figure 82 shows the estimated annual number of decommissioned turbines and their blades from Denmark that are expected to enter a second lifecycle. This is based on the fitted Weibull function as this model has the lowest MAE. There are no statistics on the actual numbers, nor are there any scientific studies available for comparison.

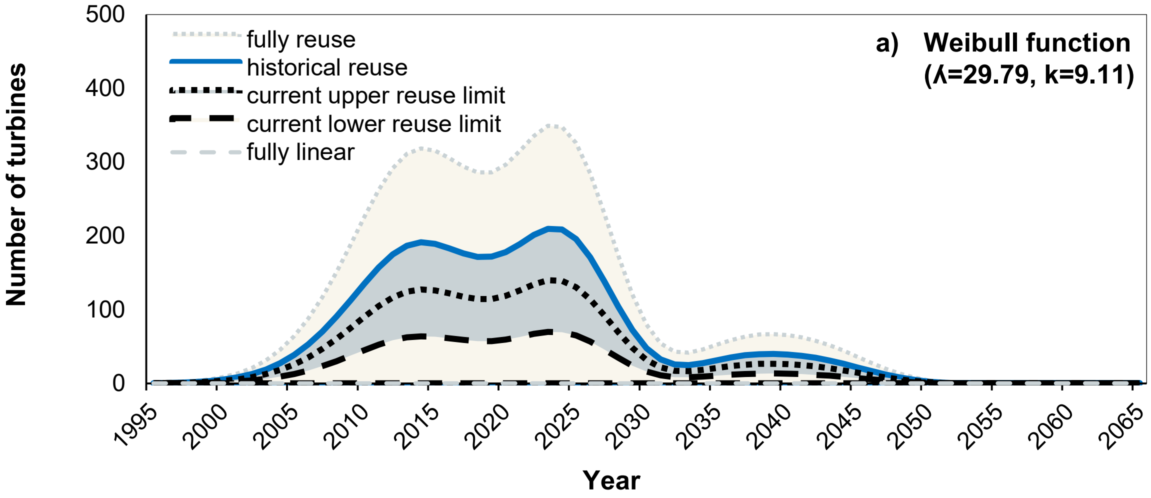


Figure 82. Expected annual second-lifecycle quantities of installed onshore wind turbines in Denmark in accordance to fitted Weibull function (Λ=29.79, k=9.11). Data based on DEA (2022).

In the context of all currently installed onshore turbines, the ‘fully reuse’ scenario ($f_{reuse}(t)$ = 100 %, light grey dotted line) amounts to 7,381 onshore wind turbines and thus equals to the annual decommissioning quantities (see 6.2.4). In contrast, the ‘fully linear’ scenario ($f_{reuse}(t)$ = 0 %, light grey dashed line) would result to 0 turbines entering the second-hand market, as it neglects the occurrence of a second lifecycle. In the ‘historical reuse’ scenario ($f_{reuse}(t)$ = 60 %, blue line), 4,429 turbines of the total installed turbines would be exported for a second lifecycle at a new project site. Lastly, in the ‘current reuse’ scenario ($f_{reuse}(t)$ = 20-40 %, black lines), a lower share of the second-hand market is assumed, with a total of 1,476-2,952 turbines.

In order to provide a basis for the long-term capacity planning by the actors in the second-lifecycle supply chain, the expected annual flows for the next ten years according to the scenarios range are as summarised in Table 23:

Table 23. Range of second-lifecycle quantities of installed onshore wind turbines in Denmark between 2022-2031. Based on fitted Weibull function (Λ=29.79, k=9.11), data based on DEA (2022).

'Fully reuse' scenario	~215-326 turbines p.a.
'Current reuse' scenario	
▪ Upper reuse limit	~86-130 turbines p.a.
▪ Lower reuse limit	~43-65 turbines p.a.
'Historical reuse' scenario	~129-196 turbines p.a.
'Fully linear' scenario	0 turbines p.a.

In case the fleet's depletion behaviour changes in the future, the adjusted Weibull functions illustrate the potential impact on the expected second-lifecycle quantities. For example, in the case of shorter depletion (Figure 94 in Appendix D2), ~11-140 turbines ('current reuse' scenario) and ~32-210 turbines ('historical reuse' scenario) are expected to enter the second-hand market annually over the next ten years. In contrast, in the case of a longer depletion (Figure 95 in Appendix D2), the annual number of second-lifecycle turbines is estimated to range between ~58-126 turbines ('current reuse' scenario) and ~175-189 turbines ('historical reuse' scenario).

Annual second-lifecycle quantities in Germany

Furthermore, the following presents the results for the estimated second-lifecycle flows from the decommissioned onshore wind turbines in Germany. Similarly to Denmark, there is no study for Germany that forecasts the number of decommissioned turbines entering a second lifecycle. Nevertheless, the various scenarios and adjusted Weibull functions offer the possibility to compare annual flows under different assumptions.

The total number of installed turbines expected to enter the second-hand market varies between 0 and 28,611 turbines, depending on the scenario. The highest share accounts to the 'fully reuse' scenario ($f_{reuse}(t)$ = 100 %, light grey dotted line), as it assumes that every decommissioned turbine would have a second lifecycle. In contrast, the 'fully linear' scenario ($f_{reuse}(t)$ = 0 %, light grey dashed line) would result to 0 turbines, as it neglects any second lifecycle pathway. Furthermore, the 'historical reuse' scenario ($f_{reuse}(t)$ = 50 %, green line) estimates 14,406 second-lifecycle turbines, while the 'current reuse' scenario ($f_{reuse}(t)$ = 30 %, 80 %, black lines) estimates 8,583-22,889 turbines.

Figure 83 presents the annual second-lifecycle flows that are based on the fitted Weibull function.

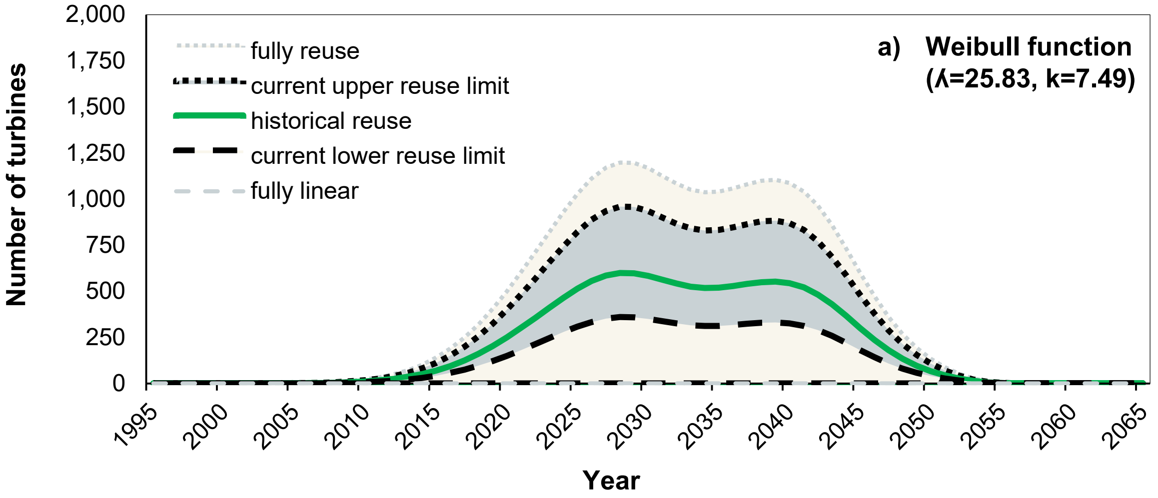


Figure 83. Expected annual second-lifecycle quantities of installed onshore wind turbines in Germany, in accordance to the fitted Weibull function (Λ=25.83, k=7.49). Data based on Bundesnetzagentur (2023).

Furthermore, Figure 84 illustrates the outcomes of the scenarios based on the adjusted Weibull function, assuming a longer period of depletion (Figure 48), as this model has shown the lowest MAE (see 6.2.4).

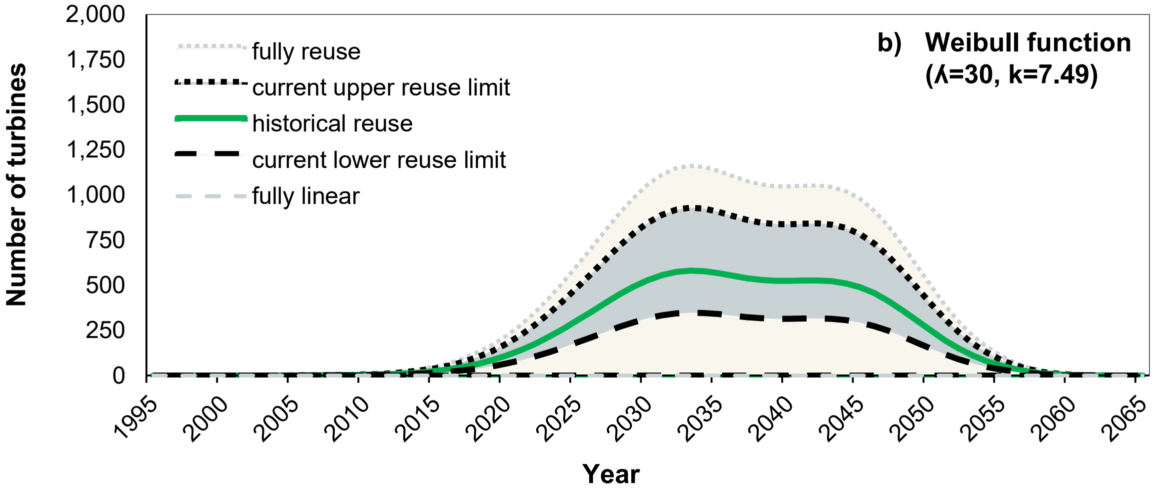


Figure 84. Expected annual second-lifecycle quantities of installed onshore wind turbines in Germany, in accordance to the adjusted Weibull function (Λ=30). Data based on Bundesnetzagentur (2023).

To further illustrate the results, the following Table 24 outlines the projected annual flows over the next ten years. It shows that the annual flows change slightly depending on which Weibull function is considered. This can suit as a basis for the capacity planning of companies active in handling second-lifecycle turbines from Germany.

Table 24. Range of second-lifecycle quantities of installed onshore wind turbines in Germany between 2024-2033. Data based on Bundesnetzagentur (2023).

Scenarios	Weibull function (λ = 25.83 years, k = 7.49)	Adjusted Weibull function (λ = 30 years, k = 7.49)
‘Fully reuse’ scenario	~929-1,198 turbines p.a.	~516-1,162 turbines p.a.
‘Current reuse’ scenario		
▪ Upper reuse limit	~743-958 turbines p.a.	~413-930 turbines p.a.
▪ Lower reuse limit	~279-359 turbines p.a.	~155-349 turbines p.a.
‘Historical reuse’ scenario	~465-599 turbines p.a.	~258-581 turbines p.a.
‘Fully linear’ scenario	0 turbines p.a.	0 turbines p.a.

In the case of a shorter time span of the fleet’s depletion (Figure 96 in Appendix D2), this again would change the annually rates, for instance in the scenario that assumes the historical reuse fraction of 50 % it would result to ~503-625 turbines annually. In the scenario of current second-lifecycle flows the annual rate is estimated between ~302-375 turbines (lower limit) and ~804-1,000 turbines (upper limit) over the next ten years. Therefore, in comparison to the above outlined annual flows, the annual flows would be larger.

Long-term capacity planning by companies handling second-lifecycle turbines

The presented results can be used for the long-term capacity planning by companies involved in the second-hand market, for instance by decommissioning companies who offer the handling of second-hand turbines, logistic companies or refurbishment companies. For future developments, it is likely to be more difficult for the existing players to maintain or increase the historical reuse rate of 50-60 %, as the absolute number of turbines increases and handling becomes more complex with increasing turbine sizes. Therefore, activities such as the development of new second-hand markets and simplification of handling processes are required to enable the scaling of second-lifecycle supply chains for the reinstallation of turbines.

At this stage, it is not possible to conduct a comprehensive evaluation of the current and required capacity of each supply chain actor (e.g. refurbishment company, logistics company) as information are not available. Nevertheless, further research could build on the findings of this study and focus on specific actors in the second-lifecycle supply chain. In this context, chapter 6.3.1 outlines the involved services and infrastructure in second-lifecycle supply chains. The developed annual flow models could be further refined for more granular capacity planning and the assessment of economic viability thresholds, for example with regard to the refurbishment of certain turbine types.

6.2.6 Forecasts of annual recycling quantities

This chapter presents the annual recycling blade mass for the Danish and German onshore wind turbine fleet as a key basis for the long-term capacity planning of the recycling industry. The annual expected blade mass of the scenarios is derived through the application of the parameters from Table 22 to the Eq. (6). The rationale behind presenting the results for overall depletion with a particular focus on the next ten years is also applicable here. In addition, the findings are put into context with the annual tonnages required for an economically viable blade recycling facility.

Annual recycling quantities in Denmark

Figure 85 illustrates the expected annual blade mass flows from decommissioned onshore wind turbines in Denmark that are anticipated to be routed to domestic recycling. This is based on the fitted Weibull function since this model has the lowest MAE. The results of the adjusted Weibull functions can moreover be found in Appendix D2. The results are compared to the commonly applied 20-year heuristic (pink dashed line) and to Abrahamsen et al. (2023, orange dashed line). A comparison with actual blade recycling statistics or more generally with blade end-of-life statistics is not possible as these are not available.

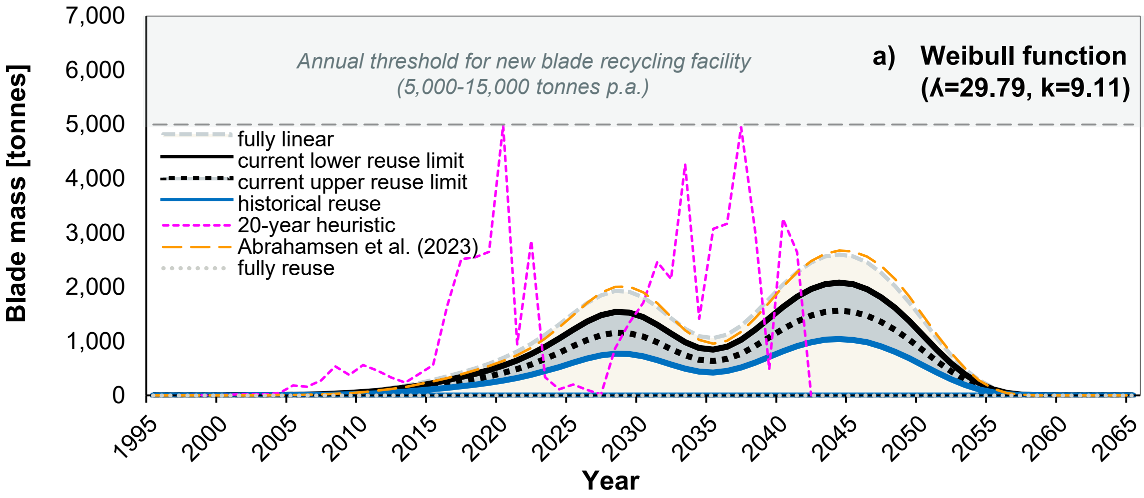


Figure 85. Expected annual recycling blade mass of installed onshore wind turbines in Denmark in accordance to fitted Weibull function (Λ=29.79, k=9.11), in comparison to a 20-year heuristic and Abrahamsen et al. (2023). Data based on DEA (2022).

The ‘fully reuse’ scenario ($f_{recycle}(t)$ = 0 %, light grey dotted line) results in 0 tonnes of blade mass for domestic recycling as it assumes a second lifecycle of the turbines and their blades abroad. In contrast, the extreme scenario, the ‘fully linear’ scenario ($f_{recycle}(t)$ = 100 %, light grey dashed line) equals to the annual decommissioning volumes (see 6.2.4) as it neglects the occurrence of a second lifecycle abroad. In the ‘historical reuse’ scenario ($f_{recycle}(t)$ = 40 %, blue line), 23,258.8 tonnes of the total installed blade mass of 58,147.0 tonnes would remain in Denmark and hence could enter domestic recycling. And finally, in the ‘current reuse’ scenario ($f_{recycle}(t)$ = 60 %, 80 %, black lines) the blade mass for domestic recycling equals to 34,888.2-46,517.6 tonnes. In terms of long-term capacity planning for domestic recycling, the next ten years are considered for illustration, and the results of the scenarios are shown in Table 25.

Table 25. Range of recycling quantities of installed onshore wind turbines in Denmark between 2022-2031. Based on fitted Weibull function (ʎ=29.79, k=9.11), data based on DEA (2022).

'Fully reuse' scenario	0 turbines p.a.
'Current reuse' scenario ▪ Upper reuse limit ▪ Lower reuse limit	 ~570-1,155 tonnes p.a. ~762-1,540 tonnes p.a.
'Historical reuse' scenario	~380-770 tonnes p.a.
'Fully linear' scenario	~950-1,900 tonnes p.a.

It shows for the ten-year period that the expected annual blade mass for domestic recycling in the 'historical reuse' scenario is at a lower level than in the 'current reuse' and 'fully linear' scenarios, but higher than in the 'fully reuse' scenario.

Furthermore, the adjusted Weibull functions – that were formulated to envision potential changes to the time of decommissioning – show that the expected blade mass in the next ten years potentially entering the domestic recycling stream would slightly differ. To illustrate the potential impact, this is described below for two scenarios, one assuming current flows and the other assuming historical second-lifecycle flows:

- In the case of a shorter depletion (Figure 97 in Appendix D2), the annual blade mass would range between ~534-1,650 tonnes ('current reuse' scenario) and ~360-820 tonnes ('historical reuse' scenario).
- In the case of a longer depletion (Figure 98 in Appendix D2), the range for the ten-year period accounts to ~420-1,490 tonnes ('current reuse' scenario) and ~280-750 tonnes ('historical reuse' scenario).

The results by Abrahamsen et al. (2023, p. 16, orange dashed line) follow closely the results of the fitted Weibull function and the scenario that assumes the non-existence of a second-hand market. However, they do note that their estimates should be treated as a maximum, which is in line with the results of this study (Kramer et al., 2024, p. 184).

Annual recycling quantities in Germany

Figure 86 shows the results of the expected annual recycling flows of decommissioned onshore wind turbines from Germany, based on the fitted Weibull function. Like in Denmark, also for Germany no statistics are available for comparison.

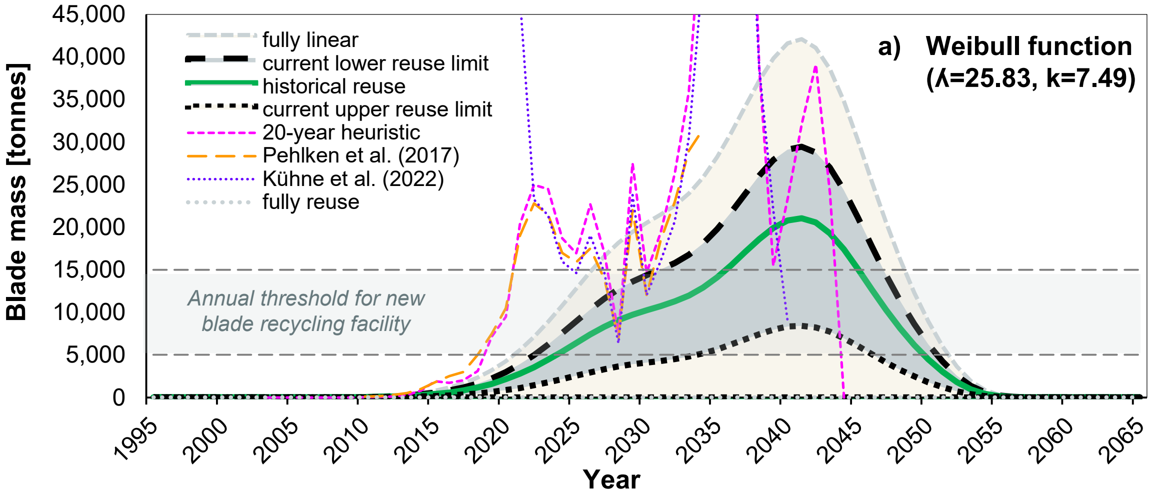


Figure 86. Expected annual recycling blade mass of installed onshore wind turbines in Germany, in accordance to the fitted Weibull function (Λ=25.83, k=7.49). In comparison to a 20-year heuristic, Kühne et al. (2022) and Pehlken et al. (2017). Data based on Bundesnetzagentur (2023).

In addition, Figure 87 presents the results for the Weibull function with an adjusted scale parameter of 30 years, as this method had the lowest MAE (see 6.2.4). Finally, the results from the Weibull function on the basis of a faster depletion (λ = 22 years) are in Appendix D2.

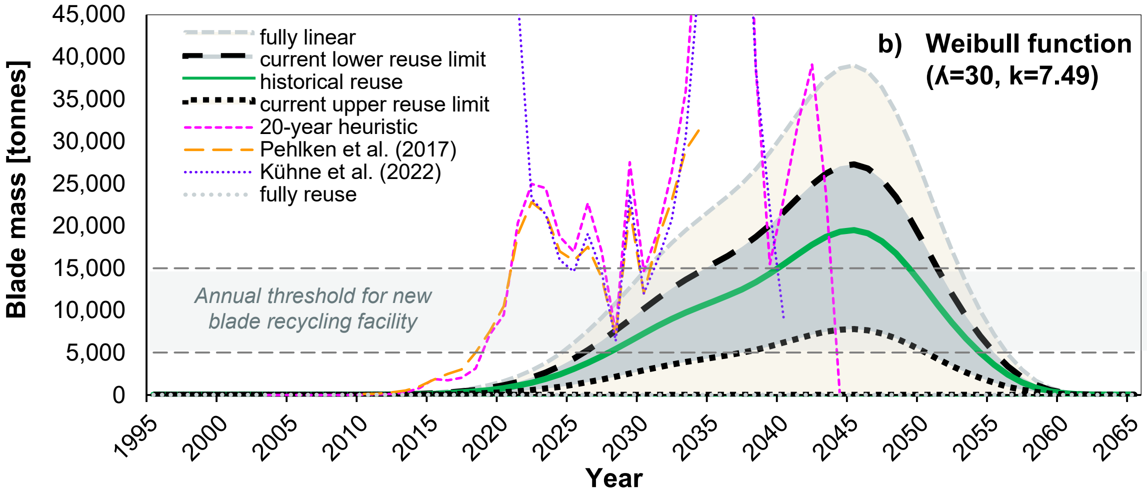


Figure 87. Expected annual recycling blade mass of installed onshore wind turbines in Germany, in accordance to the adjusted Weibull function (Λ=30, k=7.49). In comparison to a 20-year heuristic, Kühne et al. (2022) and Pehlken et al. (2017). Data based on Bundesnetzagentur (2023).

In Figure 86 and Figure 87 the total blade mass equals in the ‘fully reuse’ scenario ($f_{recycle}(t)$ = 0 %, light grey dotted line) to 0 tonnes for domestic recycling. In contrast, the ‘fully linear’ scenario ($f_{recycle}(t)$ = 100 %, light grey dashed line) is equivalent to the annual decommissioning volumes (see 6.2.4) and thus amounts to 738,718.6 tonnes. This total tonnage is reduced in the ‘historical reuse’ scenario ($f_{recycle}(t)$ = 50 %, green line) to 369,359.3 tonnes for domestic recycling (Kramer et al., 2024, p.

188). Finally, in the ‘current reuse’ scenario ($f_{recycle}(t)$ = 20 %, 70 %, black lines), 147,743.7-517,103.0 tonnes of blade mass is expected to remain in Germany for domestic waste handling.

In terms of long-term capacity planning for domestic recycling, the next ten years are of interest, and therefore further detailed in Table 26. Accordingly, there are slightly different annual flows for 2024-2033 depending on which Weibull function is considered. It shows that in particular the lower range of the reported recycling quantities varies between the two Weibull functions.

Table 26. Range of recycling quantities of installed onshore wind turbines in Germany between 2024-2033. Data based on Bundesnetzagentur (2023).

Scenarios	Weibull function (λ = 25.83 years, k = 7.49)	Adjusted Weibull function (λ = 30 years, k = 7.49)
‘Fully reuse’ scenario	0 turbines p.a.	0 turbines p.a.
‘Current reuse’ scenario		
▪ Upper reuse limit	~2,150-4,800 tonnes p.a.	~970-3,900 tonnes p.a.
▪ Lower reuse limit	~7,500-16,800 tonnes p.a.	~3,400-13,600 tonnes p.a.
‘Historical reuse’ scenario	~5,400-12,000 tonnes p.a.	~2,430-9,750 tonnes p.a.
‘Fully linear’ scenario	~10,800-24,000 tonnes p.a.	~4,860-19,500 tonnes p.a.

In case of a shorter timespan for the depletion of the onshore wind turbine fleet in Germany (λ = 22) the annual recycling blade mass would range between ~3,700-23,500 tonnes (‘current reuse’ scenario) and ~9,100-16,800 tonnes (‘historical reuse’ scenario) (see Figure 99 in Appendix D2).

Furthermore, the annual recycling masses provided by Pehlken et al. (2017, orange dashed line) and the Federal Environmental Agency (Kühne et al., 2022, purple-dotted line) follow closely the results of the 20-year heuristic. Pehlken et al. (2017, p. 255) consider that some wind turbines enter a second lifecycle (see 6.1.1), but as the figures show only a minimal difference to the 20-year heuristic, this appears to be minor. Following the finding in 6.2.4 that a 20-year heuristic is not a suitable forecasting method, the 20-year heuristic (pink dashed line) is to be understood as a benchmark.

Long-term capacity planning by blade recycling companies

The estimated domestic recycling flows for Denmark and Germany can be used to derive the year from which the operation of an economically viable blade recycling facility is feasible, and thus support the respective investment decision. In this light, the annual recycling flows are compared to a minimum range of required tonnage per year. The breakeven point for a new blade recycling facility is set at 5,000-15,000 tonnes per year, as this shows good agreement with the publicly available information summarised in Table 27 (Kramer et al., 2024, p. 185). It also acknowledges that the threshold values might vary depending on the recycling technology and the country of operation.

Table 27. Overview of publicly available information on minimum required annual blade mass for an economically feasible recycling facility. Based on Kramer et al. (2024, p. 185) and the works cited therein.

Source	Minimum annual blade mass for an economically viable recycling facility
Villadsen (2023)	For the establishment of a new pyrolysis plant for glass fibre in Denmark a minimum threshold of 10,000-15,000 tonnes per year is required.
Ricard (2023)	For the establishment of a new cement co-processing route in Denmark, 12,000 tonnes per year are required as a minimum.
Schmid et al. (2020)	An existing cement co-processing facility in northern Germany used to operate with 15,000 tonnes per year, while 10,000 tonnes came from composite blades. A minimum threshold is not indicated.
Zotz et al. (2019)	Neocomp was able to pre-process up to 25,000 tonnes per year of materials with one machine, of which around 5,000 tonnes came from glass fibre-made blades. The pre-processed material could then be used in the cement co-processing route.
Andersen et al. (2016)	For producing a filler for cement production, they state 5,000-6,000 tonnes per year.
RenerCycle (2023)	State 6,000 tons per year for a new blade recycling facility in northern Spain that aims at processing the blades with heat treatments.

For easing the planning processes for the establishment of blade recycling infrastructure, Figure 85, Figure 86 and Figure 87 illustrate the thresholds with a grey area in the range of 5,000-15,000 tonnes per year. It can be seen that none of the scenarios for Denmark would meet the specified thresholds. In Germany, the minimum tonnage requirement is exceeded in all scenarios except the 'fully reuse' scenario, but the timing is more nuanced. Once exceeded, the expected annual amount is likely to remain above the thresholds. This would only change if there were no new installations of wind turbines in the future.

Looking first at Figure 86, only the ‘fully linear’ scenario and the lower limit of the reuse fraction for the ‘current reuse’ scenario exceed the upper level of the thresholds in the next ten years. The other scenarios only reach the lower level of 5,000 tonnes per year, although the upper limit of the reuse fraction for the ‘current reuse’ scenario does not reach the 5,000 tonnes until 2034. The differences between the scenarios are further illustrated by using the threshold of 10,000 tonnes per year as an example. Accordingly, 10,000 tonnes will be exceeded for the first time in 2024, assuming that the total tonnage decommissioned from that year remains in the country for recycling. In the event of a second-hand market in the magnitude of 30 %, 10,000 tonnes will be surpassed in 2026, and at historical levels of 50 % in 2030. Should the upper limit of the reuse fraction (80 %) be met, the threshold would not be reached, given that annual recycling flows would not exceed 8,500 tonnes. For a point of comparison, it was anticipated that the 20-year heuristic would exceed the 10,000 tonnes in 2021. However, this did not materialise, as the anticipated amount was not even decommissioned.

When looking next at Figure 87, the above-mentioned timing is slightly delayed and only the ‘fully linear’ scenario would exceed the 15,000 tonnes in the next ten years. The ‘historical reuse’ scenario would only surpass the 5,000 tonnes mark in the next ten years, followed by reaching the threshold of 10,000 tonnes in 2034. In comparison, the ‘fully linear’ scenario exceeds 10,000 tonnes for the first time in 2028, while the ‘current reuse’ scenario surpasses this value only in its upper limit of the reuse fraction, then in 2030.

Furthermore, a sensitivity analysis is conducted by varying the proportion of decommissioned turbines sent for recycling ($(f_{recycle}(t))$) in 10 % increments. The results are shown in Table 42 in Appendix D2. For the decommissioning flows estimated on the basis of the fitted Weibull function, it reveals that the 10,000-tonne mark would be exceeded as long as at least 30 % of the decommissioned mass remains for domestic recycling in Germany. However, only if 50 % remains, i.e. in the order of magnitude of the past, is it estimated that it will be exceeded within the next ten years. In the case of a threshold of 5,000 tonnes, a recycling fraction of 20 % of the annual decommissioning quantities would already result in this annual value being reached, and 30 % would result in it being reached within the next ten years. Finally, the threshold of 15,000 tonnes is exceeded with a recycling fraction of at least 40 %, with $f_{recycle}(t)$ = 70 % and above reaching this threshold within the next ten years.

In conclusion, depending on the required threshold and the actual $f_{recycle}(t)$, a blade recycling plant could be economically viable on the basis of the expected annual recycling flows from onshore turbines in Germany. In Denmark, however, an annual threshold of 5,000 tonnes would not be reached, even in a scenario where the second-hand market is completely neglected. In this light, chapter 6.3.1 discusses the potential of including cross-border and cross-industry flows.

6.3 Discussion

This chapter discusses the results of the annual turbine, component and material flows for installed onshore wind turbines in Denmark and Germany, which are put into the context of long-term capacity planning for decommissioning, second lifecycle pathways and recycling (see 6.2). To ease the discussion of the results (6.3.1) and the limitations of the methodology (6.3.2), Figure 88 embeds the scope of Part C (white text boxes) in the context of the R-principle ladder (see Figure 17 of CSCM framework).

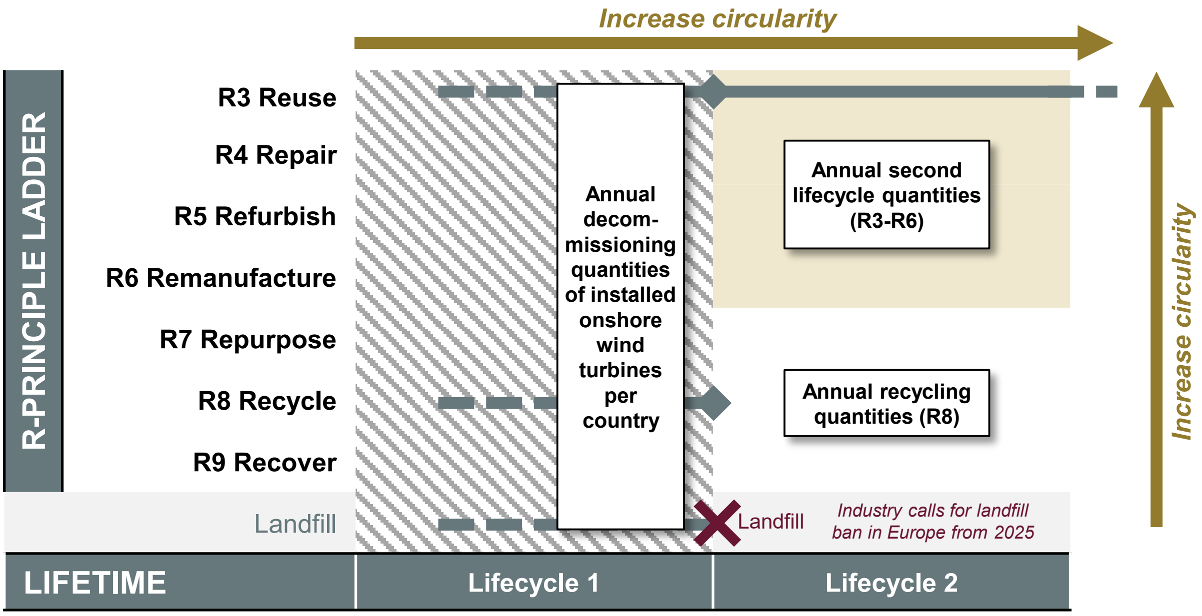


Figure 88. Scope of Part C in the context of the R-ladder. Adapted from Kramer et al. (2024, p. 181), inspired by Kramer and Beauson (2023), Potting et al. (2017), Velenturf (2021).

6.3.1 Discussion of results

In accordance to Figure 88, the annual decommissioning quantities of installed onshore wind turbines in Denmark and Germany were estimated and, on this basis, the subsequent handling, expressed in annual estimates for the second lifecycle and recycling quantities. The derived annual flows serve as a basis for the long-term capacity planning of the stakeholders. In addition, other product/service flows may also be considered for capacity planning, depending on the specific actors in the supply chain. In this light, additional orders can serve to offset annual fluctuations in wind turbine decommissioning that have been observed in the past in both countries, and enable economically viable thresholds for new investments to be reached. In contrast, however, it can also result in a deficit of capacity for wind turbine decommissioning and handling if demand signals are more pronounced in other business areas. The capacity planning is discussed for the actors involved in decommissioning, second lifecycle pathways and recycling. It thereby also considers the derived findings from the conducted interviews of Part B.

Capacity planning for annual decommissioning quantities

Decommissioning companies have been active in Denmark and Germany, and as the historical decommissioning figures show, decommissioning is an established service (see Figure 77 and Figure 80). Following the discussions from chapter 6.2.4, Table 28 summarises the initial assessment of the likelihood of bottlenecks in capacity to decommission the estimated decommissioning quantities of onshore wind turbines.

Table 28. Overview of the likelihood of bottlenecks in decommissioning capacity.

Decommissioning capacity	Are capacity bottlenecks foreseen in the next ten years?	
	Denmark	Germany
Skilled decommissioning team	Unlikely	First signs signalled by experts. Further investigations required.
Crane	Unlikely	

For Denmark, annual decommissioning is estimated to remain below around 300 turbines, and no large increase is expected of the already shallow annual decommissioning quantities (see Figure 77). In the case of Germany, the annual number of turbines is estimated to increase to more than 1,000 turbines in the next ten years (see Figure 80), and hence may require investment in new crane infrastructure and a skilled workforce capable of decommissioning and disassembling new turbine types. In this context, the average hub height of the turbine is expected by experts to gradually increase, which is in line with the characteristics of the operational turbine fleet (see Figure 70). Consequently, also larger cranes are needed that might require the investment in new crane types. According to the interviews, the crane is usually owned by a specialised crane company, hence the investment decision lies with them and not the decommissioning company. Furthermore, an expert from an OEM indicated that, on occasion, they undertake the decommissioning task as they have the larger crane infrastructure for the installation of turbines and the knowhow. However, a detailed assessment of potential bottlenecks is not possible as information on existing and planned capacity of decommissioning companies and their subcontractors is not publicly available.

To balance out fluctuations in the order flow of local decommissioning companies or to meet economically viable thresholds for new investments, project flows from other countries or industries may support accordingly. In this light, Table 29 summarises the applicability of this for the skilled workforce and the crane infrastructure.

Table 29. Applicability of cross-border and cross-industry flows to decommissioning.

Decommissioning capacity	Cross-border flows	Cross-industry flows
Skilled decommissioning team	✓	✓
Crane	(x)	✓

Accordingly, the low expected order flow of wind turbine decommissioning in Denmark may be balanced out with additional order flows from other countries or other activities in Denmark. Indeed, this practice is confirmed by the interviewed experts. For example, one of the experts interviewed reported that their skilled workforce for decommissioning can also support the other business area of turbine installation.

In the context of an investment decision for a new crane, the specialised crane companies may consider contracts from the wind industry for installations and decommission, and from other industries such as the construction industry. However, this may require additional knowledge. Moreover, it is unlikely that decommissioning jobs from other countries or regions of the same country are also considered, given the associated costs and complexities of crane transportation.

Capacity planning for annual second-lifecycle quantities

For Denmark, the second-lifecycle quantities are estimated to be roughly 20-40 % of the annual decommissioning in the ‘current reuse’ scenario. This would translate to maximum annual quantities of around 100 turbines in the next ten years. This seems feasible to be handled.

In Germany, the second-lifecycle quantities are estimated to be roughly 30-80 % of the annual decommissioning in the ‘current reuse’ scenario. For the next ten years, this would translate to the following maximum annual quantities:

- For a reuse fraction of 30 %: Around 350 turbines p.a.
- For a reuse fraction of 80 %: Around 950 turbines p.a.

Whether the available capacities are sufficient for handling the estimated second-lifecycle quantities cannot be answered with the available information. Hence, a preliminary overview of the infrastructure and workforce required is discussed below.

Typically, the company responsible for decommissioning is also responsible for handling the decommissioned turbine, while not every decommissioning company considers second lifecycle pathways. Moreover, other companies may also be involved and need to plan their capacity accordingly. In this context, a second lifecycle of entire turbines has been common in Denmark and Germany and as such it can be considered as an established service. It has often involved a direct transport of the turbine’s components from the decommissioning site without prior storage or refurbishment (see Figure 29). Referring to the overview of Figure 88 and the observed supply chain processes from Part B[8], capacities for second-lifecycle practices are outlined in Table 30. The capacity requirements in regard to storage, blade repair, refurbishment and remanufacturing are unknown. Some of these processes may require to be scaled and some still need to be established, resulting in investment requirements for new storage / repair / refurbishment / remanufacturing facilities. For a detailed assessment,

---

[8] See Figure 29 and Figure 30 for an overview of existing processes according to the observed supply chain processes.

further investigation regarding the economic and technological feasibility for the expected turbine types and their components is essential.

Table 30. Overview of the likelihood of bottlenecks in second-lifecycle capacity.

Second-lifecycle capacity	**Are capacity bottlenecks foreseen in the next ten years?**	
	Denmark	Germany
Storage facility	Unknown. Further investigations required.	
Blade repair facility	Unknown. Further investigations required.	
Refurbishment facility	Unknown. Economic and technological feasibility for the expected turbine types required.	
Remanufacturing facility		
Logistic equipment (e.g. lorries)	Unknown. Further investigations required.	
Skilled reinstallation team	To date only abroad.	To date only abroad.

Additionally, for the logistical equipment such as standard lorries, a capacity bottleneck is seen unlikely, however for specialised transport vehicles, for example for the transport of blades with lengths of above structure gauge, this is unknown. Nevertheless, those vehicles are also used for the installation of new turbines. In addition, reinstallation services have not been carried out in Denmark and Germany, and hence an assessment of capacity bottlenecks for the country of reinstallation would be required. However, it should be noted that skilled reinstallation teams can also travel to this destination, as highlighted by an interviewed expert. This leads to Table 31, which shows the applicability of cross-border and cross-industry flows to second-lifecycle practices.

Table 31. Applicability of cross-border and cross-industry flows to second-lifecycle practices.

Second-lifecycle capacity	**Cross-border flows**	**Cross-industry flows**
Storage facility	(✓) *depending on economic feasibility*	✓
Blade repair facility		x
Refurbishment facility		? *not known*
Remanufacturing facility		
Logistic equipment (e.g. lorries)	✓	(✓) *depending on component*
Skilled reinstallation team	✓	✓

Although, it is possible to transport decommissioned wind turbines and their components across borders to a facility, however, this depends on the economic feasibility, driven by the transport costs. Moreover, transport equipment commonly moves across borders, carrying different products. However, specialised vehicles may not be able to transport other products. For the skilled reinstallation teams, the possibility to move across countries is mentioned above. In addition, as discussed in the section on decommissioning, a reinstallation team can also carry out the decommissioning and installation of new wind turbines. However, the required skills may vary depending on the turbine type.

In conclusion, the discussion outlines that synergies with other countries or industries may be possible for reaching economic viability for second-lifecycle facilities. However, the development of second-lifecycle practices still needs to be further explored to enable a detailed assessment of which infrastructure and workforce is required.

Capacity planning for annual recycling quantities

Historically, in Denmark and Germany, blades that did not enter a second lifecycle were either repurposed, sent to energy recovery processes (e.g. cement co-processing) or were landfilled (see Figure 31). Landfill is however not likely to be still considered, as a landfill ban is foreseen by the industry for Europe from 2025 onwards and is already in place for Germany (Kramer & Beauson, 2023, p. 9). In this light, the establishment of infrastructure for high-quality recycling of composite materials from end-of-life blades is required. Therefore, whether threshold values of 5,000-15,000 tonnes p.a. for an economically viable blade recycling facility in Denmark and Germany are met on the basis of estimated annual recycling quantities was in-depth analysed (see 6.2.6).[9] For Denmark it is concluded that these thresholds are not reached (see Figure 85), while in Germany this could be the case within the next years, depending on the threshold (see Figure 86). For example, if at least 30 % of the annual decommissioning quantities remain in Germany, the threshold of 5,000 tonnes per year is estimated to be reached in 5 years.[10] In addition to the annual recycling flows from onshore wind turbines of the respective country, also cross-border and cross-industry flows may be of relevance, as outlined in Table 32.

Table 32. Applicability of cross-border and cross-industry flows to blade recycling.

Blade recycling capacity	Cross-border flows	Cross-industry flows
Pre-processing equipment and team	(✓) / ?	?
Blade recycling facility	(✓) currently unlikely due to regulation on waste movements	(✓) depending on recycling technology

Depending on the pre-processing processes (e.g. cutting of blades) involved, the equipment may be feasible to be transported to decommissioning sites of other countries. Furthermore, a new blade recycling facility in Denmark and/or Germany may be able to consider composite waste from other countries. However, this is currently difficult to realise as waste movements across borders involve complex regulation and is expensive to carry out (Regulation (EC) No 1013/2006, 2006). In addition, a new blade recycling facility, depending on the recycling technology, may also be able to consider waste from other industries such as offshore wind, automotive or aerospace. In particular the waste streams of offshore wind could be included, as likely similar composites materials are used as in blades of onshore turbines. In addition to waste from the

---

[9] The thresholds may differ depending on the recycling technology (e.g. pyrolysis, mechanical recycling), but more technology-specific thresholds are publicly not available.

[10] This is based on the Weibull function with $\lambda = 25.83$, $k = 7.49$.

decommissioning, waste from the manufacture and operation of wind turbines can also be considered.

In conclusion, cross-border and cross-industry flows may contribute to balancing out potential fluctuations of annual decommissioning quantities from onshore wind turbines installed in Denmark and Germany. This also underlines the importance for the establishment of a tracing system of various lifecycles of wind turbines, components and materials across countries. For example, Denmark and Germany could collaborate to facilitate easier cross-border movements between the two countries. This could support the initial establishment of a blade recycling infrastructure, as economic viability would be achieved earlier if decommissioned blade waste from both countries were processed. The analysis focused on the establishment of infrastructure for recycling of blade composites, while other strategies such as repurposing may also be relevant. It is also possible that this will have an impact on the potential recycling share of the decommissioned turbines.

6.3.2 Discussion of methodology and limitations

The provided annual flow estimates are derived from comprehensive data-based analyses of the two fundamental assumptions inherent to the forecasting models, namely the expected time of decommissioning of the installed turbine fleet and the expected reuse fraction in each country of observation (see Figure 89).

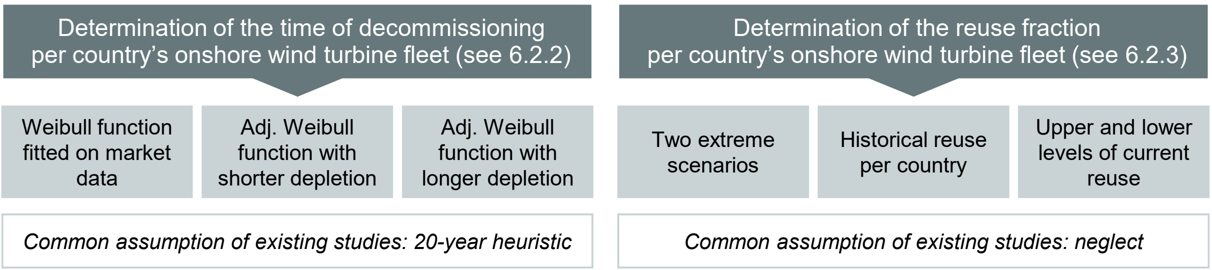


Figure 89. Overview of the scenarios for the time of decommissioning and the reuse fraction.

Discussion of expected time of decommissioning

A Weibull function is fitted in regard to the ratio of decommissioned over installed wind capacity per installation year. Hence, this method considers also the operating fleet for the calculation of the depletion curve, which is to date only applied in one previous study (see 6.1.1). Moreover, the adjusted Weibull function reflect the scenarios of earlier decommissioning of the fleet and continued operation. These scenarios are put into perspective with the commonly applied heuristic of 20 years. It can be noted that the historical decommissioning average (i.e. 18 years for the Danish decommissioning, see Figure 64) is comparable to this heuristic.

The application of the developed methodology to the Danish and German onshore turbine fleets reveals that the estimated annual decommissioning quantities are more akin to the historical decommissioning than the 20-year heuristic, in particular in terms of the annual blade mass. However, the MAE of the Danish model in terms of annual turbines is still relatively high compared to the annual flows (see Figure 78). For Germany, the MAE of the models compared to absolute annual flows is smaller than the same comparison for the Denmark. The German model may benefit from the fact that Germany has a larger fleet in operation and is therefore less sensitive to individual decommissioning projects. In addition, the deviation does not surprise given the exceptionally high number of actual decommissioning in Denmark in 2002. Future research could improve the models and include other factors in the prediction models. This is likely to improve the accuracy as the decision to decommission a wind turbine depends on various factors (see Part B, Figure 33). However, such data must first be collected for the modelling of multivariate regression models and machine learning, and could therefore not be included in this analysis. Furthermore, it is important to note that the historical data only provides an understanding of past performance and does not necessarily indicate how the models will perform going forward. To address this, several scenarios have been developed to allow supply chain actors to visualise different future outcomes, supporting more sophisticated capacity planning. Furthermore, actors of the circular supply chains should closely monitor the government's possible introduction of financial incentives for decommissioning, as such measures have had a significant impact on the annual decommissioning rate in the past (e.g. 2002 in Denmark). In addition, it is essential to track the future development of market electricity prices, as high prices may encourage a lifetime extension, while electricity prices below OPEX-levels may result in decommissioning.

Discussion of future reuse and recycling fractions

In reference to Figure 88, the estimate of the time of decommissioning and the resulting annual decommissioning quantities for the installed onshore turbine fleet in Denmark and Germany are the basis for estimating the second-lifecycle and recycling quantities. As such, the same above discussed limitations apply also to these models. In addition, it is assumed that a decommissioned wind turbine and its blades can either enter a second lifecycle or its blades can be recycled. The reuse fraction ($f_{reuse}(t)$) for the installed wind turbine fleet of each country is thus determined, and thereby also the recycling fraction ($f_{recycle}$(t)). In accordance with the methodology, four scenarios have been defined for the determination of these fractions, as illustrated in Figure 89. The scenarios are defined to assist supply chain actors in capacity planning by presenting different future outcomes.

The application of the methodology to the Danish and German onshore turbine fleets provides estimates for annual second-lifecycle and recycling quantities of the respective countries. However, an evaluation with actual data is not possible as no statistics for second-lifecycle and recycling quantities exist. Moreover, no research has been conducted to estimate the second lifecycle flows, although researchers have estimated the recycling flows, which is considered for comparison. In these studies, a common assumption is made regarding the lifetime of the turbine fleet and their blades, which is set at 20 years without a second lifecycle (see 6.1.1). Consequently, the 20-year heuristic is employed for the purposes of comparison.

Discussion of reuse scenarios

The newly collected historical averages of reuse, accounting to ~60 % for Denmark and ~50 % for Germany, provide valuable insights and offer a starting point for future estimates in the respective countries. Nevertheless, historical developments do not necessary apply to the future, which could particular be relevant in the case of determining a future reuse fraction. For instance, the characteristics of the operational fleet reveal a changing development in comparison to historical decommissioning (see 6.2.1). As such the differences of the decommissioned and operational fleet should be considered. This is acknowledged in the scenario of ‘current reuse’ in which a lower and upper limit is determined by considering various identified influencing factors for a second lifecycle from Part B and assessing their applicability to the Danish and German onshore fleet (see 6.2.3). It shows that the range of 20-40 % for Denmark is narrower than for Germany, which has a range of 30-80 %. On the one hand, the assumptions made should be evaluated through additional research studies, and on the other hand, it should be assessed whether additional factors are relevant for incorporation into the analysis. In this context, regulatory changes in the demanding or emerging countries have a particular impact on the demand for second-lifecycle turbines. However, this has not yet been investigated, subsequently this information would need to be collected in future research. Furthermore, the results of Part B show that several factors are interrelated and therefore vary depending on the circumstances. Thus, there are factors for which a precise criterion for the demand for a second lifecycle cannot be uniquely defined. Furthermore, the demand criteria already defined may change over time and in response to changing circumstances. Therefore, it would also be more accurate if a dynamic development of the annual reuse fraction ($f_{reuse}(t)$) is considered and not a static one. At this stage, the estimated annual decommissioning quantities are given as a timeseries and therefore do not provide further details on the type of turbine or other characteristics of the fleet. Consequently, a data-based determination of a time-dependent reuse fraction is not possible with the currently available data. To acknowledge the uncertainties associated to future reuse, also two extreme scenarios are defined, assuming that 0 % and 100 % of annual decommissioning is feasible for the second-hand market. Hence, the minimum and maximum annual second-lifecycle quantities are provided, which supports the supply chain actors to envision at which levels an economically viable thresholds would still be reached. Future research could further detail this for certain supply chain actors, e.g. by estimating annual second-lifecycle quantities per turbine type.

Discussion of future recycling fraction

The above outlined uncertainty in regard to the future reuse fraction for the installed fleet of each country, is addressed by providing a sensitivity analysis. This enables the assessment of how different recycling fractions impact the basis for the investment decision of a new blade recycling facility.

In reference to Figure 88, the blades could also be repurposed or sent into processes for energy recovery (e.g. cement co-processing). Accordingly, the recycling fraction could be smaller than assumed. A repurposed blade would postpone the point at which the blade materials could potentially become available for recycling. In contrast, energy recovery would result in a loss of materials for recycling. In addition, future research could refine the analysis of the economic viability thresholds for each recycling technology to possibly narrow the relatively wide range of 5,000-15,000 tonnes per year defined in this study. It should be noted that comprehensive assessments of the recycling technologies (e.g. costs, CO2 footprint) are still at an early stage of research.

Another aspect that could be considered in the recycling flow models is the additional flow of turbines and their rotor blades from the second lifecycle when they are decommissioned. As outlined, it seems at this stage not relevant for the two countries of investigation. However, it could become relevant for Denmark and Germany if cross-border movements of old turbines or reinstallations of second-lifecycle turbines in their country become feasible. In this case, the model would have to be adjusted to include the flows of turbines at the end of their additional lifecycle. This would also support the transferability of the methodology to countries that have already second-lifecycle turbines in operation (e.g. UK, Ireland, Italy).

All in all, a planning basis for circular supply chain stakeholders is provided with the annual second-lifecycle and recycling quantities. In addition, supply chain actors should carefully monitor events that could have a significant impact on the business case. For example, if Denmark or Germany were to impose an export ban on decommissioned turbines and/or components, this would significantly reduce the potential for reinstallation, as this has consistently been taken place abroad.

Conclusion

In conclusion Part C of the thesis provides annual estimations of turbine, component and material flows for installed onshore wind turbines in Denmark and Germany as a basis for long-term capacity planning of companies active in decommissioning, second lifecycle pathways and recycling. As a result, Part C gives a comprehensive answer to RQ5.

RQ5	Which turbine, component and material flows are expected for decommissioning, second lifecycle pathways and domestic recycling in Denmark and Germany?	✓

In conclusion, Part C makes the three key contributions:

- **Contribution 1:** Development of forecast models for annual decommissioning, second-lifecycle and recycling flows in terms of number of turbines and blade mass.
- **Contribution 2:** Application to the Danish and German onshore wind turbine fleet with estimating annual decommissioning, second-lifecycle and recycling quantities.
- **Contribution 3:** The derived annual decommissioning, second-lifecycle and recycling quantities offer support to the planning for the establishment and scaling of circular supply chains.

In summary, the obtained findings of Part C from two countries and various scenarios allow for concluding that the research objective 3 of the thesis is fulfilled.

RO3	Quantify expected turbine, component and material flows to establish circular supply chains for further lifecycles and end-of-life pathways.	✓

7 Overall Discussion

Due to the step-by-step development of the findings, the overall discussion of the results is situated within Part C (see chapter 6.3). This chapter thus builds on the preceding discussion and provides an overview of the contributions of the thesis, together with an evaluation of the suitability of the research design.

Overall contribution of the thesis

The overarching aim is to understand how sustainable and resilient circular supply chains can be developed for wind turbines by answering three research objectives. The research objectives are addressed through the implementation of a mixed methods research design with three main parts (Part A-C), resulting in the core contributions shown in Figure 90.

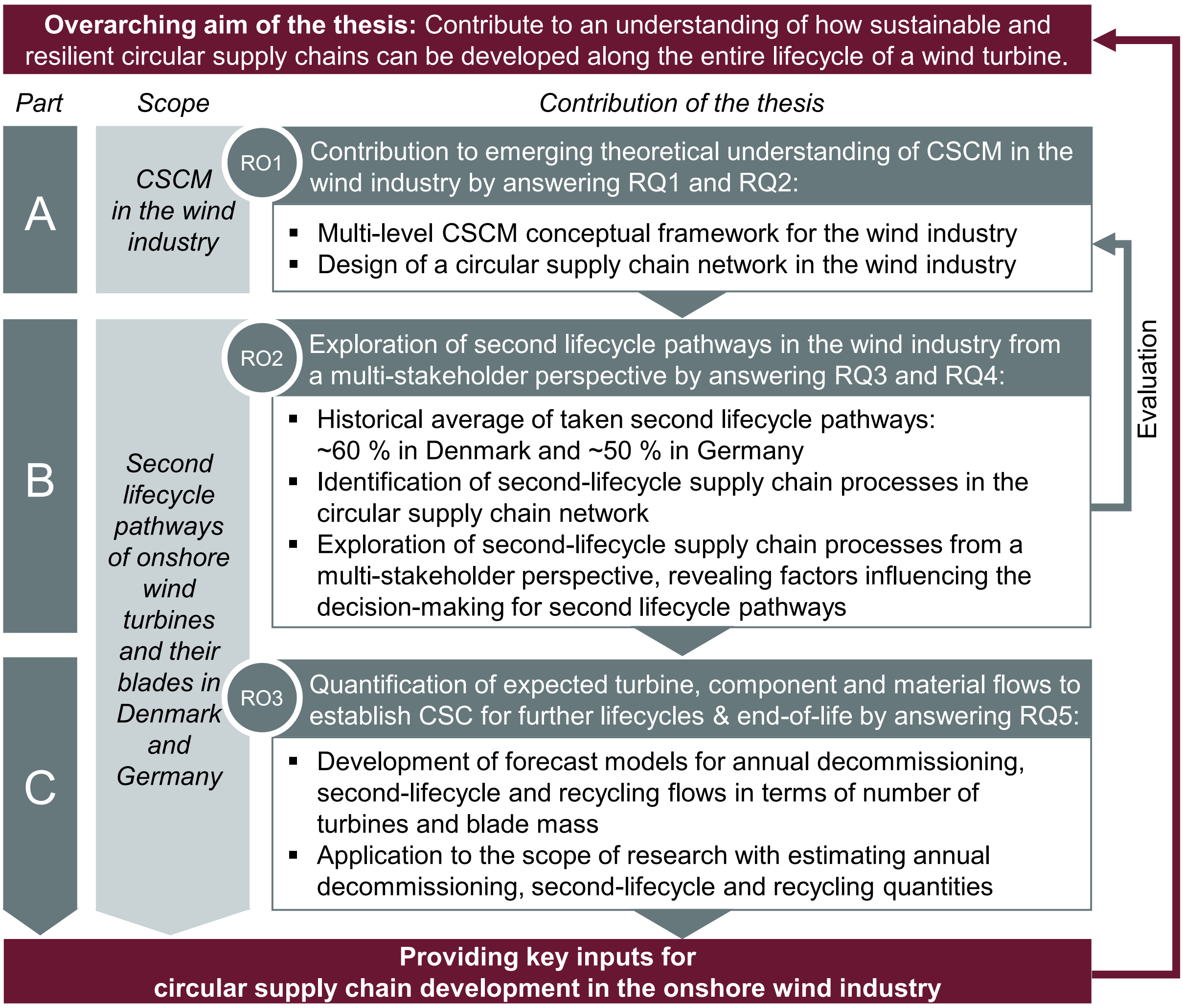


Figure 90. Contribution of the thesis.

Evaluation of research design

The nature of the research is qualitative, exploratory and empirical for the complex and emerging research area of CSCM in the wind industry and in particular for the development of circular supply chains for a second lifecycle and blade recycling. The applied mixed method approach is therefore initiated with a qualitative path and comprises of qualitative and quantitative research methods (see Figure 11).

As the nature of research is qualitative, the overall research design is evaluated by the qualitative evaluation criteria of credibility, transferability, dependability, and confirmability in regard to the trustworthiness of research (Döring & Bortz, 2016, pp. 109-110; Lincoln & Guba, 1985, p. 290). The following provides an evaluation of the thesis's research design, as summarised in Table 33. In addition, the qualitative and quantitative research methods of the respective parts are evaluated in chapter 5.3 and 6.3.

Table 33. Assessment of the trustworthiness of the research design. Method based on Lincoln & Guba (1985, p. 290), Döring & Bortz (2016, pp. 109-110).

Evaluation criteria	**Assessment of the trustworthiness of the research design**	
Credibility	▪ Triangulation with multiple data sources and methods ▪ Triangulation with mixed methods approach	✓
Transferability	▪ Thick description of scope of research (chapter 2), methodology (chapter 3), chosen research methods (4.1, 5.1, 6.1) and results (4.2, 5.2, 6.2) ▪ Transferability to other industries facilitated by grounding research in industry-neutral CSCM and CE research ▪ Transferability to other countries assessed by studying two countries	✓
Dependability	▪ Triangulation by step-by-step development of research methodology ▪ Triangulation with multiple methods ▪ Audit and expert feedback	✓
Confirmability	▪ Triangulation with multiple data sources: Scope of two countries, multi-stakeholder perspective ▪ Triangulation with mixed methods approach ▪ Audit and expert feedback	✓

In accordance to Table 33, various techniques (e.g. triangulation) are applied in this research to enable the trustworthiness of the research. The aspects of triangulation and transferability require further explanations and are therefore detailed below.

Triangulation

A key technique is triangulation, which is applied in this research through the use of a mixed methods approach as a methodology and the consideration of multiple methods and multiple data sources. This is also illustrated in Figure 11 of chapter 3 and moreover detailed in the following Table 34.

Table 34. Triangulation in the research design of this thesis.

Triangulation	Considerations in the research design
Mixed methods approach	▪ Evaluation of conceptual CSCM framework for the wind industry (Part A) with comparison to empirical findings (Part B) ▪ Scenario analysis of annual turbine, component and material flows (Part C), based on empirical findings (Part B)
Multiple data sources	▪ Two cases: Denmark and Germany ▪ Multi stakeholder perspective: Interviews with experts of different stakeholder groups representing more than 50 % of historical decommissioning in Denmark and Germany
Multiple methods	▪ Scientific literature review ▪ Semi-structured interviews with quantitative and qualitative data analysis ▪ Turbine, component, material flow forecasting with scenario analysis

Transferability to other industries

In regard to the transferability to other industries, it should be noted that the developed CSCM framework for the onshore wind industry is grounded on the industry-neutral CSCM framework by Montag et al. (2021) (see 4.1). This therefore eases transferability to other industries. In addition, the CSCM framework is detailed with industry-neutral aspects of circular economy such as the 9R-model by Potting et al. (2017, p. 15) and the extended SCOR-model by Vegter et al. (2020, pp. 6-8). However, it includes wind-specific elements, for instance, in regard to the product dimensions and circular supply chain processes. It must therefore be adapted to the specifics of the new industry under study. Additionally, the methodologies of Part B and C have to be adapted to new industries.

As outlined in the problem definition of this thesis, the implementation of circular economy practices is still marginal, with 7.2% of all materials currently being reused globally (see 1.1, Fraser et al., 2024, p. 8). Therefore, in view of the required transition towards decoupling from the use of primary materials, the study can be relevant to different industries. Onshore wind turbines are large multi-component products with a long lifetime, with a design life of at least 20 years (see 2.1). Thereof, industries with similar characteristics (e.g. offshore wind) could be a starting point for exploring potential transferability. Furthermore, a study on the reuse of hybrid vehicles and batteries from Japan (Wang et al., 2020, pp. 201-202) reveals the importance of considering a second lifecycle when estimating recycling flows, while other studies for PV modules and electric vehicles mention a lack of reuse statistics (Franco & Groesser, 2021, pp. 19, 23; Reinhardt et al., 2019, pp. 433, 442) (see 5.3.2).

In addition, at component level, the results may also be relevant for estimating other material flows from wind turbines for recycling purposes. In this context, a second lifecycle for the whole turbine also has an impact on all other components of a turbine (except the foundation). Moreover, as outlined in 5.2.2, the tower, hub and nacelle cover are likely to show similar results to those shown in this study for blades, as these have not traditionally been in demand as spare parts. Other components and parts (e.g. electronics and mechanical parts) have a demand for spare parts and may also have established repair, refurbishment and remanufacturing supply chains. The experts in this study indicate that gearboxes and generators are refurbished for reuse. This has a corresponding impact on the potential annual recycling quantities, for example for critical rare earth materials, such as those used in permanent magnets.

Transferability to other countries

Furthermore, the transferability to different countries is studied in this thesis as the developed methodology is applied to two cases, Denmark and Germany. Various findings of the applied methodology to both cases appear to be similar, for example:

- the order of magnitude of historical reuse of decommissioned onshore turbines,
- the observed circular supply chain processes,
- the observed influencing factors, although the weight of those factors may differ.

The methodology requires the availability of market data with a comprehensive history, which is not available in all countries. In addition, if reinstallation of second-lifecycle turbines takes place domestically (e.g. Ireland, Italy), this must be included in the recycling flow estimates.

Moreover, for the development of the turbine, component and material flow models the state of the art from other countries is outlined in chapter 6.1.1. It shows that studies of other countries have not yet estimated second-lifecycle quantities and moreover, estimates for recycling have widely neglected any second lifecycle pathway. As a significant reuse for wind turbines from Europe is indicated by Graulich et al. (2021, p. 52), the transfer of the study’s results and methodology can therefore be of relevance (see 5.3.2). In addition, other countries could learn from the practices observed in Denmark and Germany, as those countries are pioneers in the wind industry with a long history of installing onshore wind turbines and decommissioning those (see 2.2).

8 Summary, Critical Reflection and Future Research Agenda

The chapter presents the summary (8.1), followed by a critical reflection (8.2) and an outlook on the future research agenda (8.3).

8.1 Summary

The research objective of the work arises from the fact that a rapid scaling of wind capacity is necessary until 2050 in order to make a significant contribution to the sustainable transformation of the energy system. The necessary expansion of wind energy from 1 TW today to more than 10 TW in 2050 will require a significant input of materials and resources to manufacture the required wind turbines (IRENA, 2023, p. 78). In this light, the transition to a circular economy is seen as a promising approach to contribute to a sustainable and resilient scaling of the supply chains in the wind industry (see chapter 1.1). Despite, this recognition, research on circular supply chain management for the wind industry is rare, particularly for circular strategies that foresee to retain the structural value of wind turbines and their components (see chapter 2.4).

Consequently, the overall aim of the thesis was to contribute to the theoretical and empirical understanding of the development of sustainable and resilient circular supply chains in the wind industry by addressing the following three research objectives through a stepwise evolving mixed methods approach (see chapters 1.2, 3):

- **RO1:** Contribute to the emerging theoretical understanding of circular supply chain management in the wind industry.
- **RO2:** Explore second lifecycle pathways in the wind industry from a multi-stakeholder perspective.
- **RO3:** Quantify expected turbine, component and material flows to establish circular supply chains for further lifecycles and end-of-life pathways.

A systemic and multi-level conceptual framework for CSCM in the wind industry is provided, based on existing research of industry-neutral CSCM and wind-specific research (RQ1, see chapter 4). This is further detailed by introducing a CSC network design, considering the circular flows of wind turbines, components and materials (RQ2). It outlines the different circular economy pathways that a wind turbine can follow after decommissioning, however it is not known which pathways are commonly followed.

Consequently, the circular supply chain processes of the decommissioned onshore wind turbines and their blades in Denmark and Germany with an emphasize on second lifecycle pathways were empirically explored from a multi-stakeholder perspective (see chapter 5). Onshore wind turbines and their blades from installations in Denmark and Germany were chosen for the study because of the long history available, as both countries are pioneers in onshore wind (see chapter 2). In addition, understanding the circular economy pathways for blades is critical in order to help the industry build the recycling infrastructure for composites, which has yet to be established on an industrial scale. Therefore, interviews with 18 experts, coving more than 50 % of each decommissioning market and representing four stakeholder groups, were conducted and quantitatively and qualitatively analysed. The findings demonstrate that a second lifecycle for the historically decommissioned onshore wind turbines in Denmark and Germany is common, at least in the case of exporting wind turbines for reinstallation (RQ3). Accordingly, on average, approximately 60 % of the Danish and 50 % of the German decommissioned onshore wind turbine fleet was exported for a second lifecycle. Further insights are drawn into the factors influencing the development of second-lifecycle supply chains in the respective markets (RQ4). It is observed that the decision to decommission an onshore wind turbine and the choice of the subsequent circular economy pathway is dependent on various technical, legal/regulatory, economic, organisational and market factors.

To support capacity planning of supply chain actors and investment decisions in new infrastructure (e.g. blade recycling facility), new turbine, component and material flow models were developed and applied to the installed onshore wind turbine fleet in Denmark and Germany (RQ5, see chapter 6). Based on comprehensive market data and the newly derived empirical findings on circular economy pathways, different scenarios were formulated, resulting in annual estimates of decommissioning, second-lifecycle and recycling quantities for the current installations in the respective markets. It is therefore the first study to introduce annual second-lifecycle flows and to systematically include them in the estimation of recycling flows, thus overcoming the widespread assumption of decommissioning after 20 years and disregarding a second lifecycle. The study further emphasises that the thresholds for a new blade recycling facility of 5,000-15,000 tonnes per year are not met in any of the scenarios provided for Denmark. For Germany, however, it is estimated that the minimum tonnage requirement will be exceeded within the next five years, provided that at least 30 % of the decommissioned onshore wind turbines are retained for domestic recycling.

In conclusion, the conceptual and empirical findings of this study on CSCM and second lifecycle pathways in the wind industry offer valuable insights that can inform the planning of circular supply chains. Referring back to the problem definition, the costs and carbon emissions of a wind project are largely associated with the extraction and processing of materials, along with supply chain bottlenecks in the forward supply chains for manufacturing new wind turbines. Establishing circular supply chains can therefore support the scaling of the wind industry in a sustainable and resilient way.

8.2 Critical reflection

The research conducted is systemic and explorative in nature and thus has to be seen as a first steps towards a more comprehensive understanding of CSCM and second-lifecycle pathways of onshore wind turbines and their blades.

The developed CSCM framework for the onshore wind industry provides a systemic understanding on how circular thinking is integrated into SCM. This is partially evaluated by the empirical investigations in Part B. Nevertheless, as Part B also indicates, various interconnections at the different CSCM-levels exist, and thus adjustments might be required. In addition, further operationalisation of CSCM may necessitate additional details of the proposed framework. For example, at the products level, the dimensions of infrastructure, components and materials is used, which is also well suited to the context of the empirical study of wind turbines and their blades in Part B. Nevertheless, further detailing at part level can be useful when investigating a multi-part component such as a gearbox.

In this study, the cascading flows according to the 9R-model of Potting et al. is used as a guidance for the circular economy pathways of wind turbines and their blades. In accordance with the 9R-model, it is preferable to continue the operation of the wind turbine and its blades prior to pursuing second lifecycle pathways. Furthermore, second lifecycle pathways are to be preferred over end-of-life pathways. However, the different R-principles and the potential circular economy pathways, thus the cascade of the 9R-model, have to be assessed in regard to the applicability to onshore wind turbines and their components, parts and materials and is dependent on the given conditions at a given time and location. However, this study only explores the second lifecycle of onshore wind turbines from Denmark and Germany and does not study the occurrence of multiple lifecycles. It is important to note that an empirical study of this kind is only possible to a limited extent, given that second-lifecycle turbines and blades are likely still in operation.

The scope of the empirical investigations is on circular economy pathways of decommissioned onshore wind turbines from Denmark and Germany. A multi-stakeholder perspective is deployed by expert interviews with recyclers/dismantlers, OEMs, companies specialised on decommissioning wind turbines, wind project developers, operators and service companies active in the respective countries. However, the operators of the second-lifecycle turbines were not interviewed, although the inclusion of this perspective could further evaluate the results of this study. This is particularly important for the assessment of the assumption that the sale of decommissioned wind turbines and blades leads to a second lifecycle. As this is the first study exploring second lifecycle pathways this assumption has to be accepted at this stage, particularly as it otherwise requires extensive data collection in various countries.

Furthermore, scenarios for estimations of the second-lifecycle and recycling quantities are provided on the basis of newly collected data and a comprehensive market data analysis of the respective countries. In this light, the database of these methods is improved in comparison to previous studies, which widely neglect data on continued operation beyond the turbine design life of 20 years and the common occurrence of second lifecycle pathways. Despite the extensive new data collection and analysis, it should be noted that the information available is still limited. As a result, it is not possible to use more advanced analytics that might be better suited to integrate the complex nature of the underlying assumptions into the circular flow models. Accordingly, the supporting planning basis for the development of circular supply chains presented in this paper is based on a wide range of scenarios.

8.3 Outlook on future research agenda

CSCM in the onshore wind industry and in particular of second lifecycle pathways is currently a research niche (see chapter 2.4). The study has taken a first step towards understanding CSCM and supply chains for second lifecycle pathways. Due to the emerging field of research, further research work is indicated in all research areas covered by this study (RO1-RO3).

In view of the need to scale supply chains in the wind industry for the exponential increase in wind capacity worldwide, an improved planning basis for policy makers and supply chain actors that integrates a whole system understanding is useful. Therefore, in particular the development of empirical-based decision-making models in CSCM is seen as a crucial research topic, which first requires the establishment of an improved database. Hence, the below details a future research agenda for Part A-C of this thesis.

Part A: Future research agenda for whole system understanding of CSCM in the wind industry

A conceptual framework for CSCM in the onshore wind industry is provided in this thesis, which could be further evaluated and detailed in future research as outlined in Table 35.

Table 35. Future research agenda for whole system understanding of CSCM in the wind industry.

Research topics	Examples
CSCM target system	▪ Develop CSCM-target system (e.g. in regard to narrowing, slowing and closing flows) in collaboration with key stakeholders ▪ Develop methodology to measure targets and measurement of them ▪ Analyse measured target system, e.g. in regard to potential trade-offs
Circular turbine design for future installations	▪ Simulation of different changes of turbine design such as the impact of a modular design or durability
Multi-target and data-based logistical planning and control	▪ Optimisation of CSC design for each CSC actor and CSC network ▪ Tool for supporting decision-making of wind farm operators on most suitable circular economy pathways for certain wind projects ▪ Consider change over time

Research topics	Examples
Integration with long-term planning of energy systems and industrial policies	▪ Simulation of infrastructure, turbine, component and material flows to assess resource requirements for wind installation targets (regional, country, continent, global level) ▪ Simulate policy interactions to understand potential trade-offs between new installations, continued operation, second-lifecycle & recycling
Traceability system of circular flows	▪ Assess scope for a traceability system of circular flows of wind turbines, components and materials, incl. cross-border & cross-industry ▪ Assess possibility to adapt existing market registers in DNK and GER to enable traceability of turbines and components across lifecycles
Digital product pass	▪ Define scope for each circular strategy ▪ Define data requirements of second-lifecycle stakeholder, e.g. turbine design, operational data

Future research agenda of Part B: Exploration of second lifecycle pathways of wind turbines and their components

This thesis explored second lifecycle pathways of onshore wind turbines in Denmark and Germany, revealing the historical average of circular economy pathways taken and factors that influence the decision-making concerning second lifecycle pathways of turbines and blades. The research agenda proposed in Table 36 suggests to continue to explore the future development of second lifecycle pathways, in particular with regard to the technical and economic feasibility of second-lifecycle turbines and components.

Table 36. Future research agenda for second-lifecycle strategies of wind turbines and their components.

Research topics	Examples
Turbine design and technical remaining life of wind turbines and components	▪ Study on technical remaining lifetime assessment o Study on scope, e.g. automated, remote and continuous assessment of turbine condition o Study on data requirements, e.g. SCADA data, turbine design data ▪ Research on overall technical life of decommissioned, installed, future turbine types in different lifecycles in DNK, GER and other countries
Economic feasibility for second-lifecycle turbines and components	▪ Assessment on past, current and future demand markets for second-lifecycle turbines and spare parts management ▪ Study on economic feasibility of a second lifecycle pathways (e.g. transport costs) and define economic viable thresholds ▪ In-depth case studies of certain turbine types in Denmark and Germany and other countries
Influencing factors of decision-making on circular economy pathways	▪ Study on impact of technological progress of new wind turbines on the decision to acquire a second-lifecycle turbine and on other circular strategies such as continued operation at the initial site ▪ Study on impact of circular design criteria of new turbines ▪ Expert interviews with buyers / operators of second-lifecycle turbines ▪ In-depth case studies on pathways taken of decommissioning projects ▪ Study with new methods, e.g. causal-mapping, system dynamics

Research topics	Examples
Refurbishment and remanufacturing of turbines and their components	▪ Study on technical feasibility of refurbishment and remanufacturing of turbines and their components ▪ Case studies on certain turbine types and components ▪ Study on enablers and barriers, e.g. IP rights, product guarantee ▪ Assessment on impact on overall technical turbine life

Future research agenda for Part C: Turbine, component and material flow models for capacity planning of actors in circular supply chains

The thesis provides scenarios of annual circular flow estimates for multiple CSC actors of the installed Danish and German onshore wind turbine fleet. As this is built on the basis of the theoretical and empirical understanding of Part A and B, research on the above-mentioned research areas could also improve the planning basis for CSC actors. In this regard, Table 37 outlines a future research agenda.

Table 37. Future research agenda for circular flow models for capacity planning of CSC actors.

Research topics	Examples
Statistics on historical circular flows	▪ Collection of statistics on annual second-lifecycle and end-of-life quantities (e.g. repurposing, cement co-processing) in DNK and GER ▪ Collection of statistics on destinations of reinstallations from decommissioned turbines of Danish and German turbine fleet ▪ Collection of statistics on average lifetime of second-lifecycle turbines
Detail developed turbine, component and material flow models	▪ Study on each circular strategy (R3-R9) & cross-circular strategy flows ▪ Study on cross-national and cross-industry flows ▪ Study on open and closed loops, e.g. link circular flows to forward SC ▪ Study on multiple lifecycles for end-of-life quantities ▪ Exploration of further scenarios
Transferability of developed turbine, component and material flow models	▪ Further assessment of transferability to other countries ▪ Study on transferability to other industries ▪ Study on transferability to other components and materials of onshore wind turbines, e.g. rare earth materials in permanent magnets
Explore alternative turbine, component and material flow models	▪ Study on multi-variate regression methods (e.g. machine learning), when sufficient data becomes available ▪ Research on methods for the integration of qualitative and quantitative data, e.g. system dynamics, fuzzy logic
Actual and planned capacities of supply chain actors	▪ Collection of data on existing and planned capacities of CSC actors in DNK, GER and other countries, e.g. of remanufacturing sites ▪ Comparison of turbine, component & material flow forecasts with existing & planned CSC-capacities to understand potential gaps/bottlenecks in skilled workforce & infrastructure
Establishment of blade recycling infrastructure	▪ Detail economic viable thresholds for each recycling technology, e.g. pyrolysis, solvolysis ▪ Include cross-border and cross-industry composite flows in planning ▪ Research on decentralised and modular recycling facilities to enable economic feasibility at smaller volumes of composite waste ▪ Measure impact of recycling technologies, e.g. LCAs

9 References

8.2 Group (Ed.). (2021). *Weiterbetrieb von Windkraftanlagen*. www.8p2.de

Abrahamsen, A. B., Beauson, J., Wilhelm Lund, K., Skov Madsen, E., Philipp Rudolph, D., & Pagh Jensen, J. (2023). Method for estimating the future annual mass of decommissioned wind turbine blade material in Denmark. *Wind Energy*, Article we.2882. Advance online publication. https://doi.org/10.1002/we.2882

Alhawari, O., Awan, U., Bhutta, M. K. S., & Ülkü, M. A. (2021). Insights from Circular Economy Literature: A Review of Extant Definitions and Unravelling Paths to Future Research. *Sustainability*, *13*(2), 859. https://doi.org/10.3390/su13020859

Alves Dias, P., Bobba, S., Carrara, S., & Plazzotta, B. (2020). *The role of rare earth elements in wind energy and electric mobility: An analysis of future supply/demand balances*. *EUR: Vol. 30488*. Publications Office of the European Union.

Amer, M., Daim, T. U., & Jetter, A. (2013). A review of scenario planning. *Futures*, *46*, 23–40. https://doi.org/10.1016/j.futures.2012.10.003

Andersen, N., Eriksson, O., Hillman, K., & Wallhagen, M. (2016). Wind Turbines' End-of-Life: Quantification and Characterisation of Future Waste Materials on a National Level. *Energies*, *9*(12), 999. https://doi.org/10.3390/en9120999

Andre, P., Boneva, T., Chopra, F., & Falk, A. (2024). Globally representative evidence on the actual and perceived support for climate action. *Nature Climate Change*, *14*(3), 253–259. https://doi.org/10.1038/s41558-024-01925-3

Andreassen, S. M. (2023). *Past management and future challenges with glass fiber composites from wind turbines in Norway*. NVE Ekstern rapport nr. 22/2023 (No. 22). https://publikasjoner.nve.no/eksternrapport/2023/eksternrapport2023_22.pdf

Arnold Schwerlast (Ed.). *Schwerlast Spezialtransporte*. www.arnold-schwerlast.de/spezialtransporte/

Ayati, S. M., Shekarian, E., Majava, J., & Wæhrens, B. V. (2022). Toward a circular supply chain: Understanding barriers from the perspective of recovery approaches. *Journal of Cleaner Production*, *359*, 131775. https://doi.org/10.1016/j.jclepro.2022.131775

Bakker, C. A., Mugge, R., Boks, C., & Oguchi, M. (2021). Understanding and managing product lifetimes in support of a circular economy. *Journal of Cleaner Production*, *279*, 123764. https://doi.org/10.1016/j.jclepro.2020.123764

Bals, L., Tate, W. L., & Ellram, L. M. (Eds.). (2022). *Circular economy supply chains: From chains to systems*. Emerald Publishing Limited

Barrie, J., Salminen, I., Schroder, P., & Stucki, J. (2024). *National circular economy roadmaps: a global stocktake for 2024*. www.unido.org

Batista, L., Bourlakis, M., Smart, P., & Maull, R. (2018). In search of a circular supply chain archetype – a content-analysis-based literature review. *Production Planning & Control*, *29*(6), 438–451. https://doi.org/10.1080/09537287.2017.1343502

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

Bocken, N. M. P., Pauw, I. de, Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

Bonfante, M. C., Raspini, J. P., Fernandes, I. B., Fernandes, S., Campos, L. M., & Alarcon, O. E. (2021). Achieving Sustainable Development Goals in rare earth magnets production: A review on state of the art and SWOT analysis. *Renewable and Sustainable Energy Reviews*, *137*, 110616. https://doi.org/10.1016/j.rser.2020.110616

Bonou, A., Laurent, A., & Olsen, S. I. (2016). Life cycle assessment of onshore and offshore wind energy-from theory to application. *Applied Energy*, *180*, 327–337. https://doi.org/10.1016/j.apenergy.2016.07.058

Bressanelli, G., Perona, M., & Saccani, N. (2019). Challenges in supply chain redesign for the Circular Economy: a literature review and a multiple case study. *International Journal of Production Research*, *57*(23), 7395–7422. https://doi.org/10.1080/00207543.2018.1542176

Brunner, P. H., & Rechberger, H. (2004). *Practical handbook of material flow analysis. Advanced methods in resource and waste management: Vol. 1*. Lewis Publishers

Bundesministerium für Wirtschaft und Klimaschutz (Ed.). (2023). *Bruttobeschäftigung durch erneuerbare Energien 2000 bis 2022*. https://www.bmwk.de/Redaktion/DE/Downloads/E/ee-beschaeftigte-2000-2022.pdf?__blob=publicationFile&v=6

Bundesnetzagentur (Ed.). (2022, April 25). *Marktstammdatenregister*. https://www.marktstammdatenregister.de/MaStR/

Bundesnetzagentur. (2023). *MaStR Marktstammdatenregister: Excel*. https://www.marktstammdatenregister.de/MaStR/Einheit/Einheiten/ErweiterteOeffentlicheEinheitenuebersicht

Bundesverband WindEnergie (Ed.). *Transport von Windenergieanlagen*. https://www.wind-energie.de/themen/anlagentechnik/montage-und-errichtung/transport/

Bundesverband WindEnergie. (2019). *Rückbau und Recycling von Windenergieanlagen: Hintergrundpapier des Bundesverband WindEnergie e. V.*

Burton, T., Jenkins, N., Sharpe, D., & Bossanyi, E. (2011). *Wind energy handbook* (2nd). John Wiley & Sons

Butler, D., Cantwell, P., Paterson, L., Shelton, A., & Uflewska, O. (2023). *Barriers to a Circular Economy in Onshore Wind: A Sector Perspective*. https://circularwind.org/survey/

Carrara, S., Alves Dias, P., Plazzotta, B., & Pavel, C. (2020). *Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system*. *EUR: Vol. 30095*. Publications Office of the European Union

Cerqueira, V., Torgo, L., & Soares, C. (2019). *Machine Learning vs Statistical Methods for Time Series Forecasting: Size Matters.* https://doi.org/10.48550/arXiv.1909.13316

Chen, Y., Cai, G., Zheng, L., Zhang, Y., Qi, X., Ke, S., Gao, L., Bai, R., & Liu, G. (2021). Modeling waste generation and end-of-life management of wind power development in Guangdong, China until 2050. *Resources, Conservation and Recycling*, *169*, 105533. https://doi.org/10.1016/j.resconrec.2021.105533

Cheramin, M., Saha, A. K., Cheng, J., Paul, S. K., & Jin, H. (2021). Resilient NdFeB magnet recycling under the impacts of COVID-19 pandemic: Stochastic programming and Benders decomposition. *Transportation Research Part E: Logistics and Transportation Review*, *155*, 102505. https://doi.org/10.1016/j.tre.2021.102505

Circular Economy Indicators Coalition (Ed.). (2023). *Corporate circular target-setting guidance*. https://pacecircular.org/corporate-circular-target-setting

Colicchia, C., Creazza, A., Noè, C., & Strozzi, F. (2019). Information sharing in supply chains: a review of risks and opportunities using the systematic literature network analysis (SLNA). *Supply Chain Management: An International Journal*, *24*(1), 5–21. https://doi.org/10.1108/SCM-01-2018-0003

Cooperman, A., Eberle, A., & Lantz, E. (2021). Wind turbine blade material in the United States: Quantities, costs, and end-of-life options. *Resources, Conservation and Recycling*, *168*(1), 105439. https://doi.org/10.1016/j.resconrec.2021.105439

Corvellec, H., Stowell, A. F., & Johansson, N. (2021). Critiques of the circular economy. *Journal of Industrial Ecology*, 1–12. https://doi.org/10.1111/jiec.13187

Creswell, J. W., & Poth, C. N. (2018). *Qualitative inquiry & research design: Choosing among five traditions* (Fourth edition). Sage

Dahane, M., Sahnoun, M., Bettayeb, B., Baudry, D., & Boudhar, H. (2017). Impact of spare parts remanufacturing on the operation and maintenance performance of offshore wind turbines: a multi-agent approach. *Journal of Intelligent Manufacturing*, *28*(7), 1531–1549. https://doi.org/10.1007/s10845-015-1154-1

Damvad Analytics A/S, & Wind Denmark (Eds.). (2021). *Branchestatistik: Vindmøllebranchen | November 2021*. https://greenpowerdenmark.dk/

Danish Energy Agency. *Overview of the energy sector: The Danish Energy Agency provides data contributing to generate an overview of the Danish energy supply system*. https://ens.dk/en/our-services/statistics-data-key-figures-and-energy-maps/overview-energy-sector

Danish Energy Agency. (2022). *Master data register for wind turbines: Excel*. https://ens.dk/sites/ens.dk/files/Statistik/anlaeg.xlsx

Dao, C., Kazemtabrizi, B., & Crabtree, C. (2019). Wind turbine reliability data review and impacts on levelised cost of energy. *Wind Energy*, *22*(12), 1848–1871. https://doi.org/10.1002/we.2404

DecomBlades. (2023, April 25). *Blade manufacturers announce joint commitment to support recycling by providing material passports* [Press release]. https://decomblades.dk/index.php/2023/04/25/638/

Deeney, P., Nagle, A. J., Gough, F., Lemmertz, H., Delaney, E. L., McKinley, J. M., Graham, C., Leahy, P. G., Dunphy, N. P., & Mullally, G. (2021). End-of-Life alternatives for wind turbine blades: Sustainability Indices based on the UN sustainable development goals. *Resources, Conservation and Recycling*, *171*(12), 105642. https://doi.org/10.1016/j.resconrec.2021.105642

Defra. (2011). *Guidance on Applying the Waste Hierarchy 2011.* Department for Environment, Food & Rural Affairs. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69403/pb13530-waste-hierarchy-guidance.pdf

Delaney, E. L., McKinley, J. M., Megarry, W., Graham, C., Leahy, P. G., Bank, L. C., & Gentry, R. (2021). An integrated geospatial approach for repurposing wind turbine blades. *Resources, Conservation and Recycling*, *170*(4), 105601. https://doi.org/10.1016/j.resconrec.2021.105601

Deutsche WindGuard. (2023). *Status des Windenergieausbaus an Land in Deutschland - Erstes Halbjahr 2023*. www.windguard.de/id-1-halbjahr-2023.html

Deutsche WindGuard. (2024). *Status des Windenergieausbaus an Land in Deutschland - Jahr 2023*. www.windguard.de/statistik-jahr-2023.html

Deutsches Institut für Normung (2020). Nachhaltiger Rückbau, Demontage, Recycling und Verwertung von Windenergieanlagen, DIN SPEC 4866, 2020

Deutsches Institut für Normung (2023). Remanufacturing (Reman) – Quality classification for circular processes - English translation of DIN SPEC 91472:2023-06, 2023

Devoy McAuliffe, F., Lynch, K., Sperstad, I. B., Nonås, L. M., Halvorsen-Weare, E. E., Jones, D., Akbari, N., Wall, G., Irawan, C., Norstad, I., Stålhane, M., & Murphy, J. (2018). The LEANWIND suite of logistics optimisation and full lifecycle simulation models for offshore wind farms. *Journal of Physics: Conference Series*, *1104*, 12002. https://doi.org/10.1088/1742-6596/1104/1/012002

Döring, N., & Bortz, J. (2016). *Forschungsmethoden und Evaluation in den Sozial- und Humanwissenschaften*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-41089-5

Dresing, T., & Pehl, T. (2018). *Praxisbuch Interview, Transkription & Analyse: Anleitungen und Regelsysteme für qualitativ Forschende* (8. Auflage). Eigenverlag.

Dulman, M. T., & Gupta, S. M. (2018). Maintenance and remanufacturing strategy: using sensors to predict the status of wind turbines. *Journal of Remanufacturing*, *8*(3), 131–152. https://doi.org/10.1007/s13243-018-0050-1

Dykes, K., & Meadows, R. (2011). *Applications of Systems Engineering to the Research, Design, and Development of Wind Energy Systems: Technical Report* (WE11.0341). National Renewable Energy Laboratory (NREL)

Ellen MacArthur Foundation (Ed.). (2019). *Completing the Picture: How the Circular Economy Tackles Climate Change*. www.ellenmacarthurfoundation.org/publications

Energi Watch (Ed.). (2020, April 17). *Vindmøllevinger ender i deponi: De fleste kasserede vindmøllevinger ender i deponi, hvor glasfiberaffaldet efterlades til kommende generationer. Affaldsmængderne vil vokse drastisk i de kommende år.* Ingeniøren; Ritzau. https://energiwatch.dk/Energinyt/Renewables/article12082150.ece

Energy Transitions Commission (Ed.). (2023). *Material and Resource Requirements for the Energy Transition: The Barriers to Clean Electrification Series*. www.energy-transitions.org

Ertek, G., Chi, X., Zhang, A. N., & Asian, S. (2017). Text mining analysis of wind turbine accidents: An ontology-based framework. In *2017 IEEE International Conference on Big Data (Big Data)* (pp. 3233–3241). IEEE. https://doi.org/10.1109/BigData.2017.8258305

ETIPWind (Ed.). (2023). *Strategic Research & Innovation Agenda 2025-2027*. https://etipwind.eu/

European Commission (2019). COM(2019) 640 final: Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions - The European Green Deal. https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF

European Commission (2022). COM(2022) 230 final: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - REPowerEU Plan. https://commission.europa.eu/publications/key-documents-repowereu_en

European Commission (2023). COM(2023) 669 final: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - European Wind Power Action Plan. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52023DC0669

European Parliament. (2023). *Circular economy: definition, importance and benefits*. https://www.eumonitor.eu/9353000/1/j9vvik7m1c3gyxp/vknegugz7hwu?ctx=vjxzjv7ta8z1

European Parliament, C. o. t. E. U. (2008). EU Waste Framework Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098&from=EN

European Parliament, C. o. t. E. U. (2006). Regulation (EC) No 1013/2006 of the European Parliament and of the Council of 14 June 2006 on shipments of waste, Official Journal of the European Union. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32006R1013

European Parliament, C. o. t. E. U. (2021). Regulation (EU) No 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999. http://data.europa.eu/eli/reg/2021/1119/oj

Eurostat. (2024). *Circular Economy Monitoring framework*. https://ec.europa.eu/eurostat/web/circular-economy/monitoring-framework

Farooque, M., Zhang, A., Thürer, M., Qu, T., & Huisingh, D. (2019). Circular supply chain management: A definition and structured literature review. *Journal of Cleaner Production*, *228*, 882–900. https://doi.org/10.1016/j.jclepro.2019.04.303

Franco, M. A., & Groesser, S. N. (2021). A Systematic Literature Review of the Solar Photovoltaic Value Chain for a Circular Economy. *Sustainability*, *13*(17), 9615. https://doi.org/10.3390/su13179615

Fraser, M., Conde, Á., & Haigh, L. (2024). *The circularity gap report 2024: A circular economy to live within the safe limits of the planet*. https://www.circularity-gap.world/2024

From, L., & Dohm, K. (2022, July 30). *Vindmøller er grønne – men vindmølleaffald er langtfra grønt*. https://jyllands-posten.dk/indland/ECE14119657/vindmoeller-er-groenne-men-vindmoelleaffald-er-langtfra-groent/

Garcia-Sanz, M., Barreras, M., & Vital, P. (2011). Power Regulation Strategies for Wind Turbines. In M. Sathyajith & G. S. Philip (Eds.), *Environmental Science and Engineering. Advances in Wind Energy Conversion Technology* (pp. 159–176). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-88258-9_6

Gebhardt, M., Kopyto, M., Birkel, H., & Hartmann, E. (2021). Industry 4.0 technologies as enablers of collaboration in circular supply chains: a systematic literature review. *International Journal of Production Research*, 1–29. https://doi.org/10.1080/00207543.2021.1999521

Gesetz zum Schutz vor schädlichen Umwelteinwirkungen durch Luftverunreinigungen, Geräusche, Erschütterungen und ähnliche Vorgänge (1974 & rev. 2024). https://www.gesetze-im-internet.de/bimschg/

Gesetz für den Ausbau erneuerbarer Energien 2023 (2014 & rev. 2023). https://www.gesetze-im-internet.de/eeg_2014/

Gesetz zur Entwicklung und Förderung der Windenergie auf See (2017 & rev. 2023). https://www.gesetze-im-internet.de/windseeg/

Gläser, J., & Laudel, G. (2010). *Experteninterviews und qualitative Inhaltsanalyse: als Instrumente rekonstruierender Untersuchungen* (4th). *Lehrbuch*. VS Verlag. http://d-nb.info/1002141753/04

Global Wind Energy Council (Ed.). (2022). *GWEC | Global Wind Report 2022*. www.gwec.net

Global Wind Energy Council (Ed.). (2023a). *Global wind market development: Supply side data 2022.*

Global Wind Energy Council (Ed.). (2023b). *Global Wind Statistics 2023: Status end of 2022.*

Global Wind Energy Council (Ed.). (2023c). *GWEC | Global Wind Report 2023*. www.gwec.net

Global Wind Energy Council, & Boston Consulting Group (Eds.). (2023). *Mission Critical: Building the global wind energy supply chain for a 1.5°C world*

Golicic, S. L., & Davis, D. F. (2012). Implementing mixed methods research in supply chain management. *International Journal of Physical Distribution & Logistics Management*, *42*(8/9), 726–741. https://doi.org/10.1108/09600031211269721

Golicic, S. L., Davis, D. F., & McCarthy, T. M. (2005). A Balanced Approach to Research in Supply Chain Management. In H. Kotzab, S. Seuring, M. Müller, & G. Reiner (Eds.), *Research Methodologies in Supply Chain Management* (pp. 15–29). Physica-Verlag. https://doi.org/10.1007/3-7908-1636-1_2

González-Sánchez, R., Settembre-Blundo, D., Ferrari, A. M., & García-Muiña, F. E. (2020). Main Dimensions in the Building of the Circular Supply Chain: A Literature Review. *Sustainability*, *12*(6), 2459. https://doi.org/10.3390/su12062459

Grant, D. B., Shaw, S., Sweeney, E., Bahr, W., Chaisurayakarn, S., & Evangelista, P. (2023). Using mixed methods in logistics and supply chain management research: current state and future directions. *The International Journal of Logistics Management*, *34*(7), 177–198. https://doi.org/10.1108/IJLM-04-2023-0156

Graulich, K., Bulach, W., Betz, J., Dolega, P., Hermann, C., Manhart, A., Bilsen, V., Bley, F., Watkins, E., & Stainforth, T. (2021). *Emerging waste streams – Challenges and opportunities: Service under Framework contract EEA/HSR/20/001-3 for the provision of expert assistance to support the European Environment Agency's activities on circular economy and industrial transformation*. https://www.oeko.de/publikation/emerging-waste-streams-challenges-and-opportunities/

Groot, A. D. de, & Spiekerman, J. A. A. (1969). *Methodology*. De Gruyter. https://doi.org/10.1515/9783112313121

Guba, E. G. (Ed.). (1990). *The Paradigm dialog.* Sage Publications

Hau, E. (2016). *Windkraftanlagen*. Springer Berlin Heidelberg

Heng, H., Meng, F., & McKechnie, J. (2021). Wind turbine blade wastes and the environmental impacts in Canada. *Waste Management (New York, N.Y.)*, *133*, 59–70. https://doi.org/10.1016/j.wasman.2021.07.032

Herrmann, C. (2010). *Ganzheitliches Life Cycle Management*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-01421-5

Hyndman, R. J., & Athanasopoulos, G. (2021). *Forecasting: principles and practice*. OTexts. OTexts.com/fpp3

International Electrotechnical Commission. (2019, February 8). *IEC 61400-1:2019 RVL, Wind energy generation systems - Part 1: Design requirements*. https://webstore.iec.ch/publication/64648

International Energy Agency. (Sept 2022). *IEA Energy and Carbon Tracker 2022*. https://www.iea.org/data-and-statistics/data-product/iea-energy-and-carbon-tracker-2022

International Energy Agency. (2023a). *Denmark 2023: Energy Policy Review*. www.iea.org/reports/denmark-2023

International Energy Agency (Ed.). (2023b). *World Energy Outlook 2023*. www.iea.org

International Energy Agency (Ed.). (2024a). *Renewables 2023: Analysis and forecast to 2028*. www.iea.org

International Energy Agency. (July 2024b). *World Energy Statistics and Balances*. https://www.iea.org/data-and-statistics/data-product/world-energy-statistics-and-balances

International Organization for Standardization (ISO) (2024). *ISO 59004:2024:* Circular economy — Vocabulary, principles and guidance for implementation (Edition 1). www.iso.org/standard/80648.html

International Renewable Energy Agency (Ed.). (2023). *World energy transitions outlook 2023: 1.5°C pathway*

International Resource Panel. (2018). *Re-defining Value – The Manufacturing Revolution. Remanufacturing, Refurbishment, Repair and Direct Reuse in the Circular Economy: United Nations Environment Programme*

Jawahir, I. S., & Bradley, R. (2016). Technological Elements of Circular Economy and the Principles of 6R-Based Closed-loop Material Flow in Sustainable Manufacturing. *Procedia CIRP*, *40*, 103–108. https://doi.org/10.1016/j.procir.2016.01.067

Jensen, J. P., Prendeville, S. M., Bocken, N. M., & Peck, D. (2019). Creating sustainable value through remanufacturing: Three industry cases. *Journal of Cleaner Production*, *218*, 304–314. https://doi.org/10.1016/j.jclepro.2019.01.301

Jensen, P. D., Purnell, P., & Velenturf, A. P. (2020). Highlighting the need to embed circular economy in low carbon infrastructure decommissioning: The case of offshore wind. *Sustainable Production and Consumption*, *24*, 266–280. https://doi.org/10.1016/j.spc.2020.07.012

Joustra, J., Flipsen, B., & Balkenende, R. (2021). Structural reuse of wind turbine blades through segmentation. *Composites Part C: Open Access*, *5*, 100137. https://doi.org/10.1016/j.jcomc.2021.100137

Kaczmarek, S., Hogreve, S., Greten, A., Schröder, M., & Tracht, K. (2016). Improving Design Efforts and Assembly Efficiency of Rotor Blade Carriers through Modularisation. *Procedia CIRP*, *50*, 76–81. https://doi.org/10.1016/j.procir.2016.05.021

Kara, S., Hauschild, M., Sutherland, J., & McAloone, T. (2022). Closed-loop systems to circular economy: A pathway to environmental sustainability? *CIRP Annals*, *71*(2), 505–528. https://doi.org/10.1016/j.cirp.2022.05.008

Khalid, M. Y., Arif, Z. U., Hossain, M., & Umer, R. (2023). Recycling of wind turbine blades through modern recycling technologies: A road to zero waste. *Renewable Energy Focus*, *44*, 373–389. https://doi.org/10.1016/j.ref.2023.02.001

Kirchherr, J., Piscicelli, L., Bour, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A., & Hekkert, M. (2018). Barriers to the Circular Economy: Evidence From the European Union (EU). *Ecological Economics*, *150*, 264–272. https://doi.org/10.1016/j.ecolecon.2018.04.028

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

Kirchherr, J., Yang, N.-H. N., Schulze-Spüntrup, F., Heerink, M. J., & Hartley, K. (2023). Conceptualizing the Circular Economy (Revisited): An Analysis of 221 Definitions. *Resources, Conservation and Recycling*, *194*, 107001. https://doi.org/10.1016/j.resconrec.2023.107001

Klima-, Energi- og Forsyningsministeriet (2001). Bekendtgørelse om nettilslutning af vindmøller og prisafregning for vindmølleproduceret elektricitet m.v. https://www.retsinformation.dk/eli/lta/2001/187

Klima-, Energi- og Forsyningsministeriet (2013). Bekendtgørelse om teknisk certificeringsordning for vindmøller. https://www.retsinformation.dk/eli/lta/2013/73

Komoto, K., Held, M., Agraffeil, C., Alonso-Garcia, C., Danelli, A., Lee, J.-S., Fang, L., Bilbao, J., Deng, R., Heath, G., Ravikumar, D., & Sinha, P. (2022). *Status of PV Module Recycling in Selected IEA PVPS Task12 Countries.* International Energy Agency (IEA)

Koschate, B.-P. (2020). *Optimierung der Auftragszuordnung in strategischen Projektnetzwerken unter Berücksichtigung von Risiken.* Technische Universität Hamburg

Koumoulos, E. P., Trompeta, A.-F., Santos, R.-M., Martins, M., Santos, C. M. d., Iglesias, V., Böhm, R., Gong, G., Chiminelli, A., Verpoest, I., Kiekens, P., & Charitidis, C. A. (2019). Research and Development in Carbon Fibers and Advanced High-Performance Composites Supply Chain in Europe: A Roadmap for Challenges and the Industrial Uptake. *Journal of Composites Science*, *3*(3), 86. https://doi.org/10.3390/jcs3030086

Kramer, K. J., Abrahamsen, A. B., Beauson, J., Hansen, U. E., Clausen, N.-E., Velenturf, A. P., & Schmidt, M. (2024). Quantifying circular economy pathways of decommissioned onshore wind turbines: The case of Denmark and Germany. *Sustainable Production and Consumption*, *49*, 179–192. https://doi.org/10.1016/j.spc.2024.06.022

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

Kramer, K. J., Behn, N., & Schmidt, M. (2022). *The Potential of AutoML for Demand Forecasting*. Hannover: publish-Ing. https://doi.org/10.15488/12162

Kramer, K. J., & Schmidt, M. (2022). Circular supply chain management for the wind energy industry – Conceptional ideas towards more circularity. In P. Plapper (Ed.), *Digitization of the work environment for sustainable production* (pp. 61–80). GITO Verlag. https://doi.org/10.30844/WGAB_2022_4

Kramer, K. J., & Schmidt, M. (2023). Circular Supply Chain Management in the Wind Energy Industry – A Systematic Literature Review. In H. Kohl, G. Seliger, & F.

Dietrich (Eds.), *Lecture Notes in Mechanical Engineering. Manufacturing Driving Circular Economy* (pp. 85–93). Springer International Publishing. https://doi.org/10.1007/978-3-031-28839-5_10

Kühne, C., Stapf, D., Holz, P., Baumann, W., Mülhopt, S., Wexler, M., Hauser, M., Kalkreuth, J., Mahl, J., Zeller, M., Volk, R., Stallkamp, C., Steffl, S., Schultmann, F., Schweppe, R., Pico, D., Seiler, E., Forberger, J., Brantsch, P., . . . Beckmann, M. (2022). *Entwicklung von Rückbau- und Recyclingstandards für Rotorblätter*, Umweltbundestamt

Kurbel, K. (2016). *Enterprise resource planning and supply chain management in der Industrie: Von MRP bis Industrie 4.0* (8., vollst. überarb. und erw. Auflage). *De Gruyter Studium*. Walter de Gruyter GmbH

Kwon, E., Pehlken, A., Thoben, K.-D., Bazylak, A., & Shu, L. H. (2019). Visual Similarity to Aid Alternative-Use Concept Generation for Retired Wind-Turbine Blades. *Journal of Mechanical Design*, *141*(3), 505. https://doi.org/10.1115/1.4042336

Lahuerta, F., Gesto, D., Prieto, C., Johst, P., Kucher, M., Mozas, E., Gracia, O., Böhm, R., & Bielsa, J. M. (2023). Decommissioning Inventory for Wind Turbine Blades Installed Until 2022 in Europe. *Materials Circular Economy*, *5*(1). https://doi.org/10.1007/s42824-023-00084-8

Lapko, Y., Trianni, A., Nuur, C., & Masi, D. (2019). In Pursuit of Closed-Loop Supply Chains for Critical Materials: An Exploratory Study in the Green Energy Sector. *Journal of Industrial Ecology*, *23*(1), 182–196. https://doi.org/10.1111/jiec.12741

Laurentis, C. de, & Windemer, R. (2024). When the turbines stop: Unveiling the factors shaping end-of-life decisions of ageing wind infrastructure in Italy. *Energy Research & Social Science*, *113*, 103536. https://doi.org/10.1016/j.erss.2024.103536

Lefeuvre, A., Garnier, S., Jacquemin, L., Pillain, B., & Sonnemann, G. (2019). Anticipating in-use stocks of carbon fibre reinforced polymers and related waste generated by the wind power sector until 2050. *Resources, Conservation and Recycling*, *141*(8), 30–39. https://doi.org/10.1016/j.resconrec.2018.10.008

Lengyel, P., Bai, A., Gabnai, Z., Mustafa, O. M. A., Balogh, P., Péter, E., Tóth-Kaszás, N., & Németh, K. (2021). Development of the Concept of Circular Supply Chain Management—A Systematic Review. *Processes*, *9*(10), 1740. https://doi.org/10.3390/pr9101740

Lenton, T. M., Benson, S., Smith, T., Ewer, T., Lanel, V., Petykowski, E., Powell, T. W. R., Abrams, J. F., Blomsma, F., & Sharpe, S. (2022). Operationalising positive tipping points towards global sustainability. *Global Sustainability*, *5.* https://doi.org/10.1017/sus.2021.30

Lichtenegger, G., Rentizelas, A. A., Trivyza, N., & Siegl, S. (2020). Offshore and onshore wind turbine blade waste material forecast at a regional level in Europe until 2050. *Waste Management (New York, N.Y.)*, *106*, 120–131. https://doi.org/10.1016/j.wasman.2020.03.018

Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic inquiry*. SAGE Publications

Liu, P., & Barlow, C. Y. (2017). Wind turbine blade waste in 2050. Advance online publication. https://doi.org/10.17863/CAM.9257

Lüers, S., Wallasch, A.-K., Jachmann, H., Clausen, E., Lustig, J., Blew, J., Sailer, F., & Wegner, N. (2023). *Vorbereitung und Begleitung bei der Erstellung eines Erfahrungsberichtes gemäß § 97 Erneuerbare-Energien-Gesetz (EEG 2017) zum spartenspezifischen Vorhaben Windenergie an Land: Wissenschaftlicher Endbericht* (SP23011A0). Bundesministerium für Wirtschaft und Klimaschutz (BMWK). https://www.bmwk.de/Redaktion/DE/Downloads/E/eg-eb-wal-03map393-endbericht.pdf?__blob=publicationFile&v=2

Manwell, J. F., McGowan, J. G., & Rogers, A. L. (2009). *Wind energy explained: Theory, design and application* (2nd). John Wiley & Sons

Martinez-Marquez, D., Florin, N., Hall, W., Majewski, P., Wang, H., & Stewart, R. A. (2022). State-of-the-art review of product stewardship strategies for large composite wind turbine blades. *Resources, Conservation & Recycling Advances*, *15*(17), 200109. https://doi.org/10.1016/j.rcradv.2022.200109

Martín-Martín, A., Orduna-Malea, E., Thelwall, M., & López-Cózar, E. D. (2018). Google Scholar, Web of Science, and Scopus. A systematic comparison of citations in 252 subject categories. *Journal of Informetrics*, *12*(4), 1160–1177

Mathur, N., Last, N., & Morris, K. C. (2023). A process model representation of the end-of-life phase of a product in a circular economy to identify standards needs. *Frontiers in Manufacturing Technology*, *3*, Article 988073. https://doi.org/10.3389/fmtec.2023.988073

Mayring, P. (2010). Qualitative Inhaltsanalyse. In G. Mey & K. Mruck (Eds.), *Handbuch Qualitative Forschung in der Psychologie* (pp. 601–613). VS Verlag für Sozialwissenschaften. https://doi.org/10.1007/978-3-531-92052-8_42

Mayring, P. (2014). *Qualitative content analysis: Theoretical foundation, basic procedures and software solution.* http://nbn-resolving.de/urn:nbn:de:0168-ssoar-395173

Mayring, P. (2022). *Qualitative Inhaltsanalyse: Grundlagen und Techniken* (13.th ed.). Beltz Verlagsgruppe.

Megahed, A., & Goetschalckx, M. (2018). Tactical supply chain planning under uncertainty with an application in the wind turbines industry. *Computers & Operations Research*, *100*, 287–300. https://doi.org/10.1016/j.cor.2017.12.015

Mendoza, J. M. F., Gallego-Schmid, A., Velenturf, A. P., Jensen, P. D., & Ibarra, D. (2022). Circular economy business models and technology management strategies in the wind industry: Sustainability potential, industrial challenges and opportunities. *Renewable and Sustainable Energy Reviews*, *163*, 112523. https://doi.org/10.1016/j.rser.2022.112523

Mignacca, B., Locatelli, G., & Velenturf, A. (2020). Modularisation as enabler of circular economy in energy infrastructure. *Energy Policy*, *139*, 111371. https://doi.org/10.1016/j.enpol.2020.111371

Mishnaevsky, L. (2021). Sustainable End-of-Life Management of Wind Turbine Blades: Overview of Current and Coming Solutions. *Materials (Basel, Switzerland)*, *14*(5). https://doi.org/10.3390/ma14051124

Mishnaevsky, L., Branner, K., Petersen, H. N., Beauson, J., McGugan, M., & Sørensen, B. F. (2017). Materials for Wind Turbine Blades: An Overview. *Materials (Basel, Switzerland)*, *10*(11). https://doi.org/10.3390/ma10111285

Mølholt Jensen, F., & Branner, K. (2013). Introduction to wind turbine blade design. In *Advances in Wind Turbine Blade Design and Materials* (pp. 3–28). Elsevier. https://doi.org/10.1533/9780857097286.1.3

Montag, L., Klünder, T., & Steven, M. (2021). Paving the Way for Circular Supply Chains: Conceptualization of a Circular Supply Chain Maturity Framework. *Frontiers in Sustainability*, *2*, Article 781978. https://doi.org/10.3389/frsus.2021.781978

Nagle, A. J., Delaney, E. L., Bank, L. C., & Leahy, P. G. (2020). A Comparative Life Cycle Assessment between landfilling and Co-Processing of waste from decommissioned Irish wind turbine blades. *Journal of Cleaner Production*, *277*, 123321. https://doi.org/10.1016/j.jclepro.2020.123321

Nagle, A. J., Mullally, G., Leahy, P. G., & Dunphy, N. P. (2022). Life cycle assessment of the use of decommissioned wind blades in second life applications. *Journal of Environmental Management*, *302*(Pt A), 113994. https://doi.org/10.1016/j.jenvman.2021.113994

Nair, A., & Reed-Tsochas, F. (2019). Revisiting the complex adaptive systems paradigm: Leading perspectives for researching operations and supply chain management issues. *Journal of Operations Management*, *65*(2), 80–92. https://doi.org/10.1002/joom.1022

Năstase, E.-V. (2017). Influence of the material used to build the blades of a wind turbine on their starting conditions. *MATEC Web of Conferences*, *112*, 1–6. https://doi.org/10.1051/matecconf/201711210017

Netztransparenz. (2023). *Marktwertübersicht [Market value overview], Netztransparenz.de*. www.netztransparenz.de/EEG/Marktpraemie/Marktwerte

Nilsson, F., & Gammelgaard, B. (2012). Moving beyond the systems approach in SCM and logistics research. *International Journal of Physical Distribution & Logistics Management*, *42*(8/9), 764–783. https://doi.org/10.1108/09600031211269749

Nilsson, F. R. (2019). A complexity perspective on logistics management. *The International Journal of Logistics Management*, *30*(3), 681–698. https://doi.org/10.1108/IJLM-06-2019-0168

Ortegon, K., Nies, L. F., & Sutherland, J. W. (2012). Remanufacturing: An Alternative for End of Use of Wind Turbines. In D. A. Dornfeld & B. S. Linke (Eds.), *Leveraging Technology for a Sustainable World* (pp. 155–160). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-29069-5_27

Ortegon, K., Nies, L. F., & Sutherland, J. W. (2013). Preparing for end of service life of wind turbines. *Journal of Cleaner Production*, *39*(7), 191–199. https://doi.org/10.1016/j.jclepro.2012.08.022

Ortegon, K., Nies, L. F., & Sutherland, J. W. (2014). The Impact of Maintenance and Technology Change on Remanufacturing as a Recovery Alternative for Used

Wind Turbines. *Procedia CIRP*, *15*, 182–188. https://doi.org/10.1016/j.procir.2014.06.042

Paul, M., & Smyers, M. (2010). Wind energy packaging design and reverse logistics management. In *European Wind Energy Conference & Exhibition 2010: EWEC 2010: Warsaw, Poland, 20-23 April 2010* (Vol. 4, pp. 2972–2982). European Wind Energy Association; Curran Associates Inc.

Pehlken, A., Albers, H., & Germer, F. (2017). Rotorblätter aus Windkraftanlagen - Herausforderungen für das Recycling. In K. J. Thomé-Kozmiensky, S. Thiel, E. Thomé-Kozmiensky, & D. Goldmann (Eds.), *Recycling und Rohstoffe* (Vol. 10, pp. 247–260). TK-Verlag Karl Thomé-Kozmiensky

Piel, J. H., Stetter, C., Heumann, M., Westbomke, M., & Breitner, M. H. (2019). Lifetime Extension, Repowering or Decommissioning? Decision Support for Operators of Ageing Wind Turbines. *Journal of Physics: Conference Series*, *1222*(1), 12033. https://doi.org/10.1088/1742-6596/1222/1/012033

Potočnik, J., & Teixeira, I. (2023). *Enabling the energy transition: Mitigating growth in material and energy needs, and building a sustainable mining sector*. An Opinion Piece of the International Resource Panel Co-Chairs. https://www.resourcepanel.org/reports/enabling-energy-transition

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *Circular Economy: Measuring innovation in product chains.* PBL Netherlands Environmental Assessment Agency

Poulsen, T., & Lema, R. (2017). Is the supply chain ready for the green transformation? The case of offshore wind logistics. *Renewable and Sustainable Energy Reviews*, *73*, 758–771. https://doi.org/10.1016/j.rser.2017.01.181

Quentin, J., & Sudhaus, D. (2016). *Status des Windenergieausbaus und Repowering in Schleswig-Holstein*. https://www.fachagentur-windenergie.de/fileadmin/files/Veroeffentlichungen/FA-Wind_RepoweringSituation_SH_02-2016.pdf

Rathore, N., & Panwar, N. L. (2023). Environmental impact and waste recycling technologies for modern wind turbines: An overview. *Waste Management & Research: The Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, *41*(4), 744–759. https://doi.org/10.1177/0734242X221135527

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

Reinhardt, R., Christodoulou, I., Gassó-Domingo, S., & Amante García, B. (2019). Towards sustainable business models for electric vehicle battery second use: A critical review. *Journal of Environmental Management*, *245*, 432–446. https://doi.org/10.1016/j.jenvman.2019.05.095

RenerCycle. (2023, December 11). *RenerCycle and ACCIONA join forces to build a pioneering blade recycling plant in Navarra* [Press release]. https://renercycle.com/en/renercycle-and-acciona-join-forces-to-build-a-pioneering-blade-recycling-plant-in-navarra/

Rentizelas, A., Trivyza, N., Oswald, S., & Siegl, S. (2022). Reverse supply network design for circular economy pathways of wind turbine blades in Europe. *International Journal of Production Research*, *60*(6), 1795–1814. https://doi.org/10.1080/00207543.2020.1870016

Ribrant, J., & Bertling, L. M. (2007). Survey of Failures in Wind Power Systems With Focus on Swedish Wind Power Plants During 1997–2005. *IEEE Transactions on Energy Conversion*, *22*(1), 167–173. https://doi.org/10.1109/TEC.2006.889614

Ricard, L. M. (2023). *Kortlægning af mængder og behandlingsmuligheder for vindmøllevinger: Initiativ 115*. *Miljøprojekt: nr. 2241*. Miljøstyrelsen. https://www2.mst.dk/Udgiv/publikationer/2023/04/978-87-7038-511-4.pdf

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., Bloh, W. von, Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., . . . Rockström, J. (2023). Earth beyond six of nine planetary boundaries. *Science Advances*, *9*(37), eadh2458. https://doi.org/10.1126/sciadv.adh2458

Roser, M. (2020). *Why did renewables become so cheap so fast?* https://ourworldindata.org/cheap-renewables-growth

Rystad Energy. (2023, April 14). *The State of the European Wind Energy Supply Chain: A «what-would-it-take» analysis of the European supply chain's ability to support ambitious capacity targets towards 2030*

Sahu, A., Agrawal, S., & Kumar, G. (2021). Integrating Industry 4.0 and circular economy: a review. *Journal of Enterprise Information Management.* Advance online publication. https://doi.org/10.1108/JEIM-11-2020-0465

Saunders, M. N. K., Lewis, P., & Thornhill, A. (2019). *Research methods for business students* (Eighth edition). Pearson Education Limited. https://elibrary.pearson.de/book/view/99.150005/9781292208794?

Schaffarczyk, A. P. (Ed.). (2023). *Wind Power Technology: An Introduction* (2nd ed. 2023). Springer International Publishing

Schmid, M., Gonzalez Ramon, N., Dierckx, A., & Wegman, T. (2020). *Accelerating wind turbine blade circularity*. https://windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Accelerating-wind-turbine-blade-circularity.pdf

Schmidt, M., & Nyhuis, P. (2021). *Produktionsplanung und -steuerung im Hannoveraner Lieferkettenmodell*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-63897-2

Schmitt, R. H., Bergs, T., Brecher, C., & Schuh, G. (Eds.). (2023). *Empower Green Production. Tagungsband*. 31. Aachener Werkzeugmaschinen-Kolloquium (AWK). https://doi.org/10.24406/publica-939

Schoemaker, P. J. H. (1991). When and how to use scenario planning: A heuristic approach with illustration. *Journal of Forecasting*, *10*(6), 549–564. https://doi.org/10.1002/for.3980100602

Schoemaker, P. J. H. (1993). Multiple scenario development: Its conceptual and behavioral foundation. *Strategic Management Journal*, *14*(3), 193–213. https://doi.org/10.1002/smj.4250140304

Schou, L., Høstrup, H., Lyngsø, E. E., Larsen, S., & Poulsen, I. (2012). Validation of a new assessment tool for qualitative research articles. *Journal of Advanced Nursing*, *68*(9), 2086–2094. https://doi.org/10.1111/j.1365-2648.2011.05898.x

Schröder, P., Bengtsson, M., Cohen, M., Dewick, P., Hofstetter, J., & Sarkis, J. (2019). Degrowth within – Aligning circular economy and strong sustainability narratives. *Resources, Conservation and Recycling*, *146*, 190–191. https://doi.org/10.1016/j.resconrec.2019.03.038

Schuh, G., & Schmidt, C. (2014). *Produktionsmanagement*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-54288-6

Sehnem, S., Chiappetta Jabbour, C. J., Farias Pereira, S. C., & Sousa Jabbour, A. B. L. de (2019). Improving sustainable supply chains performance through operational excellence: circular economy approach. *Resources, Conservation and Recycling*, *149*, 236–248. https://doi.org/10.1016/j.resconrec.2019.05.021

Seuring, S., Müller, M., Westhaus, M., & Morana, R. (2005). Conducting a Literature Review — The Example of Sustainability in Supply Chains. In H. Kotzab, S. Seuring, M. Müller, & G. Reiner (Eds.), *Research Methodologies in Supply Chain Management* (pp. 91–106). Physica-Verlag. https://doi.org/10.1007/3-7908-1636-1_7

Sommer, V., Stockschläder, J., & Walther, G. (2020). Estimation of glass and carbon fiber reinforced plastic waste from end-of-life rotor blades of wind power plants within the European Union. *Waste Management (New York, N.Y.)*, *115*, 83–94. https://doi.org/10.1016/j.wasman.2020.06.043

Stehly, T., Duffy, P., & Mulas Hernando, D. (2023). *2022 Cost of Wind Energy Review*. https://www.nrel.gov/docs/fy24osti/88335.pdf

Stetter, C., Wielert, H., & Breitner, M. H. (2022). Hidden repowering potential of non-repowerable onshore wind sites in Germany. *Energy Policy*, *168*(280), 113168. https://doi.org/10.1016/j.enpol.2022.113168

Straßenverkehrs-Zulassungs-Ordnung, 2012. https://www.gesetze-im-internet.de/stvzo_2012/

Straßenverkehrs-Ordnung, 2013. www.gesetze-im-internet.de/stvo_2013/StVO.pdf

Sultan, A. A. M., Mativenga, P. T., & Lou, E. (2018). Managing Supply Chain Complexity: Foresight for Wind Turbine Composite Waste. *Procedia CIRP*, *69*(8), 938–943. https://doi.org/10.1016/j.procir.2017.11.027

The Supply Chain Council. (2012). *SCOR supply chain operations reference model* (11th ed.)

The Supply Chain Council. (2017). *APICS supply chain operations reference model: SCOR* (12th ed.). APICS. www.apics.org

Surana, K., Doblinger, C., Anadon, L. D., & Hultman, N. (2020). Effects of technology complexity on the emergence and evolution of wind industry manufacturing locations along global value chains. *Nature Energy*, *5*(10), 811–821. https://doi.org/10.1038/s41560-020-00685-6

Tazi, N., Kim, J., Bouzidi, Y., Chatelet, E., & Liu, G. (2019). Waste and material flow analysis in the end-of-life wind energy system. *Resources, Conservation and Recycling*, *145*(8), 199–207. https://doi.org/10.1016/j.resconrec.2019.02.039

Tota-Maharaj, K., & McMahon, A. (2021). Resource and waste quantification scenarios for wind turbine decommissioning in the United Kingdom. *Waste Disposal & Sustainable Energy*, *3*(2), 117–144. https://doi.org/10.1007/s42768-020-00057-6

Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British Journal of Management*, *14*, 207–222

United Nations Economic Commission for Europe. (2021). *Life Cycle Assessment of Electricity Generation Options*

United Nations Environment Programme (Ed.). (2024). *Global Resources Outlook 2024: Bend the Trend – Pathways to a liveable planet as resource use spikes.* International Resource Panel. wedocs.unep.org/20.500.11822/44901

United Nations Framework Convention on Climate Change (UNFCCC) (2015). Paris Agreement

Vegter, D., van Hillegersberg, J., & Olthaar, M. (2020). Supply chains in circular business models: processes and performance objectives. *Resources, Conservation and Recycling*, *162*, 105046. https://doi.org/10.1016/j.resconrec.2020.105046

Velenturf, A. P. M. (2021). A Framework and Baseline for the Integration of a Sustainable Circular Economy in Offshore Wind. *Energies*, *14*(17), 5540. https://doi.org/10.3390/en14175540

Velenturf, A. P., & Purnell, P. (2021). Principles for a sustainable circular economy. *Sustainable Production and Consumption*, *27*, 1437–1457. https://doi.org/10.1016/j.spc.2021.02.018

Vestas (Ed.). (2023). *Life Cycle Assessment: of electricity production from an onshore V162-6.2 MW wind plant*. www.vestas.com

Vestas Wind Systems A/S. (2022, April 5). *Vestas introduces the V172-7.2 MW, enhancing performance in low to medium wind conditions* [Press release]. https://www.vestas.com/en/media/company-news/2022/vestas-introduces-the-v172-7-2-mw--enhancing-performanc-c3539648

Villadsen, I. B. V. (2023, November 30). *Makeen Enviro Tech A/S, Decomblades: Full circularity for wind turbine blades*. Wind Energy Denmark Conference, Horsens, Denmark

Volk, R., Stallkamp, C., Herbst, M., & Schultmann, F. (2021). Regional rotor blade waste quantification in Germany until 2040. *Resources, Conservation and Recycling*, *172*(12), 105667. https://doi.org/10.1016/j.resconrec.2021.105667

Wang, S., Yu, J., & Okubo, K. (2020). Estimation of End-of-Life Hybrid Vehicle number in Japan considering secondhand vehicle exportation. *Waste Management (New York, N.Y.)*, *104*, 198–206. https://doi.org/10.1016/j.wasman.2020.01.022

Werner, H. (2020). *Supply Chain Management*. Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-32429-2

Wieland, A., Handfield, R. B., & Durach, C. F. (2016). Mapping the Landscape of Future Research Themes in Supply Chain Management. *Journal of Business Logistics*, *37*(3), 205–212. https://doi.org/10.1111/jbl.12131

WindEurope. (2020). *How to build a circular economy for wind turbine blades through policy and partnerships*. https://windeurope.org/wp-content/uploads/files/policy/position-papers/WindEurope-position-paper-how-to-build-a-circular-economy.pdf

Woo, S. M., & Whale, J. (2022). A mini-review of end-of-life management of wind turbines: Current practices and closing the circular economy gap. *Waste Management & Research: The Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, *40*(12), 1730–1744. https://doi.org/10.1177/0734242X221105434

Yadav, G., Mangla, S. K., Bhattacharya, A., & Luthra, S. (2020). Exploring indicators of circular economy adoption framework through a hybrid decision support approach. *Journal of Cleaner Production*, *277*, 124186. https://doi.org/10.1016/j.jclepro.2020.124186

Ziegler, L., Gonzalez, E., Rubert, T., Smolka, U., & Melero, J. J. (2018). Lifetime extension of onshore wind turbines: A review covering Germany, Spain, Denmark, and the UK. *Renewable and Sustainable Energy Reviews*, *82*, 1261–1271. https://doi.org/10.1016/j.rser.2017.09.100

Zotz, F., Kling, M., Langner, F., Hohrath, P., Born, H., & Feil, A. (2019). *Entwicklung eines Konzepts und Maßnahmen für einen ressourcensichernden Rückbau von Windenergieanlagen: Abschlussbericht*. Umweltbundestamt. http://www.umweltbundesamt.de/publikationen

10 Appendices

Appendix A: Semi-structured expert interviews

A1. Interview guide

The final interview guide was initially published in Kramer et al. (2024) and is shown in the following.

First, I would like to thank you for your participation in this study. The length of the interview will be approximately 45-60 minutes.

Is it okay for you to record this interview?

START RECORDING

The interview will be recorded and data will be analysed. The data is intended to be scientifically published in an aggregated form and publicly available. Of course, all personal information will be anonymized. We will inform you about the final results after processing the data.
Do you agree to the recording of the interview, the storage and processing of your data and the publication of the anonymised and aggregated results?

My name is __________ and I am from the_________ university. (…).

The objective of this study is to identify which paths were chosen for the already decommissioned onshore wind turbines in Denmark and Germany. We would like to understand common practices in the waste handling process, e.g. are old wind turbines often exported to run for some further years in another country or is it more common by the decommissioning company that the wind turbine is dismantled into parts and then most materials are recycled or the energy is recovered?

Intro questions

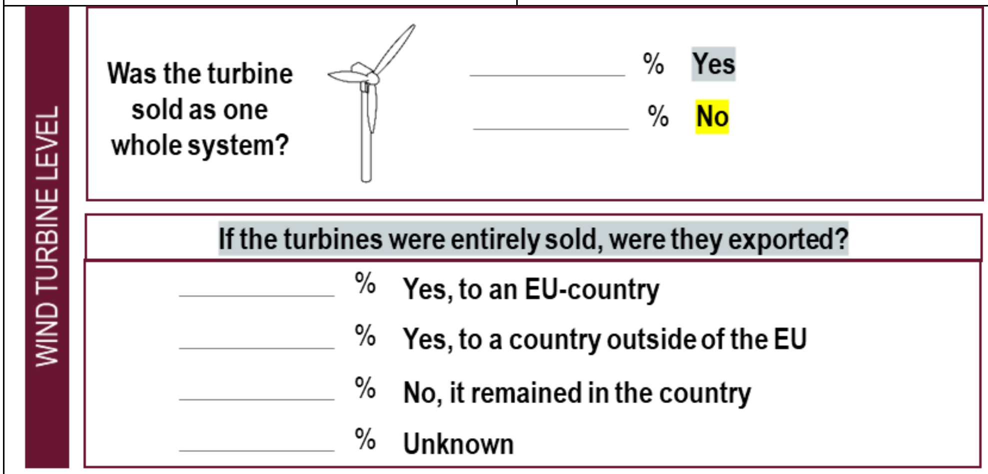
Question 1	What is your and your company's name?	
Question 2	What is your current job title?	
Question 3	In which countries does your company operate?	*Follow-up: How are the company's revenues roughly split between those countries? Stating rough percentages is suitable.*

Filter questions

Question 4	What is your personal role in decommissioning wind turbines and waste handling?	*If no direct involvement of the person: do you have access to the data of the historical decommissioning projects?* *Or should we talk to someone else at your company? If yes, to whom?*
Question 5	How many years of working experience do you have with decommissioning and the waste handling of wind turbines?	*Selection criteria: at least one completed project. If less, then end the interview.*
Question 6	How many wind turbines onshore and offshore have you decommissioned and handled the waste? All at the same company or at which companies?	

Key questions on the general waste handling process of the company

From here onwards, all questions are only referring to onshore / land-based wind turbines in Germany/Denmark. We also exclude small-scale turbines (Denmark below 25 kW/Germany below 50 kW installed capacity). The following questions refer to the company at which you are currently employed.		
Question 7	How many years has the company been active with decommissioning and the waste handling of wind turbines? Which role does the company play? E.g. do you take down the turbines using your cranes etc. – Please explain.	
Question 8	Is the company usually contracted to take care of the entire turbine or only of parts? If only parts, which? Does it differ from client to client?	
Question 9	How many onshore wind turbines has the company decommissioned and handled the waste?	*If the track record does not equal the personal track record, ask at the end of the interview for further contacts in the company.*
Question 10	How many of which turbine types have your company decommissioned?	*If they cannot remember the quantities per turbine type, ask:* • *Do you remember which turbine type was the most decommissioned?* • *Do you roughly know how many tonnes of blade mass your company has handled so far?*
Question 11	Does the company handle turbines from one or several OEMs? Which size of turbines did the company decommission the most, what was the smallest and what was the largest?	

	Which age had the decommissioned turbines typically? What was the minimum and what was the maximum age? How many were below the design life of 20 years and how many were above 20 years? In which year(s) did your company decommission turbines the most? How many and which size has your company decommissioned last year? How many turbines were decommissioned due to a breakdown/ complete failure of the turbine?	
Question 12	How does the waste handling after decommissioning a wind turbine generally work at your company? Could you please briefly describe it?	*If the person doesn't say anything about the blades, ask what waste handling practice is common.*
Question 13	Referring to the below figure, could you please estimate which paths were chosen for the already decommissioned onshore wind turbines at your company?	*Is any path missing in the figure? If yes, which one? Could you please do the split again?*
	 WIND TURBINE LEVEL **Was the turbine sold as one whole system?** ________ % **Yes** ________ % **No** **If the turbines were entirely sold, were they exported?** ________ % **Yes, to an EU-country** ________ % **Yes, to a country outside of the EU** ________ % **No, it remained in the country** ________ % **Unknown**	

KEY COMPONENT LEVEL

If not entirely sold, what happened to the following key components?

In %	Entire component kept by owner	Entire component sold	Other waste handling*	Un-known	Sum
Blades					100%
Hub					100%
Gearbox					100%
Generator					100%
Nacelle Cover					100%
Rest of Nacelle					100%
Tower					100%

* Selling of dismantled sub-components/parts, recycling, energy recovery, incineration, landfill, etc.

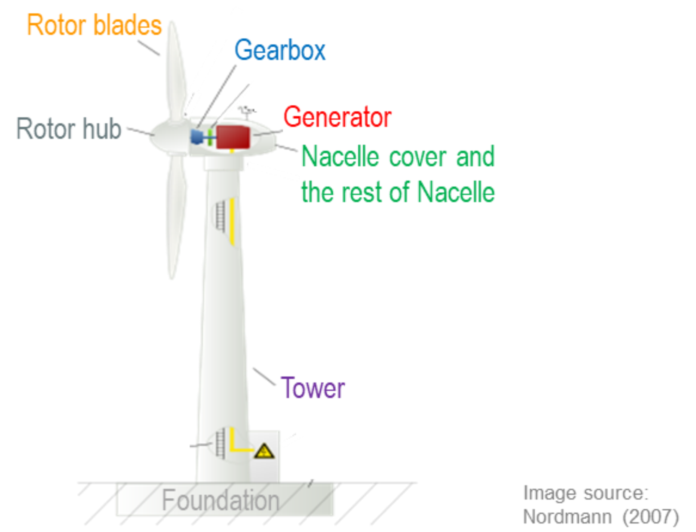


Image source: Nordmann (2007)

If entire blades were sold, were they exported?

________ % Yes, to an EU-country

________ % Yes, to a country outside of the EU

________ % No, it remained in the country

________ % Unknown

MATERIAL LEVEL

If blades were not kept by the owner or sold, what happened?

In %	Energy recovery/ incineration/ landfill	Material Recycling	Others	Sum
Blade				100%

Question 14	Could you please explain what caused these splits?	*Ask for every ratio provided. In particular, ask for blades.* *In particular ask for the split between kept & sold blade vs. waste → depending on the given answer: what would increase the reuse of a blade OR why are already so many turbines sold/kept?* *In case no reasons are provided. Ask again for an explanation and the most important factors influencing decision-making (e.g. economic, technical, ecological, regulatory factors or others)*
Question 15	Does the threshold of the design lifetime, thus the age of 20 years, have an influence on the choice of the decommissioning path? At which age does it become difficult to sell an entire turbine or an entire blade?	*Please explain.* *How does the split from question 13 change when looking at turbines below the age of 20 years? And how for turbines above the age of 20 years?*

Key questions on the company's business model

Question 16	Are the company or related companies involved in other activities along the end-of-lifecycle or end-of-life supply chain of wind turbines?	*e.g. operating a secondary market or recycling facility*
Question 17	Does the client sell the turbine/parts to you OR does the ownership stay with the client? Please explain how it usually works.	*If the ownership remains with the client, are you receiving a fixed fee or are the realised revenues split between you and the client?* *Does this vary from client to client?*
Question 18	Were the waste handling pathways specified by the client?	*Does this vary from client to client?*
Question 19	Did you report back on the taken paths to the client?	*Does this vary from client to client?*

Key questions on the outlook

Question 20	Referring to the figure of question 13, which development do you expect in the next 10 years in Germany and or Denmark?	*Please explain.*
Question 21	*In case the answer to question 6 was that the person handled decommissioning projects also for other companies:*	

	Do you mind if we quickly have a look at your given answers and check if they would look different for the company you were previously employed by?	
Question 22	Is there anything else you would like to say?	
Question 23	Do you mind sharing which projects your company has decommissioned so far? As mentioned at the beginning of the interview, this would be treated confidentially. If we could identify your projects and the ones from the other interviewees, we would be able to draw conclusions about the market. The drawn overall market insights will be provided to you. If yes, could I perhaps leave a list of projects/turbines and ask you to mark the ones your company has decommissioned?	*Do I have the e-mail address? If not ask for it.*
Question 24	Is there anyone else we should speak to?	*e.g. in your company, operator or other decommissioning company?* *If yes, could you please provide contact details or introduce us?*
Thank you so much for participating in this study and answering my questions. If it is fine with you, I will stop the recording now.		
STOP RECORDING		

A2. Overview of conducted interviews

Table 38. Overview of conducted interviews (I1-I18), partially based on Kramer et al. (2024).

Expert	Position of expert	Stakeholder group	Interview duration	Market share DNK	Market share GER
I1	Senior Manager	Recycling & dismantling	60 minutes	~19-22 %	-
I2	Executive	Decommissioning wind turbines	120 minutes	~25 %	-
I3	Executive	Project developer & operator or service company	60 minutes	< 1 %	-
I4	Executive	Decommissioning wind turbines	100 minutes	~16 %	~11 %
I5	Senior Manager	OEM	50 minutes	~ 2 %	-
I6	Executive	Decommissioning wind turbines	20 minutes	~ 3 %	-
I7	Executive	Project developer & operator or service company	75 minutes	~2-3 %	-
I8A-D	Senior Manager	OEM	240 minutes	< 1 %	~3 %
I9	Senior Manager	Recycling & dismantling	90 minutes	< 1 %	-
I10	Executive	Company K: Recycling & dismantling; Company J: Project developer & operator or service company	120 minutes	-	~9 %
I11	Senior Manager	Project developer & operator or service company	120 minutes	-	~3-4 %
I12	Executive	Decommissioning wind turbines	40 minutes	-	~3 %
I13	Executive	Recycling & dismantling	15 minutes	-	< 1 %
I14	Senior Manager	Decommissioning wind turbines	120 minutes + 4 hours	-	~22 %
I15	Executive	Decommissioning wind turbines	70 minutes	~1-2 %	< 1 %
I16A-C	Senior Manager	OEM	60 minutes	-	~12 %
I17	Mid-level Manager	OEM	60 minutes	-	-
I18	Executive	Project developer & operator or service company	60 minutes	-	~1 %

Appendix B: Circular supply chain processes in practice

B1. Overview of circular supply chain processes in practice

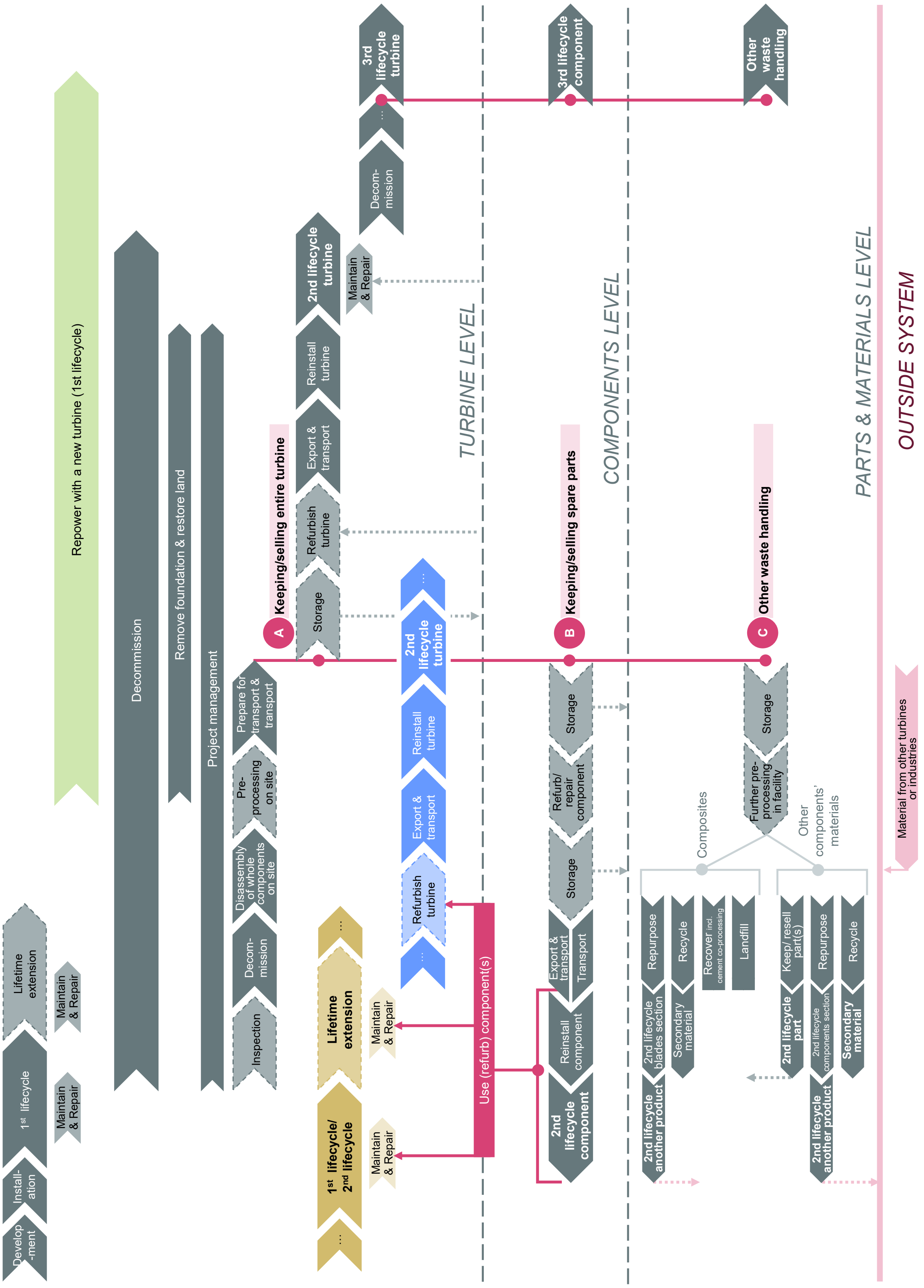


Figure 91. Overview of observed circular supply chain processes. Based on conducted interviews.

B2. Overview of key factors influencing circular economy pathways

Table 39. Overview of key factors influencing circular economy pathways. Based on conducted interviews.

	End of 1st lifecycle	**Decommission at site**	**Handling of decommissioned turbine and blades**	**Buyer for second-lifecycle turbine**	**Buyer for second-lifecycle blades**
Technical	▪ Turbine design ▪ Turbine condition ▪ Wind conditions at project site ▪ Availability of spare parts	▪ Turbine design ▪ Turbine condition ▪ Wind conditions at project site	▪ Turbine design ▪ Turbine condition & expected remaining lifetime	▪ Turbine design ▪ Turbine condition & expected remaining lifetime ▪ Expected maintenance plan ▪ Wind conditions at new project site ▪ Availability of spare parts	▪ Blade design ▪ Blade condition & expected remaining lifetime ▪ Blade compatibility to wind turbine types
Legal/ regulatory	▪ Compensation ▪ Land lease ▪ Requirements for repowering ▪ Requirements for lifetime extension	▪ Requirements of public authorities ▪ Monitoring of authorities ▪ Standardisation across authorities	▪ Transport requirements ▪ Export requirements ▪ Waste handling regulation and classification ▪ Product guarantee & warranty	▪ Import requirements ▪ Available grid connection at site ▪ Grid code of country ▪ Requirements for certification beyond design lifetime ▪ Permitting requirements (e.g. minimum distances to households, height restrictions, environmental standards)	*No factor mentioned.*
Economic	▪ Economic feasibility to continue operation ▪ Economic feasibility to repower	▪ Decommissioning costs ▪ Disassembly costs ▪ Pre-processing costs	▪ Purchase price ▪ Transportation costs ▪ Storage costs ▪ Costs for refurbishment, repair or upgrading ▪ Sales price ▪ Economics of alternative handling options	Economic feasibility of project: ▪ Initial investment ▪ Expected income ▪ Expected operational costs ▪ Expected decommissioning costs Economics of alternative turbines	▪ Economic feasibility
Organisational	▪ Operator's business strategy	▪ Choices of operator on scope & responsible company ▪ Business model & strategy of responsible company ▪ Time window for decision-making and execution ▪ Access to lifting data & gear ▪ Skills & standards of responsible company ▪ Chosen handling pathway	▪ Business model & strategy of responsible company ▪ Time window for decision-making and execution ▪ Access to operational & design data ▪ Skills & standards of responsible company ▪ Access to potential buyers on second-hand market	▪ Skills of responsible company ▪ Type of buyer	▪ Spare parts management and current stock levels
Market	▪ Number of operating turbines per turbine type ▪ Ownership structure ▪ Size of wind farm	▪ Industry standards	▪ Safety situation of countries ▪ Industry standards ▪ Supply and demand situation at time window of sale	▪ Crane infrastructure in country ▪ Available land in country ▪ Safety situation in country ▪ Experience with second-hand turbines ▪ Energy system & long-term planning ▪ Economic status of country ▪ Grid voltage	▪ Total installed wind turbines with blade type

Appendix C: Further information on market data

C1. Overview of data attributes from the Danish market register

Table 40. Overview of data attributes from the Danish market register of the dataset on onshore wind turbines above 25 kW installed capacity (DEA, 2022). As of 31/01/2022.

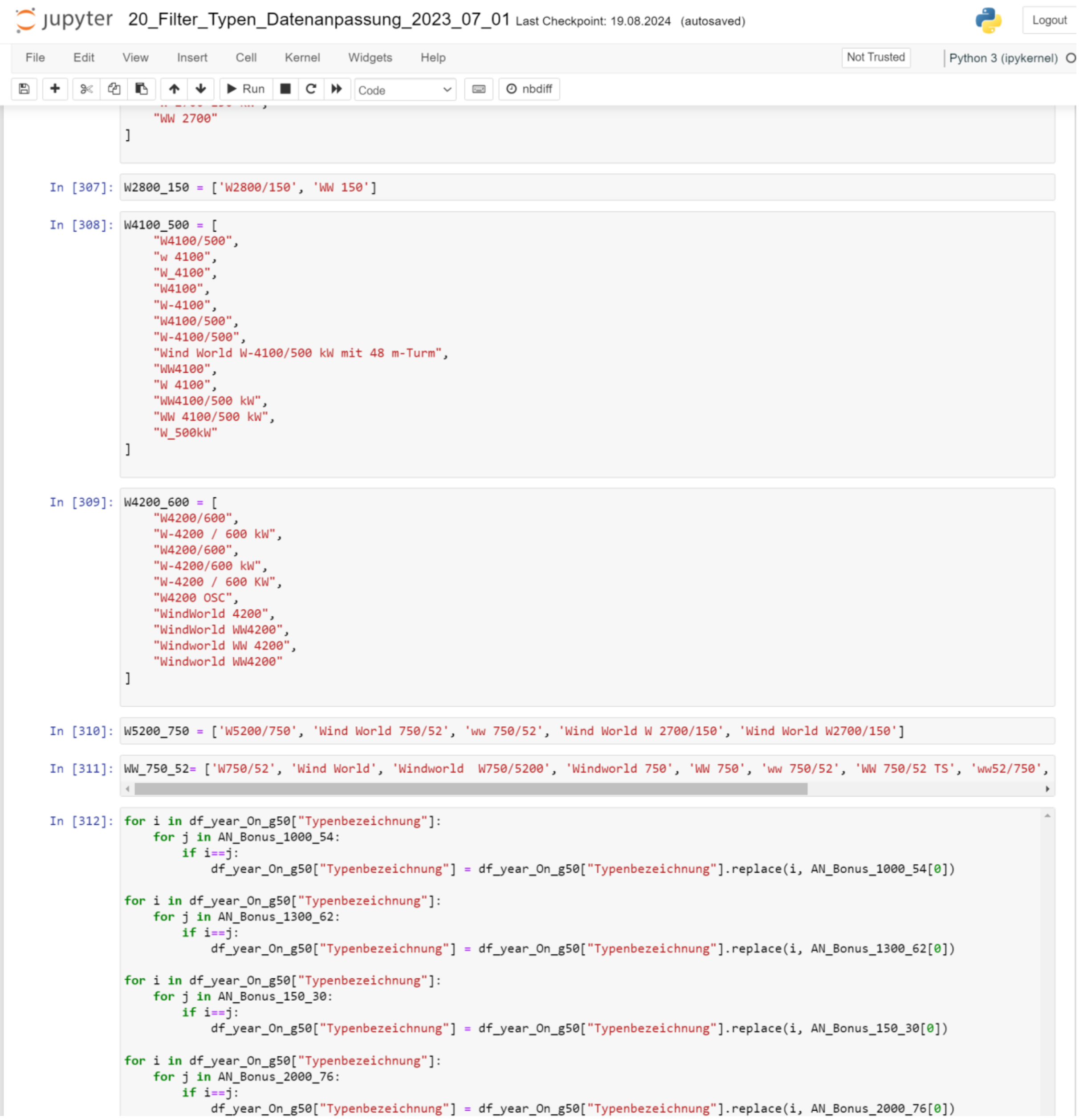
	Operational onshore wind turbines		**Decommissioned onshore wind turbines**	
Attribute	Number of data values	Share of missing values [%]	Number of data values	Share of missing values [%]
Turbine identifier (GSRN)	4186	0 %	3195	0 %
Date of original connection to grid	4186	0 %	3195	0 %
Date of decommissioning	-	-	3195	0 %
Capacity (kW)	4186	0 %	3195	0 %
Rotor diameter (m)	4186	0 %	3195	0 %
Hub height (m)	4186	0 %	3195	0 %
Manufacture	3859	7.81 %	2470	22.60 %
Model/Type designation	3859	7.81 %	2473	22.60 %
Local authority no	4186	0 %	3195	0 %
Local authority name	4186	0 %	3155	1.25 %
Type of location	4186	0 %	3195	0 %
Cadastral district	4179	0.17 %	3078	3.66 %
Cadastral no.	4186	0 %	3195	0 %
X (east) coordinate UTM 32 Euref89	4186	0 %	3195	0 %
Y (north) coordinate UTM 32 Euref89	4186	0 %	3195	0 %
Origin of coordinates	4186	0 %	3148	1.47 %
Distribution company installation number	4095	2.17 %	3182	0.41%

C2. Overview of data attributes from the German market register

Table 41. Overview of data attributes from the German market register of the dataset on onshore wind turbines above 50 kW installed capacity (Bundesnetzagentur, 2023). As of 30/06/2023.

	Operational onshore wind turbines		Decommissioned onshore wind turbines	
Attribute (English translation)	Number of data values	Share of missing values [%]	Number of data values	Share of missing values [%]
UnitMastrNumber	28610	0 %	1029	0 %
LocationMaStRNumber	28610	0 %	207	79.88 %
SystemoperatorMastrNumber	28610	0 %	209	79.69 %
Country	28610	0 %	1029	0 %
Federal_state	28610	0 %	1029	0 %
County	28610	0 %	1029	0 %
Municipality	28610	0 %	1029	0 %
Municipal_key	28610	0 %	1029	0 %
Postcode	28610	0 %	1029	0 %
Area	24155	15.57 %	838	18.56 %
Town	28610	0 %	1029	0 %
Longitude	28610	0 %	1029	0 %
Latitude	28610	0 %	1029	0 %
Registration_date	28610	0 %	1029	0 %
Commissioning_date	28610	0 %	1029	0 %
UnitSystem_status	28610	0 %	1029	0 %
UnitOperating_status	28610	0 %	1029	0 %
NamePower_generation_unit	28610	0 %	1029	0 %
Nominal_net_power	28610	0 %	1029	0 %
Feed-in_type	28181	1.50 %	1012	1.65 %
GenMastrNumber	21474	24.94 %	598	41.89 %
NameWindfarm	28008	2.10 %	1013	1.55 %
Location	28610	0 %	1029	0 %
Manufacturer	28406	0.71 %	1014	1.46 %
Technology	28610	0 %	1029	0 %
Turbine Type	28392	0.76 %	1024	0.49 %
Hub_height	28055	1.94%	1019	0.97 %
Rotor_diameter	28272	1.18 %	1019	0.97 %
EegMaStRnumber	28610	0 %	1029	0 %
Date_of_final_decommissioning	0	100 %	1029	0 %
Citizen_energy	501	98.25 %	0	100 %
Operating_time	28610	0 %	1029	0 %

C3. Correction of data attribute ‘turbine type’



```
    "WW 2700"
]
```

```
In [307]: W2800_150 = ['W2800/150', 'WW 150']
```

```
In [308]: W4100_500 = [
              "W4100/500",
              "w 4100",
              "W_4100",
              "W4100",
              "W-4100",
              "W4100/500",
              "W-4100/500",
              "Wind World W-4100/500 kW mit 48 m-Turm",
              "WW4100",
              "W 4100",
              "WW4100/500 kW",
              "WW 4100/500 kW",
              "W_500kW"
          ]
```

```
In [309]: W4200_600 = [
              "W4200/600",
              "W-4200 / 600 kW",
              "W4200/600",
              "W-4200/600 kW",
              "W-4200 / 600 KW",
              "W4200 OSC",
              "WindWorld 4200",
              "WindWorld WW4200",
              "Windworld WW 4200",
              "Windworld WW4200"
          ]
```

```
In [310]: W5200_750 = ['W5200/750', 'Wind World 750/52', 'ww 750/52', 'Wind World W 2700/150', 'Wind World W2700/150']
```

```
In [311]: WW_750_52= ['W750/52', 'Wind World', 'Windworld  W750/5200', 'Windworld 750', 'WW 750', 'ww 750/52', 'WW 750/52 TS', 'ww52/750',
```

```
In [312]: for i in df_year_On_g50["Typenbezeichnung"]:
              for j in AN_Bonus_1000_54:
                  if i==j:
                      df_year_On_g50["Typenbezeichnung"] = df_year_On_g50["Typenbezeichnung"].replace(i, AN_Bonus_1000_54[0])

          for i in df_year_On_g50["Typenbezeichnung"]:
              for j in AN_Bonus_1300_62:
                  if i==j:
                      df_year_On_g50["Typenbezeichnung"] = df_year_On_g50["Typenbezeichnung"].replace(i, AN_Bonus_1300_62[0])

          for i in df_year_On_g50["Typenbezeichnung"]:
              for j in AN_Bonus_150_30:
                  if i==j:
                      df_year_On_g50["Typenbezeichnung"] = df_year_On_g50["Typenbezeichnung"].replace(i, AN_Bonus_150_30[0])

          for i in df_year_On_g50["Typenbezeichnung"]:
              for j in AN_Bonus_2000_76:
                  if i==j:
                      df_year_On_g50["Typenbezeichnung"] = df_year_On_g50["Typenbezeichnung"].replace(i, AN_Bonus_2000_76[0])
```

Figure 92. Excerpt from the Python script for the correction of typographical errors in the turbine type, stated in the market register.

Appendix D: Further information on annual flow estimates

D1. Adjusted funnel diagram for Denmark

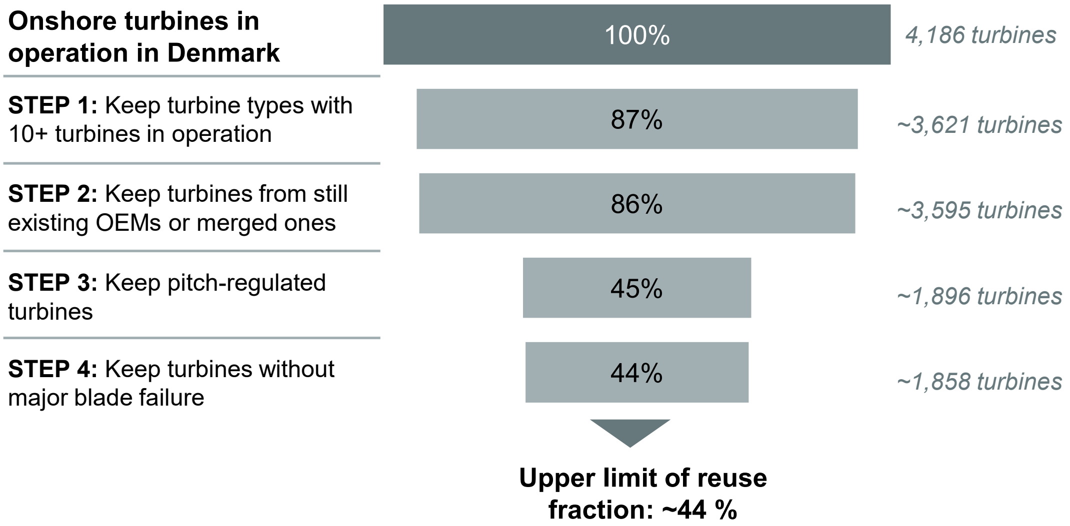


Figure 93. Funnel diagram for the upper limit of the reuse fraction of onshore wind turbines in operation in Denmark, with an adjusted first step of assuming 10 turbines per turbine type.

D2. Estimated annual second-lifecycle and recycling quantities

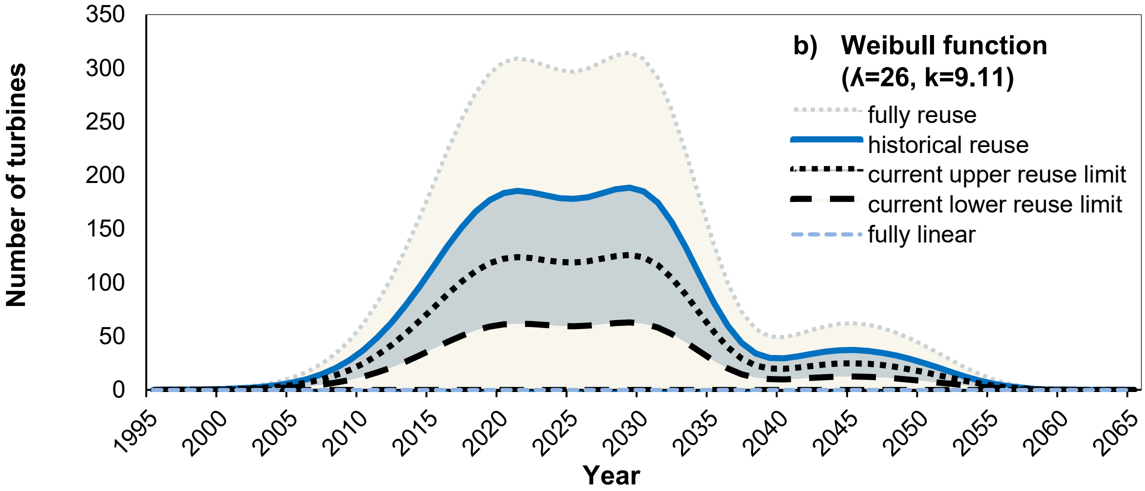


Figure 94. Expected annual second-lifecycle quantities of installed onshore wind turbines in Denmark in accordance to the adjusted Weibull function (Λ=26, k=9.11). Data based on DEA (2022).

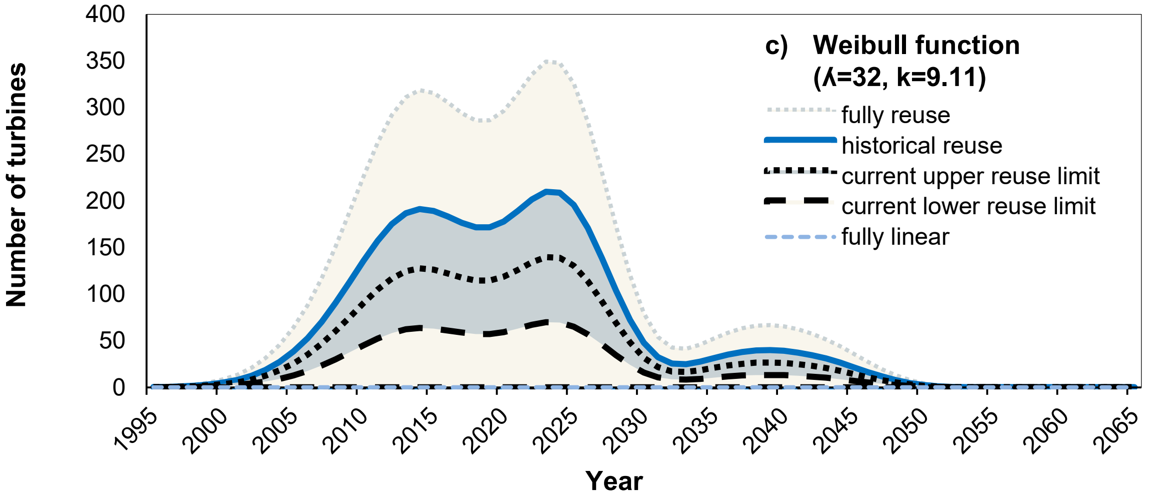


Figure 95. Expected annual second-lifecycle quantities of installed onshore wind turbines in Denmark in accordance to the adjusted Weibull function (ʎ=32, k=9.11). Data based on DEA (2022).

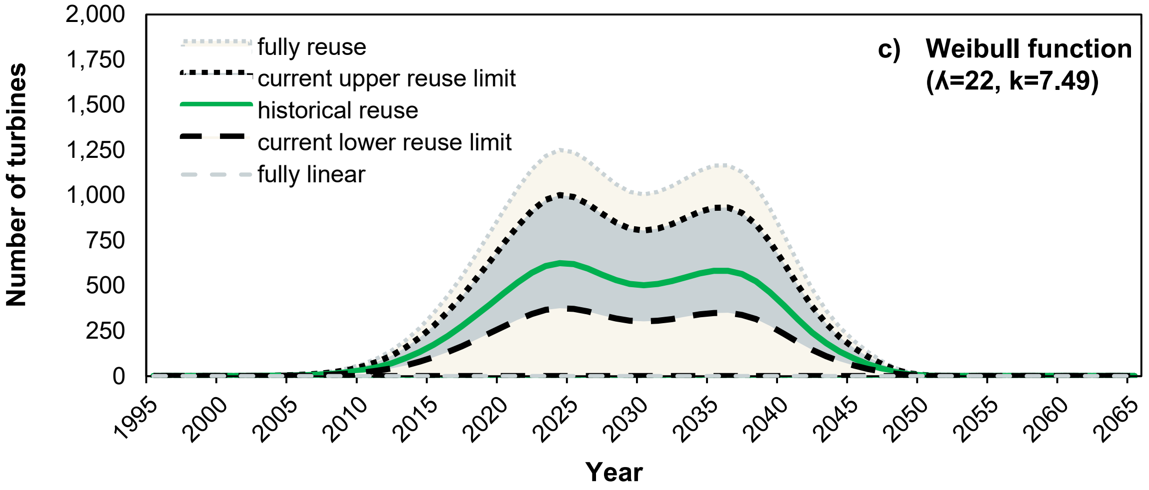


Figure 96. Expected annual second-lifecycle quantities of installed onshore wind turbines in Germany, in accordance to the adjusted Weibull function (ʎ=22). Data based on Bundesnetzagentur (2023).

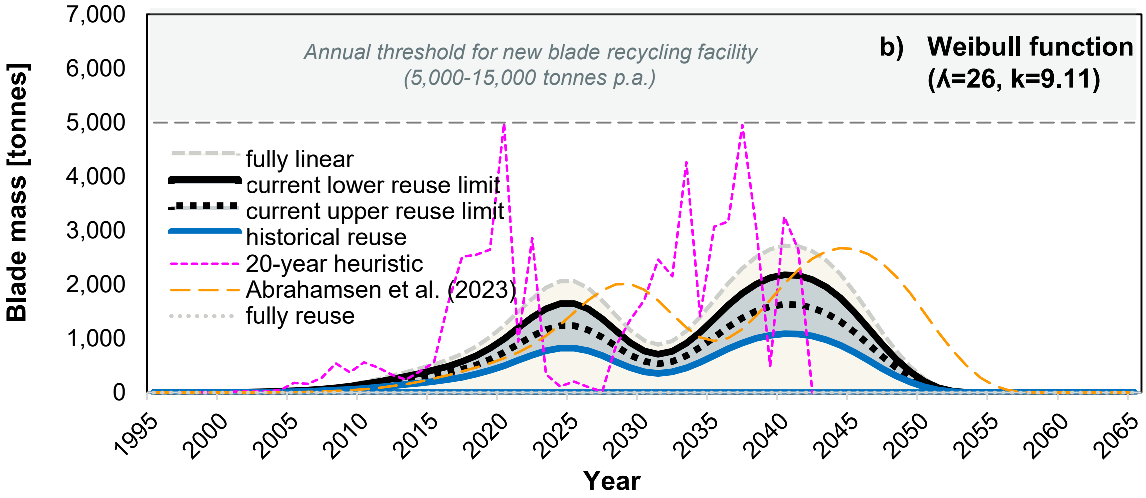


Figure 97. Expected annual recycling blade mass of installed onshore wind turbines in Denmark in accordance to the adjusted Weibull function (ʎ=26, k=9.11), in comparison to a 20-year heuristic and Abrahamsen et al. (2023). Data based on DEA (2022).

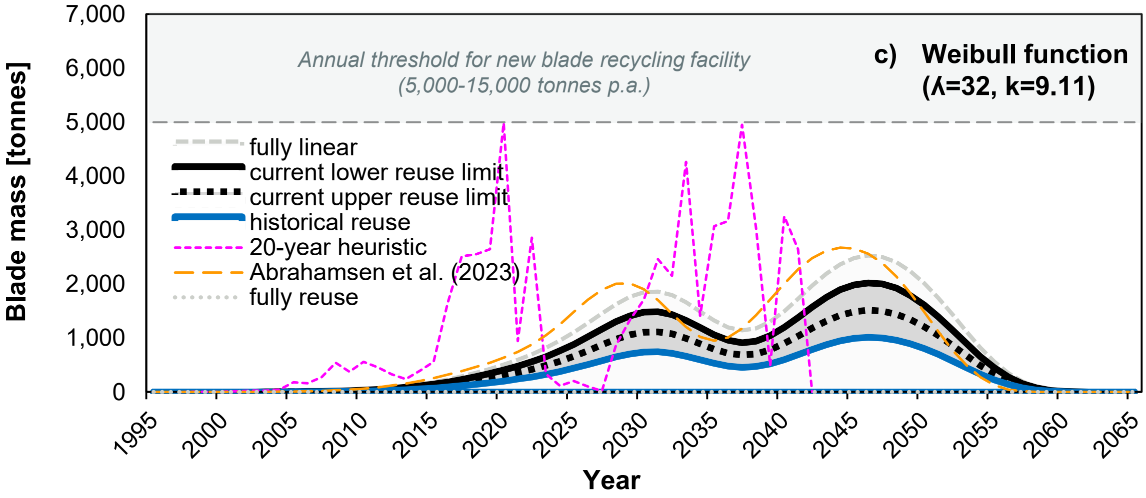


Figure 98. Expected annual recycling blade mass of installed onshore wind turbines in Denmark in accordance to the adjusted Weibull function (ʎ=32, k=9.11), in comparison to a 20-year heuristic and Abrahamsen et al. (2023). Data based on DEA (2022).

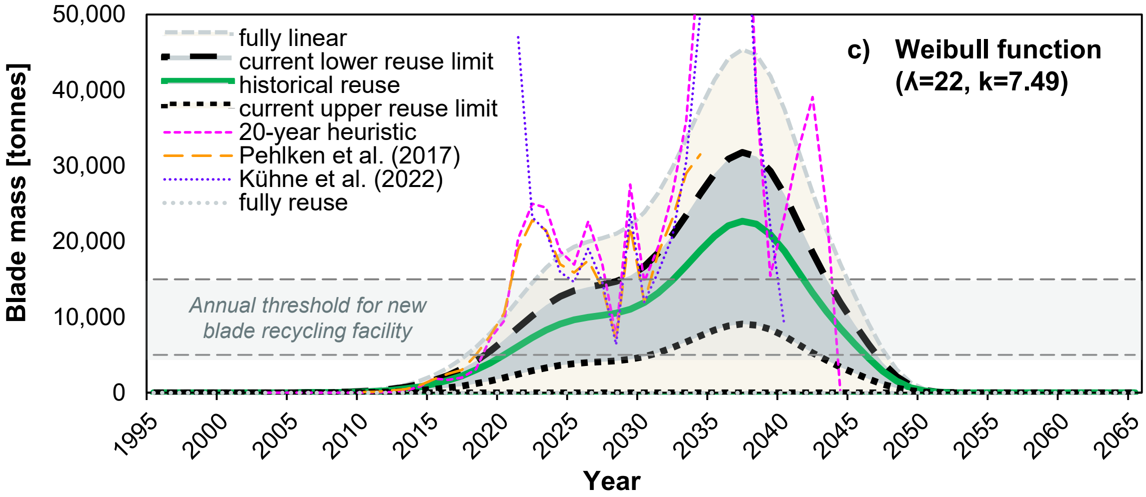


Figure 99. Expected annual recycling blade mass of installed onshore wind turbines in Germany, in accordance to the adjusted Weibull function (ʎ=22, k=7.49). In comparison to a 20-year heuristic, Kühne et al. (2022) and Pehlken et al. (2017). Data based on Bundesnetzagentur (2023).

Table 42. Sensitivity analysis of recycling share from the annual decommissioning of the installed onshore wind turbine fleet in Germany, in accordance to the fitted Weibull function (ʎ=25.83, k=7.49)

Thresholds

☐ **15,000 tonnes** ☐ **10,000 tonnes** ☐ **5,000 tonnes**

Annual blade mass of the installed German onshore fleet, Weibull function (ʎ=25.83, k=7.49)											
	share of decommissioning quantity remaining for domestic recycling										
Year	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
2024	0	1,077	2,155	3,232	4,309	5,387	6,464	7,542	8,619	9,696	10,774
2025	0	1,278	2,556	3,834	5,112	6,390	7,668	8,946	10,224	11,502	12,780
2026	0	1,476	2,952	4,428	5,904	7,381	8,857	10,333	11,809	13,285	14,761
2027	0	1,660	3,319	4,979	6,638	8,298	9,957	11,617	13,276	14,936	16,595
2028	0	1,818	3,636	5,454	7,272	9,090	10,908	12,726	14,544	16,362	18,180
2029	0	1,947	3,895	5,842	7,789	9,736	11,684	13,631	15,578	17,525	19,473
2030	0	2,053	4,105	6,158	8,210	10,263	12,315	14,368	16,421	18,473	20,526
2031	0	2,149	4,297	6,446	8,595	10,743	12,892	15,041	17,189	19,338	21,486
2032	0	2,257	4,513	6,770	9,026	11,283	13,539	15,796	18,052	20,309	22,565
2033	0	2,397	4,795	7,192	9,589	11,987	14,384	16,781	19,178	21,576	23,973

Appendix E: Access to raw data and analyses

The anonymised raw data, the anonymised transcripts of the conducted interviews, the python programme code, the MAXQDA coding and the Excel analyses of this thesis are archived digitally by the Institute of Production Technology and Systems. Access is possible after prior consultation with the Institute's management.