University of Southern Denmark

Circular economy value chains for decommisioned wind turbine blades

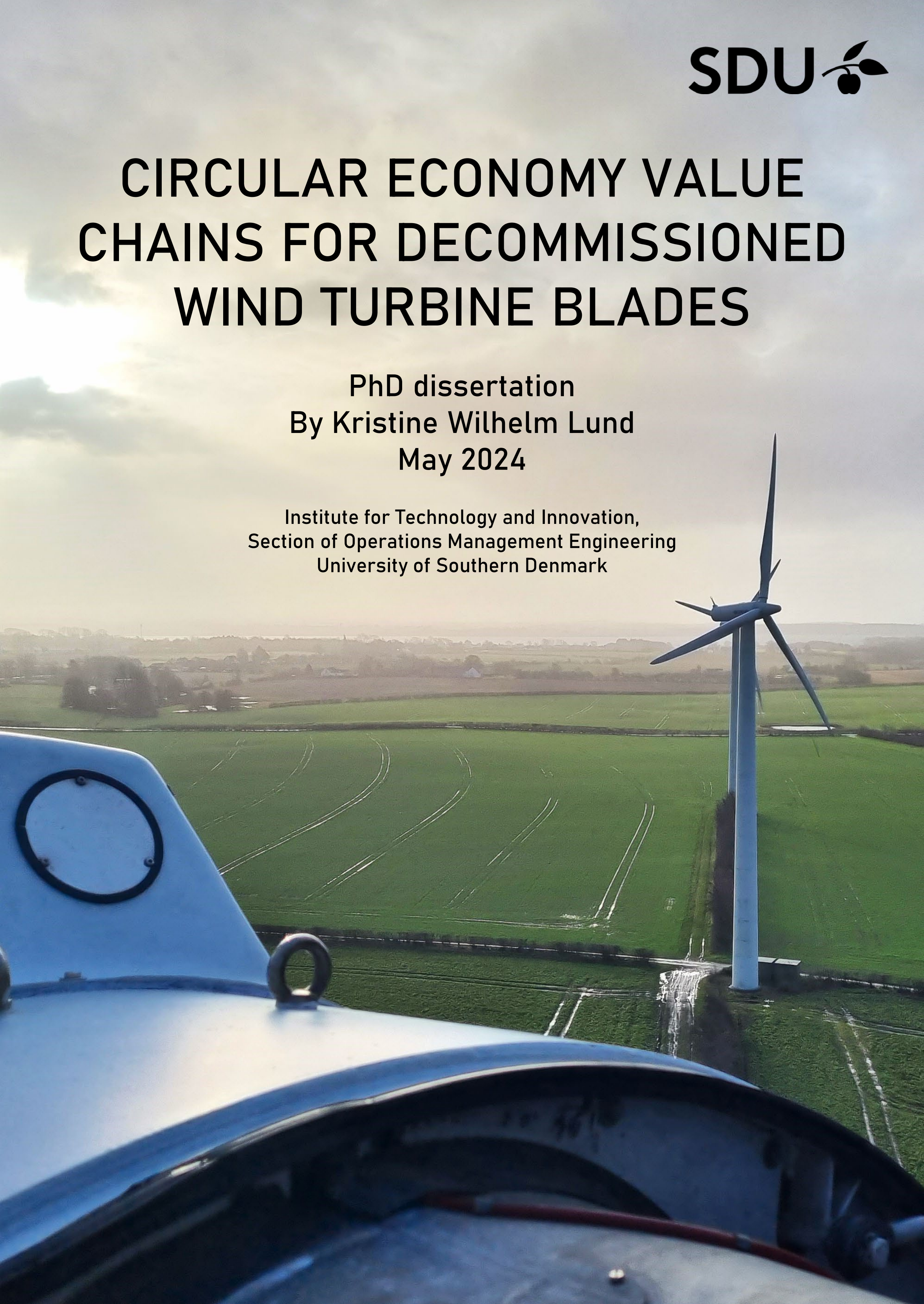
Lund, Kristine Wilhelm

DOI:
10.21996/9vb2-v060

Publication date:
2024

Document version:
Final published version

Citation for pulished version (APA):
Lund, K. W. (2024). *Circular economy value chains for decommisioned wind turbine blades*. [Ph.D. thesis, SDU]. Syddansk Universitet. Det Tekniske Fakultet. https://doi.org/10.21996/9vb2-v060



CIRCULAR ECONOMY VALUE CHAINS FOR DECOMMISSIONED WIND TURBINE BLADES

PhD dissertation
By Kristine Wilhelm Lund
May 2024

Institute for Technology and Innovation,
Section of Operations Management Engineering
University of Southern Denmark

CIRCULAR ECONOMY VALUE CHAINS FOR DECOMMISSIONED WIND TURBINE BLADES

PhD dissertation
By Kristine Wilhelm Lund
May 2024

Institute for Technology and Innovation,
Section of Operations Management Engineering
University of Southern Denmark

Dissertation submitted: 28 May 2024

PhD Supervisor: Erik Skov Madsen, PhD, Associate Professor
University of Southern Denmark

Co-supervisors: Jonas Pagh Jensen, PhD, Head of Sustainability Value Chain Engagement
Siemens Gamesa Renewable Energy A/S

Mads Bruun Larsen, PhD, Associate Professor
University of Southern Denmark

PhD Committee: Julia Pahl, PhD, Associate professor
University of Southern Denmark,
SDU Engineering Operations Management

Anna Frederiksson, PhD
Deputy Head of Department, Professor
Department of Science and Technology
Linköping University
Sweden

Paul Leahy, PhD, Lecturer
Civil, Structural and Environmental Engineering
University College Cork
Ireland

PhD series: Faculty of Engineering,
University of Southern Denmark

Institute: Technology and Innovation

Section: Engineering Operations Management

Published by:
Faculty of Engineering
University of Southern Denmark
Campusvej 55,
5230 Odense
DENMARK

Printed in Denmark by Grafisk Center, SDU, 2024

Summary

Wind turbine blades are large, complex products made from a mix of materials but consist mainly of glass fiber composite materials that are difficult to reuse or recycle in a circular economy. For these reasons, the blades reaching their end of life have been landfilled, which is unsustainable and causes a loss of resources. Thus, new systems and value chains must be designed and implemented for end-of-life wind turbine blades in accordance with circular economy principles. Yet, the operationalization of circular economy is sparingly described in academic literature.

The aim of this PhD dissertation is therefore to answer the following main research question: **How can value chains for end-of-life wind turbine blades be designed, operated, and industrialized in accordance with a circular economy?** This is supported by several objectives and four research sub-questions. The research sub-questions answered are: 1) Why do circular end-of-life value chains for wind turbine blades not exist today? 2) Which end-of-life value chain routes are potential end-to-end solutions for wind turbine blades and what technologies and processes are included in the design of these solutions? 3) How can fully functioning value chains for end-of-life wind turbine blades be operated at an industrial scale to support a circular economy? 4) How can it be evaluated which circular value chains for end-of-life wind turbine blades should be industrialized and what variables influence this decision? To provide a comprehensive answer to the posed research questions, this PhD dissertation combines seven individual research papers and is based on a mixed-methods approach.

The first sub-research question is addressed in Chapter 5 by exploring and elaborating on barriers for establishing circular value chains through a combination of the results presented in Paper I combined with additional literature review and analysis. Paper I applies a mathematical modeling using a Weibull distribution to the master data register for wind turbines in Denmark to identify the future waste masses from wind turbine blades. Its findings show how the average time for decommissioning of wind turbine generators in Denmark is 29 years, which is 9–11 years longer that previous studies have predicted. In addition, the results of

Chapter 5 include the identification of eight barriers for implementing circular value chains for end-of-life wind turbine blades that must be solved or mitigated for circular solutions for waste management of wind turbine blades to become a reality.

The second sub-research question is answered based on Paper II and a separate study of future research agendas and emerging technologies in Chapter 6. In Paper II, a systematic literature review methodology is combines with a meta-analysis of literature resulting in the development of a roadmap for sustainable value chains for wind turbine blades. The findings of Paper II were combined with a separate research study of 17 ongoing collaborative research projects on end-of-life blades to map expected technological developments. The results of the two studies were consolidated in a modified roadmap for sustainable value chains for end-of-life wind turbine blades that was discussed and validated by a group of academic and industrial experts. The roadmap includes eight interlinked process steps for the design of end-to-end value chains of six sustainable end-of-life routes for wind turbine blades. Five of the routes pertain to circular principles of repurposing and recycling and include cement-co-processing, mechanical recycling, solvolysis, pyrolysis, and structural repurposing. The sixth route of incineration with energy recovery is excluded, since it does not provide a sufficient level of material circularity.

The third sub-research question is answered based on Paper III and Paper IV in Chapter 7, in which empirical findings are presented and consolidated from four industrial case studies of wind turbine blades at their end of life that have been recycled though circular value chains. The case study research methodology was applied and based on a comprehensive research protocol including research design, preparation, data collection, data analysis, and data sharing. Data was obtained from key actors through semi-structured interviews, site-visits, photos, product information data sheets, and other relevant data, and followed by a comprehensive analysis within each case and across cases. The findings include the mapping of four end-of-life recycling value chains, all of which include more than ten metric tons of blade material being recycled through cement co-processing, pyrolysis, and mechanical recycling. Across the cases, it is found that end-of-life value chains must be designed as a complete system that include up to eight different value chain processes and multiple transportations. The findings are found to validate the roadmap developed in Chapter 6 and demonstrate that functioning recycling value chains for wind turbine blades are both technically and operationally feasible at an industrial scale. Additional, findings from Paper III are consolidated and presented in a framework for decommissioning of large complex products.

The fourth sub-research question is answered based on findings from Paper V and Paper VI in Chapter 8. In Paper V, a structured literature review approach was applied and based on the findings of a three-step framework for sustainable decision-making. The framework was developed and adopts a multi-criteria decision-making approach. The framework was successfully validated through an application and test with a Danish waste management organization to identify the preferred technology for wind turbine blade sectioning on-site. Paper IV adopted a structured literature approach followed by scenario development and a framework for future value chain assessment using life-cycle-assessment. The findings from both Papers I and VI include the development of two frameworks for sustainable assessment of processes and technologies (Paper V) and of full future value chains (Paper VI). The findings also include the identification and presentation of a complex set of variables that should be included in these assessments.

The collective results of this dissertation are collected in a cohesive model for circular value chains for end-of-life wind turbine blades which summaries all of the identified value chain processes and technologies while considering the technological readiness level and circularity level. The results do not point out one preferred value chain route but illustrate that five end-of-life routes are feasible and present appropriate solutions for wind turbine blades at end of life. Nevertheless, most of the identified processes, including (1) on-site demolition, (2) on-site operations for sectioning, (3) first pre-processing, (4) landfilling (of non-recyclable parts), and (5) second pre-processing, are almost identical across the four assessed recycling routes. Thus, it is beneficial to optimize and standardize these processes across value chains.

The findings from this dissertation lead to the conclusion that circular value chains for end-of-life wind turbine blades can be successfully achieved by (1) applying a value chain approach to system development; (2) applying the model of circular value chains for end-of-life wind turbine blades to design and implement industrial facilities; (3) assessing value chain routes using life-cycle-assessment and multi-criteria decision-making methods based on specific case variables; (4) working on standardization, optimization, and automatization of common value chain processes between end-of-life routes to reduce complexity and cost; (5) investing in research and development to improve technological readiness levels of pyrolysis and solvolysis; and (6) ensuring collaboration between value chain actors, including sharing of knowledge and material data.

The novel contributions of this dissertation include several frameworks for design, assessment, operationalization, and industrialization of end-of-life value chains for wind turbine blades and for other large, complex products. In addition, this dissertation provides a cohesive model for circular value chains for end-of-life wind turbine blades that set a new state-of-the-art for the research topic of circular economy implementation the in composite and wind energy sectors. The applied value chain perspective and use of empirical data from industrial cases provides a novel contribution to both academia and practice. The results also contribute to the literature on circular economy and its implementation through the design and development of successful value chain solutions based on collaboration between the involved stakeholders.

Resume

Vindmøllevinger er store komplekse konstruktioner, fremstillet af en blanding af materialer. De består hovedsageligt af glasfiberkompositmaterialer, som er svære at genbruge eller genanvende i en cirkulær økonomi. Derfor er vingerne indtil nu hovedsageligt blevet deponeret, når de har udtjent deres levetid, hvilket ikke er bæredygtigt og medfører tab af ressourcer. Nye systemer og værdikæder skal således designes og implementeres til udtjente vindmøllevinger i overensstemmelse med principperne for cirkulær økonomi. Samtidig er operationaliseringen af cirkulær økonomi sparsomt beskrevet i akademisk litteratur.

Formålet med denne ph.d.-afhandling er derfor at besvare forskningsspørgsmålet: **Hvordan kan værdikæder for udtjente vindmøllevinger designes, driftes og industrialiseres i overensstemmelse med en cirkulær økonomi?** Dette spørgsmål understøttes af et antal mål og fire delforskningsspørgsmål. Delforskningsspørgsmålene er: 1) Hvorfor eksisterer cirkulære værdikæder til udtjente vindmøllevinger ikke i dag? 2) Hvilke værdikæderuter er potentielle løsninger for udtjente vindmøllevinger, og hvilke teknologier og processer indgår i designet af disse løsninger? 3) Hvordan kan fuldt fungerende værdikæder for udtjente vindmøllevinger drives i industriel skala for at understøtte en cirkulær økonomi? 4) Hvordan kan det evalueres, hvilke cirkulære værdikæder for udtjente vindmøllevinger, der skal industrialiseres, og hvilke variabler påvirker denne beslutning? For at give et fyldestgørende svar på disse forskningsspørgsmål, sammenfatter denne ph.d.-afhandling resultater fra syv individuelle forskningsartikler, baseret på en kombineret metodisk tilgang

Første delforskningsspørgsmål behandles i Kapitel 5 ved at udforske og uddybe barrierer for etablering af cirkulære værdikæder gennem resultater af Artikel I kombineret med yderligere litteraturgennemgang og analyse. Artikel I anvender matematisk modellering ved hjælp af en Weibull-fordeling på data fra stamdataregisteret for vindmøller i Danmark, for at identificere fremtidige affaldsmængder fra vindmøllevinger. Resultatet viser hvordan den gennemsnitlige levetid inden nedtagelse for vindmøllevinger i Danmark er 29 år, hvilket er 9-11 år længere end tidligere undersøgelser har forudsagt. Derudover omfatter resultaterne af Kapitel 5 identifikationen af otte forskellige barrierer for implementering af

cirkulære værdikæder for udtjente vindmøllevinger, som skal løses for at cirkulære løsninger til affaldshåndtering kan blive en realitet.

Andet delforskningsspørgsmål besvares i Kapitel 6 på baggrund af resultaterne fra Artikel II samt en separat undersøgelse af fremtidige forskningsdagsordener og nye teknologier. I Artikel II kombineres en systematisk litteraturgennemgangsmetodologi med en meta-analyse af litteraturen, hvilket resulterer i udviklingen af en model for bæredygtige værdikæder for udtjente vindmøllevinger. Resultaterne af Artikel II kombineres med en separat forskningsundersøgelse af 17 igangværende samarbejdsprojekter om udtjente vinger for at kortlægge den forventede teknologiske udvikling indenfor området. Resultaterne af de to undersøgelser kombineres i en modificeret model for bæredygtige værdikæder for udtjente vindmøllevinger, som blev diskuteret og valideret af en gruppe akademiske og industrielle eksperter. Modellen inkluderer otte sammenkædede procestrin der skal inkluderes i designet af værdikæder fra start til slut for seks forskellige bæredygtige teknologier der kan anvendes til genbrug eller genanvendelse af vindmøllevinger. Fem af værdikæderne vedrører cirkulære principper for genbrug og genanvendelse og omfatter teknologierne for cementproduktion, mekanisk genanvendelse, solvolyse, pyrolyse og strukturel genbrug. Den sjette rute, materialeforbrænding til energiudnyttelse, fravælges, da den ikke giver et tilstrækkeligt niveau af materialecirkularitet.

Tredje delforskningsspørgsmål besvares i Kapitel 7 med udgangspunkt i Artikel III og Artikel IV, hvor empiriske resultater præsenteres og konsolideres fra fire industrielle casestudier af udtjente vindmøllevinger der er blevet genanvendt gennem cirkulære værdikæder. Casestudiets forskningsmetodologi er baseret på en omfattende forskningsprotokol, som inkluderer forskningsdesign, forberedelse, dataindsamling, dataanalyse og datadeling. Data er indhentet fra nøgleaktører gennem semistrukturerede interviews, site-besøg, fotos, produktdatablade og andre relevante kilder efterfulgt af en omfattende analyse inden for hver case og dernæst på tværs af cases. Resultaterne leder til kortlægningen af fire genanvendelsesværdikæder, der alle omfatter mere end ti tons vingemateriale, der genanvendes gennem cementproduktion, pyrolyse og mekanisk genanvendelse. På tværs af casene konstateres det, at genanvendelsesværdikæder skal designes som et samlet komplet system, der omfatter op til otte forskellige værdikædeprocesser og flere separate transporter. Resultaterne viser sig at validere værdikædemodellen udviklet i

Kapitel 6 og demonstrerer, at genanvendelsesværdikæder for vindmøllevinger er både teknisk og operationelt mulige i industriel skala. Yderligere leder resultaterne fra Artikel III til udviklingen af en model for nedlukning og nedtagning af store komplekse produkter.

Fjerde delforskningsspørgsmål besvares i Kapitel 8 på baggrund af resultaterne fra Artikel V og Artikel VI. I Artikel V er der som metode anvendt en struktureret litteraturgennemgang, og baseret på resultaterne er der udviklet en tretrinsmodel for bæredygtig beslutningstagning. Modellen er baseret på en metode for evaluering af mange kriterier (multi-criteria decision-making). Modellen er succesfuldt valideret igennem en implementering og test hos en dansk affaldsorganisation, for at identificere den foretrukne teknologi til sektionering af vindmøllevinger. I Artikel IV anvendes en struktureret litteraturgennemgang efterfulgt af udviklingen af en model for vurdering af fremtidige værdikæder ved hjælp af livscyklusvurdering (life cycle asessment). Resultaterne fra både Artikel V og VI omfatter udviklingen af to modeller for bæredygtig vurdering af processer og teknologier (Artikel V) og af fremtidige værdikæder (Artikel VI). Resultaterne omfatter også identifikation og præsentation af et komplekst sæt af variabler, som bør inkluderes i disse vurderinger.

De samlede resultater af denne ph.d.-afhandling er samlet i en model for cirkulære værdikæder for udtjente vindmøllevinger, som opsummerer alle de identificerede værdikædeprocesser og teknologier, mens der tages højde for teknologisk udviklingsniveau samt cirkularitetsniveau. Resultaterne peger ikke på én enkel foretrukken teknologi eller værdikædeløsning, men illustrerer, at fem forskellige ruter er mulige og præsenterer passende løsninger for udtjente vindmøllevinger. Ikke desto mindre er de fleste af de identificerede værdikædeprocesser tæt på identiske på tværs af de fire genanvendelsesværdikæder. Dette omfatter 1) nedrivning på stedet 2) vinge-sektionering 3) første forbehandling, 4) deponering (af ikke-genanvendelige dele) samt 5) anden forbehandling ved mekanik nedbrydning. Der kan således med fordel standardiseres og optimeres på disse processer på tværs af værdikæder.

Resultaterne fra denne afhandling fører til den konklusion, at cirkulære værdikæder for udtjente vindmøllevinger med succes kan opnås ved 1) at anvende en værdikædetilgang til systemudvikling, 2) at anvende modellen for cirkulære værdikæder til udtjente vindmøllevinger til at designe og implementere industrielle faciliteter, 3) en vurdering af værdikæderuter ved hjælp af beslutningstagningsmetoder baseret på livscyklusvurderinger samt evaluering af flere kriterier baseret på case relaterede variabler, 4) at arbejde med standardisering, optimering og automatisering af fælles værdikædeprocesser mellem de forskellige teknologiske løsninger og værdikæder for at reducere kompleksitet og omkostninger, 5) at investere i forskning og udvikling for at forbedre det teknologiske udviklingsniveau for pyrolyse og solvolyse, og 6) at samarbejde på tværs mellem værdikædeaktører, herunder deling af viden og materialedata.

De nye videnskabelige bidrag fra denne ph.d.-afhandling omfatter flere modeller for design, evaluering, operationalisering og industrialisering af værdikæder for udtjente vindmøllevinger og for andre store, komplekse produkter. Derudover leverer denne afhandling en sammenhængende model for cirkulære værdikæder for udtjente vindmøllevinger, som fremsætter en ny state-of-the-art inden for forskningsemnet vedrørende implementering af cirkulær økonomi i komposit- og vindenergisektorerne. Det anvendte værdikædeperspektiv og brug af empiriske data fra industrielle cases giver et nyt bidrag til både videnskaben og praksis. Resultaterne bidrager til viden om cirkulær økonomi og dens implementering gennem design og udvikling af succesfulde værdikædeløsninger baseret på samarbejde mellem de involverede aktører.

Preface

This PhD dissertation is the fruit of my three-year PhD journey to become a researcher. The dissertation is article-based and carries my academic work from June 2021 until May 2024 as part of the Engineering Operations Management section at University of Southern Denmark and the DecomBlades research project, funded by Innovation Fund Denmark grant 0177-00006B.

The work presented in this dissertation could not have been accomplished without the help, guidance, and support of a large group of people, to whom I wish to express my sincere gratitude.

First and foremost, I owe the greatest gratitude to my supervisor, Associate Professor **Erik Skov Madsen** PhD, for his tremendous help and support. You have not only supported my academic development by providing detailed feedback and meeting with me on a weekly basis, you have also lent your summer house on Langeland when I needed to get away, supported my ideas, secured finances for numerous conferences and courses, while continuously insisting that I should enjoy myself and not take on too many tasks. Your concern for my development and well-being will truly serve as an inspiration for other PhD supervisors.

I would also like to thank my two co-supervisors, **Jonas Pagh Jensen** PhD and Associate Professor **Mads Bruun Larsen,** for their guidance and support along the way. I have genuinely appreciated your advice and feedback on my work, your pragmatic approach and your guidance on academic dos and don’ts. In addition, I particularly want to thank Jonas for opening doors and referring me to your network in the wind energy sector. I do not believe that I would have come as far without it.

The work presented in this dissertation also tells a story of collaboration and the importance of working together. First and foremost, I wish to truly express my gratitude to all the **DecomBlades partners** and the people who have participated in the project group or the steering committee during the past three years. Through your commitment and collaboration, you have all contributed to the success of the research project and to the coming into being of this dissertation.

I would also like to express my gratitude to all the co-authors of the included papers. First to Postdoc. **Samaneh Fayyaz** PhD, Assistant Professor, **Benyamin Khoshnevisan** PhD and Professor, **Morten Birkved** PhD. During the entire PhD period, we have worked in close collaboration, which has resulted in several reports and in the appended Paper VI. Your expertise in green technologies and life cycle assessment have been of great importance to our work.

Next, my thanks go to researchers at the Technical University of Denmark: Development Engineer **Justine Beauson** PhD and Senior Researcher **Asger Bech Abrahamsen** PhD for your valued collaboration on Paper I and for sharing your immense knowledge on the research topic. I have truly enjoyed working with you both.

During the past three years, I have had the pleasure of working with student-assistants **Anja Bakkensen Bruun, Pietro Degasperi, Emil Engstrøm Christensen, Nusret Hasic and Mikkel Liep Nielsen**, who have all contributed immensely to the research outcomes by digging up relevant literature, assisting with reviews and other research tasks while showing a great interest and asking interesting questions. A massive thank you to all of you for your contributions. I would particularly like to thank **Nusret and Mikkel** for your collaboration and great contributions to Papers III and V, which also resulted in our joint presentations at the EurOMA conference in 2022 and 2023.

As a part of my PhD journey, I also spent three months at University of Cambridge, where Associate professor, Dr **Veronica Martinez** PhD warmly welcomed me into her research group. A special thank-you Veronica for this opportunity, which has greatly impacted my research abilities. I truly appreciate your help, support, and supervision of my academic work and for welcoming me to the research community of Cambridge as one of your own PhD students. I would also thank the **Centre for Digital Value** research group at University of Cambridge.

To all my colleagues at the SDU **Engineering Operations Management**, I have really appreciated being part of the section and thank you all for being great colleagues who have made my employment at the section a great pleasure. A particular thank-you to my **fellow PhDs,** with whom I have discussed research and shared ups and downs.

My sincerest appreciation and thankfulness go out to all my **friends and family** for your love and support, and for your enthusiasm when listening to all my research ideas and findings, even though your interest might lie elsewhere. Many of my academic reflections have been sparked by your interesting questions, and I could not have done this without the support from you all. Special thanks to my mother **Connie** and my farther **Poul Erik**. Thank you for always loving me and encouraging me to pursue things out of personal interest and joy and for cheering me on no matter where I went or what I decided to do.

Finally, my utmost gratitude goes to my partner **Sebastian**. Thank you for your love and care, for being a massive inspiration to me, for being my greatest support and for your interest in hearing and learning about my research because you know it matters to me.

Odense, May 2024

Kristine Wilhelm Lund

List of Appended Papers

Paper I – Appendix I
Abrahamsen, A. B., Beauson, J., Lund, K. W., Madsen, E.S., Philipp Rudolph, D. and Jensen, J.P. Method for estimating the future annual mass of decommissioned wind turbine blade material in Denmark. Wind Energy, 2024. 27(2): pp. 165-178. Status: Published.

Paper II – Appendix II
Lund, K.W. and Madsen, E.S., State-of-the-art value chain roadmap for sustainable end-of-life wind turbine blades. Renewable and Sustainable Energy Reviews, 2024. 192: p. 114234. Status: Published.

Paper III – Appendix III
Lund, K.W., Hasic, N., Madsen, E.S. and Martinez, V. Circular Economy Operations for Large Complex Products at End-of-life: The Wind Turbine Case, Section of Engineering Operations Management, University of Southern Denmark, 2024.
Status: Submitted to journal, not published.

Paper IV – Appendix IV
Lund, K.W., Value Chains for Recycling End of life Wind Turbine Blades: A Multiple Case Study, Section of Engineering Operations Management, University of Southern Denmark, 2024. Status: Submitted to journal, not published.

Paper V – Appendix V
Lund, K.W., M.L. Nielsen, and E.S. Madsen, Sustainability assessment of new technologies using multi-criteria decision-making: A framework and application in sectioning end-of-life wind turbine blades. Renewable and Sustainable Energy Reviews, 2023. 184: p. 113542. Status: Published.

Paper VI – Appendix VI
Fayyaz, S., Lund, K. W., Khoshnevisan, B., Madsen, E. S. and Birkved, M. Sustainable end-of-life value chain scenarios for wind turbine blades. in Journal of Physics: Conference Series. 2023. IOP Publishing. Status: Published.

Paper VII –– Appendix VII
Lund, K.W. and E.S. Madsen, The Operations Management Researcher's Role: The Observer or the Facilitator of New Sustainable Business Eco-systems, in EurOMA 2023. 2023: Leuven, Belgium. Status: Presented, not published.

Content

Part I - Introduction, Background, and Research Design

Part II - Research results

Part III - Discussion and Conclusion

List of Figures and Tables

List of Abbreviations

WTG	Wind turbine generator
WTB	Wind turbine blade
EoL	End-of-life
GFRP	Glass fiber reinforced plastics
CFRP	Carbon fiber reinforced plastics
MW	Megawatt
LCA	Life cycle assessment
TRL	Technological readiness level
MCDM	Multi-criteria decision-making
OM	Operations management
CE	Circular economy
OEM	Original equipment manufacturer
WMP	Waste management partner
3PL	Third-party logistics provider
3BL	Tripple-bottom line
PoC	Proof-of-concept
R-technologies	Technologies for material reuse, recycling, and recovery

Part I

Introduction, Background, and Research Design

01 Introduction

Creating new systems that support the green transition is more important than ever. To meet the goals of the Paris Agreement and the intentions of the latest United Nations Climate Change Conference (COP28) (United Nations, 2015a, United Nations, 2024) radical changes are needed. Thie goal of this legally binding contract between 196 countries and parties "to limit the temperature increase to 1.5°C above pre-industrial levels." (United Nations, 2015a), which signifies the urgency of the climate crisis but also the global political willingness to solve it.

The term "pre-industrial levels" is used in the Paris Agreement, which testifies to the industrial contribution to this challenge and underlines that industries and organizations play a major role in achieving the set goal. For these ambitions to manifest, we must reduce climate impact and resource depletion, and our natural resources must be protected and treated as essential elements of our natural world. Thus, resources must be circulated in a circular economy (CE) for as long as possible to maintain resource values and avoid over-production and energy consumption (MacArthur, 2013).

To achieve this change, materials should always be seen as value even when meeting their end-of-life (EoL), and systems designed for material circularity must be developed and implemented. As an engineer and a researcher, I find that we have an obligation to support this agenda and development with research and knowledge that can aid this transformation. Hence, this PhD dissertation has been conducted with the aim of identifying how to design, operate, and implement new industrial systems and their value chains for materials meeting the EoL. By studying the current challenge of EoL wind turbine blades (WTBs) in Europe, this dissertation will outline processes, technologies, and decision-making-methods for full EoL value chains. Of course, one research dissertation will not solve the problem, but the aim is to provide a piece of the puzzle by contributing to knowledge, science, and industry practices across value chains.

In this dissertation, the domain of WTBs meeting the EoL will be studied. The wind power industry is at an early stage of establishing EoL value chains, while research illustrates how waste masses of EoL

WTBs will reach 325,000 tonnes yearly by 2050 in Europe (Lichtenegger et al., 2020). WTBs are large complex products (LCPs) made from mixed materials such as wood, PVC, and metals. The main component is fiber-reinforced polymers (FRPs), which due to the nature and properties of the material present an immense challenge for material circularity (Mishnaevsky Jr et al., 2017). For this reason, WTBs have historically been landfilled or incinerated (Ribeiro et al., 2016) which is the least favorable option for waste management according to the European Commission waste hierarchy and the circular economy principles (MacArthur, 2013, European Commission, 2020b) since resources are lost and the material degradation can have a negative impact on the environment (Ramirez-Tejeda et al., 2017).

With vastly increasing waste masses and with landfilling being the only available waste management option, the importance of establishing new circular systems for WTBs is clear – a fact also recognized by the wind energy sector (Jensen and Skelton, 2018). Yet, this challenge is also an opportunity to move both research and industry forward in designing and establishing viable EoL value chains for this purpose. The challenge is cross-sectoral; hence, to achieve large-scale solutions, systems must be designed and implemented across organizations through cooperation and cannot be achieved by single organizations alone (WindEurope, 2020). To support this development where entire business eco-systems must cooperate to design new industrial systems and value chains, collaboration between research and industry is also important (Jensen and Skelton, 2018). This can aid the development of new industrial systems, ensure transparent assessments, generalizable conclusions, and result validity.

Circular technologies and potential pathways for EoL WTBs – like structural reuse, mechanical recycling, chemical recycling, thermal recycling, and cement co-processing – have been identified as viable solutions, but are not yet available at an industrial scale (Beauson et al., 2021, Sakellariou, 2018). Previous and current research have primarily evolved around the technological potential of these EoL pathways rather than the full value chains required for scaling and industrialization (Appended Paper II). Thus, there is a knowledge gap within practices for the design, operational execution, scaling and impact evaluation of the entire value chain (Beauson et al., 2021). Operations management perspectives, including (1) sectioning of blades transportation, (2) design and optimization of logistics, (3) pre-processing, and (4) considerations for natural the environment and working environment, are missing in particular. Hence, the aim of the research documented in this dissertation is to mature the value chains of these recycling technologies by designing and establishing the required value chain steps, including logistics, sectioning, pre-processing, recycling, and post-processing of EoL WTBs, and to provide the frameworks and assessment tools needed for decision-making and implementation.

Zooming out of from the challenge faced by the wind power sector, full EoL solutions are needed for all sorts of products if the CE is to be realized. From an engineering and systems perspective, there is an interesting research gap in understanding the role of operations management in this context. Thus, the scientific research motivation is to investigate the design and implementation of new systems and value chains to assist the operational implementation of a CE, particularly the principle of recycling. The objective of this research study is therefore to map the operational execution of recycling for CE implementation.

This dissertation combines the results of my three-year PhD research program at University of Southern Denmark, Engineering Operations Management. The work presented in this dissertation, has been developed and conducted in close collaboration with research colleagues and industrial partners as part of the DecomBlades research project (DecomBlades, 2023). The DecomBlades research project was established and completed to foster cross-sector collaboration with both industrial and academic partners with the aim of enabling CE value chains for decommissioned wind turbine blades. The ten project partners have provided knowledge, data, and expertise as well as access to processes, materials, and suppliers. This has resulted in a unique research environment and generated research results and implications that are considered significant and meaningful contributions both to the industry and to academia.

01.01 Objectives and Research Questions

Based on the scientific and industrial research motivation, an overarching set of research objectives were defined, leading to the main research question and four sub-research questions. The objectives of this dissertation are:

- To identify and document the current state-of-the-art for EoL technologies and value chains for WTBs.
- To provide a complete roadmap of full EoL value chains in accordance with CE principles that can be implemented and operated at an industrial scale for future WTBs reaching their EoL.
- To design and document full end-to-end value chains for EoL WTBs that have been validated by the actors in those value chains.
- To identify and evaluate best practices across value chains and recycling technologies including pre-processing and logistics operations.
- To develop frameworks and decision support tools to evaluate impact and feasibility of the potential value chains of decommissioned WTBs, including assessment of sustainability.
- To solve a well-documented problem in materials recycling of composites by creating a knowledge base for material recycling in accordance with CE principles.
- To move both research and practice forward on the implementation of circular EoL value chains that can be upscaled internationally and to set the standard for sustainable waste handling, thus contributing to the green transition globally.
- To outline the role of operations management within operational execution of CE principles, thus demonstrating new business systems for recycling and to document an approach that can be applied in other industrial contexts.

01.01.01 Research Questions

Based on the research objectives, the main research question that will be answered in this PhD dissertation is:

Main research question:
How can value chains for end-of-life wind turbine blades be designed, operated, and industrialized in accordance with a circular economy?

To support the answer to this research question, four sub-research questions are
defined to address different aspects of the main research question, each with a set of objectives:

- **Sub-RQ1: Why do circular end-of-life value chains for wind turbine blades not exist today?**
  The aim of the first sub-research question is to identify, understand and map the main barriers to creating sustainable or circular value chains for EoL WTBs. This question is important to answer in order to create a solid understanding and knowledge base for solving the problem of circular management of waste materials from WTBs. Sub-RQ1 is addressed and answered in Chapter 5 in combination with Paper I.

- **Sub-RQ2: Which end-of-life value chain routes are potential end-to-end solutions for wind turbine blades and what technologies and processes are included in the design of these solutions?**
  The aim of the second sub-research question is to identify, map and consolidate the current state-of-the-art within research of EoL management of WTBs. This is necessary to understand what literature has already concluded and consolidate knowledge into complete end-to-end value chain solutions. Thus, the objective is to map the necessary processes and technologies that must be included in the **design** of future value chains in accordance with CE principles. Thus, sub-RQ2 targets the design aspect of the main research questions and is answered by Chapter 6 in combination with Paper II.

- **Sub-RQ3: How can fully functioning value chains for end-of-life wind turbine blades be operated at an industrial scale to support a circular economy?**
  The aim of the third research question is to document, map and consolidate empirical cases of full EoL value chains for WTBs, to fully understand how such value chains are operated and what implications are present. The objective is to study multiple cases representing different circular principles. This knowledge will address an important gap in research on EoL WTBs specifically but also the research gap of operations management as an enabler of CE implementation. Sub-RQ3 addresses the **operation** aspect of the main research question and is answered by Chapter 7 in combination with Paper III and Paper IV.

- **Sub-RQ4: How can it be evaluated which circular value chains for end-of-life wind turbine blades should be industrialized and what variables influence this decision?**
  The final aim of this dissertation is to address the ongoing discussion among both practitioners and academics of which EoL value chain for WTBs is the preferred solution for future scaling and industrialization. This is a very complex question that cannot be answered without considering numerous criteria and agendas. Thus, the aim is to identify and test different assessment methods for this evaluation. Sub-RQ4 targets the **industrialization** aspect of the main research questions and is answered by Chapter 8 in combination with Paper V and Paper VI.

01.02 Delimitations

To establish the research scope, several delimitations have been determined. This is done to focus the study and address the research questions precisely. The following delimitations apply:

- This research will only address the EoL of WTBs that have already been produced and does not include the design, material science or material selection of future blades for sustainable end-of-life management. In other words, blades that are made of alternative materials, such as recyclable resins, are excluded from this research. This delimitation is in place, since such WTBs were only launched in 2021 (Siemens Gamesa Renewable Energy, 2021), and given the design life of a blade of minimum 20-25 years (International Electrotecnical Commission, 2019b, International Electrotecnical Commission, 2019a) these WTBs will not reach their EoL for decades.

- The research focus is on EoL value chains for WTBs located in Europe. This delimitation is in place since the European countries are some of the first to meet the challenges of managing EoL WTBs (Lichtenegger et al., 2020) and since they operate under common European waste legislation (European Commission, 2018).

- This dissertation is developed based on an engineering foundation with a systems focus, thus focusing on processes, technologies, and industrial value chains. This dissertation will therefore not include social-science or business perspectives and will not seek to make contributions to theories within these research fields.

- As stated, the focus of the research is on entire value chains and the processes and technologies involved. However, this research will not seek to describe, develop, or test the technical, chemical, or mechanical specifications of the recycling processes covered. Nor will the cost of establishing or operating the assessed circular value chains be addressed in this research. This is because of the varying technological readiness levels (TRL) of the researched solutions and technologies (Paulsen and Enevoldsen, 2021). Thus, several processes are not established yet, resulting in insufficient data for cost assessment.

- To scope this research, the CE principle of recycling is mainly investigated, but structural repurposing and energy recovery are also included. Yet, the principles for life-time extension including reuse, repair, refurbish or remanufacturing (Potting et al., 2017) are not included since these principles will extend the lifetime and thus postpone the material meeting its EoL. Hence, these strategies are considered very important and relevant strategies to implement before EoL but must occur prior to the principles addressed in this dissertation of repurposing, recycling, and recovering.

01.03 Dissertation Outline

This dissertation builds on six research papers that are consolidated in the four result chapters (5-8). In Chapters 5 and 6, the appended papers are combined and supported with additional literature, analysis, and discussion to address research gaps that enable a full answer to the research questions and objectives. Chapters 7 and 8 both present and consolidate the findings of two papers each and discuss the combined results to answer the research questions. In combination, a full picture is provided of the research field, fulfilling the research objectives and questions posed in this dissertation. A seventh paper is included and discussed in Chapter 9. Figure 1 explains the sequence of chapters in correspondence with the appended papers and the posed research questions. Each chapter is outlined here:

- Chapter 1 contains the introduction to the dissertation, research topic, research questions and objectives.

- Chapter 2 introduces the research context of the wind industry, wind turbine generators, wind turbine blades – including material and design.

- Chapter 3 lays out the theoretical concepts and foundations that are addressed throughout the dissertation, including CE and sustainability, operations management, and value chains.

- Chapter 4 describes the research design and explains the applied research methodology, while also reflecting on the implications of the research context on the research design.

- Chapter 5 answers the first sub-research question by exploring and elaborating on barriers to establishing circular value chains through Paper I and additional literature and analysis.

- Chapter 6 answers the second sub-research question through Paper II and a separate study of future research agendas and emerging technologies.

- Chapter 7 answers the third sub-research question by presenting and consolidating empirical findings from Paper III and IV for EoL value chains.

- Chapter 8 contains a presentation and comparison of findings from Papers V and VI to answer the fourth sub-research question of how to evaluate and compare future value chain solutions and map the variables influencing decision-making.

- Chapter 9 discusses the collective research results across the different chapters and papers and presents a cohesive framework based on the consolidated findings.

- Chapter 10 contains a full conclusion, an outline of the research limitations, and a recommendation of future research.

	Chapters	Research question	Papers
Part I	**1.** Introduction **2.** Research context **3.** Theoretical background **4.** Research design and methodology		
Part II	**5.** Circular end-of-life value chains for wind turbine blades: Why the industrial-scale solutions are absent.	**Sub RQ1:** Why do circular end-of-life value chains for wind turbine blades not exist today?	**Paper I**: Method for estimating the future annual mass of decommissioned wind turbine blade material in Denmark
	6. Development of roadmap for end-of-life wind turbine blades	**Sub RQ2:** Which EoL value chain routes are potential end-to-end solutions for wind turbine blades and what technologies and processes are included in the design of these solutions?	**Paper II:** State-of-the-art value chain roadmap for sustainable end-of-life wind turbine blades.
	7. Design and operation of fully functioning value chains for end-of-life wind turbine blades	**Sub RQ3:** How can fully functioning value chains for end-of-life wind turbine blades be operated at an industrial scale to support a circular economy?	**Paper III:** Circular economy operations for large complex products at end-of-life: The wind turbine case **Paper IV:** Value Chains for Recycling End-of-life Wind Turbine Blades: A Multiple Case Study
	8. Evaluation of circular value chains for end-of-life wind turbine blades	**Sub RQ4:** How can it be evaluated which circular value chains for end-of-life wind turbine blades should be industrialized and what variables influence this decision?	**Paper V:** Sustainability assessment of new technologies using multi criteria decision making: A framework and application in sectioning end-of-life wind turbine blades **Paper VI:** Sustainable end-of-life value chain scenarios for wind turbine blades
Part III	**9.** Discussion **10.** Conclusion and research limitations	Main RQ and sub-RQ1, 2, 3 & 4	**Paper VII:** The operations management researcher's role: The observer or facilitator of new sustainable business eco-systems?

Figure 1 - Dissertation outline

02 Research Context

With the discovery of electromagnetism by Danish physicist H.C. Ørsted, the foundation for generating electricity from wind was laid. Later, in 1891, also in Denmark, Poul la Cour merged existing wind energy technologies with electromagnetism and developed a power generator driven by wind. By 1918, 3% of electricity consumption in Denmark was covered by wind energy (Anderson, 2020). In 1956, the Danish engineer Johannes Juul continued the development and built what is considered the first modern wind turbine generator (WTG) (Anderson, 2020). Later, in 1975, the Danish institution Tvind built the world's biggest WTG at the time, which is still running today nearly 50 years later (Tygesen, 2022), and in 1978 Henrik Stiesdal developed the "Danish concept" of wind turbines, which has been the dominating concept since (Mortensen, 2024). Denmark and Germany introduced national incentives for WTG producers as the first countries in the world, resulting in early adaption of R&D and manufacturing of WTGs (Anderson, 2020). Technical developments have been made globally in the wind industry over the past decades, but the development outlined explains why Denmark has a pioneering position in wind technology.

Since then, the energy production capacity of WTGs has grown exponentially, and WTG producers have pursued the competitive strategy of continuously introducing new and more efficient WTG models to win market shares. This is demonstrated by recent model launches reaching a capacity of 15MW (Memija, 2022) and OEMs even announcing the launch of a 22MW model by 2025 (Durakovic, 2023). The capacity increase has been facilitated by efficient and continuous material and engineering innovation. This innovation has driven the development of all parts of the WTGs, but specifically the WTBs have been the key to this increase in capacity, by introducing new blade designs and innovative materials for increased mechanical properties such as stiffness and strength (Anderson, 2020).

The history and development of WTGs in Denmark is also signified by the large number of WTGs commissioned in Denmark. In 2022, electricity generation from WTGs reached 53.2% in Denmark (Energinet, 2022). However, due to the early adoption of wind energy in Denmark, an increasing number of WTGs are reaching their EoL and will need to be decommissioned. Denmark is therefore also one of the nations that must handle the challenge of WTBs first.

02.01 An Introduction to Wind Turbine Blades and Composites

A WTG consists of a foundation, tower, nacelle, and rotor. In the nacelle, electricity is generated by a generator, transformed to higher voltage, and sent into the grid via large cables. A number of sensors and control systems ensure that the WTG is operating and can be monitored and controlled remotely (Anderson, 2020). The rotor consists of the hub and three identical WTBs. The primary function of the rotor is to harvest the wind and transfer the wind power into movement which drives the induction process in the nacelle. To optimize this function, the blades are large aerodynamic structures designed for optimum wind utilization, which is key for energy efficiency (Anderson, 2020).

The length of the blades directly determines the rotor diameter and thus the area swept for wind power. In other words, the longer the blades, the more wind energy is harvested and the more energy output of the WTG. Around 1990, a typical blade had a length of 20 meters (Molina and Mercado, 2011). However, since then the length has grown rapidly with 115-meter-long WTBs being launched in 2023 (Memija, 2022). The length and geometry of the blade has increased the complexity and cost of logistics and operations (Veers et al., 2003), which also applies at the EoL.

A wind turbine typically has a design life of 20 years for onshore and 25 years for offshore (International Electrotecnical Commission, 2019a, International Electrotecnical Commission, 2019b) and must through its entire lifetime withstand years of extreme weather conditions (Bortolotti et al., 2016). At the same time, the blades must be light weight and stiff for efficient energy production. Therefore, WTBs are made from FRP including glass fibers (GFRP) and carbon fibers (CFRP), which ensures both performance and reliability (Mishnaevsky Jr et al., 2017). These materials are also commonly found in other industries including automotive, leisure boats, construction and aerospace (WindEurope et al., 2020).

Figure 2 depicts the design and materials of a WTB and illustrates how WTBs are made from a combination of materials but consist primarily of

GFRP. They also include other materials such as wood, metals, coatings, cobber, and foams, such as PVC, and increasingly utilize CFRP materials for improved material performance (Mishnaevsky Jr et al., 2017, Morini et al., 2021, Sakellariou, 2018).

A WTB has an aero foil design for optimal wind utilization which includes a round leading edge and a pointed trailing edge (Bortolotti et al., 2016, Anderson, 2020). The thickness of the WTB differ around the cross-section and the blade length, with the maximum thickness being around the root end (Mishnaevsky Jr et al., 2017).

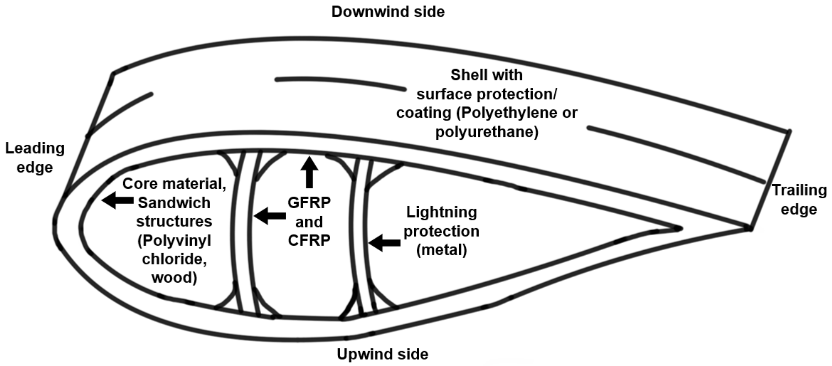


Figure 2 - Figure made by author based on Morini, A. A., et al. (2021) and Jensen and Skelton (2018)

All the materials are molded together in large molds that are designed and shaped according to the individual blade model. Here, materials are first layered according to the blade design specification, and then resin is infused and cured, either at room temperature or by application of additional heat, through the process of vacuum infusion molding. After this process, the blade is one complete structure (Mishnaevsky Jr et al., 2017).

GFRP materials used in WTB manufacturing are characterized by the combination of thin glass fiber filaments, either in the form of mats, tows or prepreg, combined with a polymer-matrix in the form of a resin, typically based on epoxy, polyester, or vinyl ester (Mishnaevsky Jr et al., 2017). When combined through this process, the resin fills the small gaps between the filament and, when cured, creates a bond which creates a light-weight material with high-performing mechanical properties of stiffness and strength (Anderson, 2020). It is important to note that different blade OEMs use different blade designs and materials. The material systems for the GFRP material differ especially between manufactures and are considered one of the main value propositions. These material differences can influence the EoL management and secondary applications of materials (Sakellariou, 2018). It is, however, common for OEMs to use thermoset-based resin systems, which by nature cannot be re-heated or re-shaped after curing (Kazemi et al., 2021). As the resin is used throughout the entire WTB structure, this also applies to the entire blade. However, even though composite materials are reliable and ensure high performance, due to the nature of the materials, they are difficult to separate at their EoL. Thus, EoL composite materials have so far largely ended up as landfill, which has been an easy, accessible and a low-cost solution (Ribeiro et al., 2016). Also, virgin composite materials are not considered a scarce or valuable resource; thus, the pressure for finding sustainable alternatives has been low. The barriers to implementing circular waste solutions are further analyzed and discussed in Chapter 5.

The Wind Europe association predicted in 2020 that 350,000 metric tons of blade material would be decommissioned by 2030 with Spain, Germany and Denmark facing the largest volumes first (WindEurope, 2020). These predictions warn that decommissioned WTBs present a significant challenge in terms of EoL management and material circularity. The rapid increase in predicted waste volumes and the lack of sustainable options for handling this material constitute a “burning platform” for the development and implementation of sustainable and circular value chains.

02.02 DecomBlades – the Research Project

This PhD dissertation has been connected to the DecomBlades research project on CE value chains for decommissioned WTBs. The project started in January 2021 and ended in January 2024 with a vision of developing and demonstrating circular recycling of wind turbine blades to enable a fully sustainable wind power sector (DecomBlades, 2023).

The cross-sector consortium was set up to investigate the scaling potentials of promising recycling technologies for composite materials, with a focus on developing full scale solutions that would be both economically and environmentally sustainable. Through a common vision and objectives, the DecomBlades project addressed both challenges and opportunities associated with the establishing of large-scale recycling solutions for WTBs. This included the infrastructure and identification of market potentials of recycled materials.

Ten Danish partners participated in the project, including Vestas Wind Systems, Siemens Gamesa Renewable Energy, LM Wind Power, Ørsted Wind Power, MAKEEN Power, FLSmidth, H.J. Hansen, Technical University of Denmark (DTU), University of Southern Denmark (SDU), and Energy Cluster Denmark. The industrial partners in the DecomBlades project represent different fields of expertise and detailed knowledge across potential value chains for decommissioned blades. Vestas Wind Systems, Siemens Gamesa Renewable Energy and LM Wind Power all participated as manufactures of WTBs and supplied knowledge of designs, compositions, and materials. Ørsted participated as an operator of WTGs and supplied knowledge on blade locations. This knowledge supported the partners from the recycling industry in their understanding of future waste streams.

Three industrial partners brought expertise about three promising EoL solutions for processing of composite materials, i.e. mechanical recycling, pyrolysis, and cement co-processing, with the aim of developing business cases and scaling up technologies. H.J. Hansen offered end-of-life blade logistics, and pre-processing of blades such as cutting and shredding. MAKEEN Power supplied knowledge and facilities for pyrolysis and FLSmidth supplied knowledge about production facilities for cement production.

The academic partners included University of Southern Denmark and Technical University of Denmark, participating to ensure academic rigor in the assessment of material flows, value chains and technologies, and in mechanical testing of recovered materials. Multiple participants from each organization have been involved throughout the three-year project. The project has included large workshops with all participants approximately every three months. Bi-weekly meetings and additional ad-hoc meetings have been held throughout the project for coordination and information sharing. I have personally participated actively in the project, including workshops, meetings, and report generation. Thus, the work presented in this dissertation has been developed and conducted in the context of the DecomBlades project and vision. The implications of this context on research design and methodology are addressed and discussed in Chapter 4 – Methodology. The DecomBlades project was funded by the Grand Solutions research program of Innovation Fund Denmark (grant number: 0177-00006B)

02.03 End-of-life Wind Turbine Blades

As part of this dissertation, a full systematic literature review was conducted and consolidated in the appended Paper II. The findings from Paper II are presented and discussed in relation to sub-RQ2 in Chapter 6, while the full overview of literature findings, including concepts, themes and topics, are found in Paper II.
In addition to the literature review, a short introduction of key terms pertaining specifically to WTBs are introduced below.

In this dissertation, distinction is made between WTB decommissioning and WTB EoL. The term “decommissioning” is often applied in industries dealing with large complex products and is defined as *“*a formal process to remove an installation from an active status at the end of its service life” (Paik, 2022). The term “decommissioning projects” builds on this definition, but includes the activities of planning, preparation and post-decommissioning as well as the specific activities of the actual removal (Centre for Energy Resources, 2018).

The term “end-of-life (EoL)” refers to a product that can no longer be used (Vanson et al., 2022), and in this dissertation the EoL of a WTB is considered to be when a WTB can no longer be used according to its original purpose. Thus, at the EoL the circular principles of maintenance, repair or refurbishment are no longer possible. However, the empirical findings from this dissertation have also revealed that even though WTGs (and WTBs) might be decommissioned, that does not mean that they have reached their EoL. The WTG can be commissioned again elsewhere or the WTBs can be reused again as spare parts for WTGs at other wind farms.

03 Theoretical Background and Key Concepts

The purpose of this chapter is to position this PhD dissertation by introducing and defining key concepts and to outline the theoretical background of supply chains, value chains, operations management, circular value chains, and the operational execution gap in CE transition. The introduced concepts and theoretical principles define the theoretical background on which this dissertation is built with a focus on CE in value chains and operations management.

03.01 Supply Chains and Value Chains

Supply chain management was first introduced as a term by Oliver and Webber (1982), who argued that a supply chain management approach was required to improve how supply chains performed. A supply chain is defined as “A network of connected and independent organizations mutually and co-operatively working together to control, manage and improve the flow of materials and information from supplier to end users” (Aitken, 1998), while supply chain management is the management of upstream and downstream relationships to deliver customer value (Christopher, 2016). The definition implies the close management of relationships, making it different from the concept of logistics. As argued by Christopher (2016), the term chain could also be exchanged with the word network, and thus supply chain management, or supply network management, are considered the same.

The term “value chain” is often used interchangeably with the term “supply chain”, yet the value chain concept builds on the supply chain concept, and they are not the same thing. According to Porter (1985), who first coined the value chain concept, the primary activities of a value chain is inbound logistics, operations, outbound logistics, marketing and sales, and services. This is supported by activities within firm infrastructure, human resource management, technology development, and procurement (Porter, 1985).

A competitive advantage can be achieved based on how organizations perform these activities to deliver customer value and differentiate themselves from their competitors (Christopher, 2016). Porter (1985) argued that if an organization does not enjoy a competitive advantage within an activity, it should be outsourced to a partner with better capabilities. Yet, this action would also lead to a higher level of management. Thus, value is no longer created by a single organization, but depends on all the connected organizations, meaning that the supply chain becomes a value chain. The term value chain will therefore be adopted in this dissertation as new waste solutions will be investigated in relation to design, operation, and industrialization in co-creation between organizational partners, based on their respective competencies and capabilities.

03.02 Sustainable Operations Management

A key concept applied throughout this dissertation is operations management, which is an essential part of all value chains. The definition of operations management adopted in this dissertation is by Slack et al. (2010) and states that “operations management is the activity of managing the resources which produce and deliver products and services”, which can include people, facilities, machinery and knowledge. The building blocks of any operation is processes. Processes are defined as “an arrangement of resources that produce some mixture of products and services” (Slack et al., 2010). These building blocks, their characteristics, and their sequence transform inputs for the efficient creation of a product or service, and if standardized can result in reduced cost, lead times and improved quality (Slack et al., 2010).

Building on the above definitions, businesses can therefore be analyzed at three levels i.e. at supply network level, at operational level and at process level (Slack et al., 2010). This dissertation explores and analyzes all three levels, i.e. (1) the full supply network/value chains of EoL WTB operations and management, (2) the operational processes, their sequence, and the flow of material resources between them for product value creation, and finally (3) individual technical processes for EoL WTB material resource processing.

The triple bottom line (3BL) was first introduced by Elkington (1998) as a measure to ensure sustainable operations, through the three pillars of people, planet, and profit. The 3BL has since then been one of the backbones of sustainable operations management where organizations work to reduce, measure and report on the three aspects in their operations and their value chains (Kleindorfer et al., 2005). In relation to the planet aspect, also referred to as environmental impact, reducing energy and resource consumption in value chains and operations is central to reducing CO2 emissions and resource depletion. Back in 2005, Kleindorfer et al. (2005) called for operations management research to include the planet and people aspects in both research and practice due to (1) increase in cost of materials and energy, (2) public pressure for sustainable practices, (3) increasing customer demand for sustainable products, and (4) people aversion to globalization.

03.03 Circular Economy

To further position this study, the theoretical concept of CE is introduced. CE promotes the idea of reducing unsustainable linear flows of material and energy into circular systems where resources are used in consecutive cycles (Korhonen et al., 2018). Korhonen et al. (2018) clearly expresses the logic behind why CE should be implemented by stating: “It makes common sense, that if you extract a resource from nature and work hard for it to become a product or a service that has an economic value, you use this value many times, not only once”. Since 2010, the Ellen MacArthur Foundation has been one of the leading academic authorities in defining and exploring the concept and practices of CE. In this research, the following definition by the Ellen MacArthur Foundation is adapted: “The circular economy is a system where materials never become waste and nature is regenerated. In a circular economy, products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting.” (Ellen MacArthur Foundation, 2024). The CE principles highlighted by this definition are: Reduce, Reuse, Recycle and Recover, also referred to as the 4R framework (Kirchherr et al., 2017). Other and more elaborate versions of the frameworks have been proposed, such as a the 6R framework (Sihvonen and Ritola, 2015) and the 10R framework (Potting et al., 2017). Nevertheless, the 4R framework remains the most widely adopted one (Kirchherr et al., 2017).

CE as a concept has been created mainly by practitioners and policymakers and has been criticized for being superficial and unorganized in academic literature (Korhonen et al., 2018). In a study by Kirchherr et al. (2017), 114 definitions of CE were systematically analyzed, and findings showed that the CE concept is highly diffuse, used differently by scholars and often excludes the waste hierarchy. A repetition of the study by

Kirchherr et al. (2023) analyzed another 221 definitions of CE from 2017 until 2023, where findings concluded that CE has more meaning for academia than for practice, thus emphasizing the need to turn concepts into practical applications to create real impact. In terms of criticism, Corvellec et al. (2022) goes even further by concluding that CE is focused on economic rather that social impact, and with simplified contributions to environmental impact. Thus, CE becomes a reassuring discourse for policymakers rather than “an actual solution to actual problems” (Corvellec et al., 2022).

For CE to create sustainable development, all three dimensions of sustainability must be positively impacted, i.e. environmental, social, and economic impact (Korhonen et al., 2018). CE is often considered as a sustainable concept and solution, but since CE as a concept focuses on material flows based on technological and economic perspectives (Corvellec et al., 2022), it can in fact result in negative impacts on the environment and society (Velenturf and Purnell, 2021). The recovery and recycling of materials in a CE can result in new energy demands and use of water, while materials are not kept in the cycle consecutively. To avoid this, CE must contribute to sustainability using a systems perspective that considers the optimization of social, environmental, technical, and economic value through the entire value chain (Velenturf and Purnell, 2021). Nonetheless, if done right and based on the application of critical sustainability assessments, CE can be used as a platform for sustainable development (Korhonen et al., 2018) and be beneficial for sustainability (Geissdoerfer et al., 2017). Thus, research and scientific work are needed to ensure that CE results generate a positive environmental impact (Korhonen et al., 2018).

03.04 Circular Value Chains

As stated by Kleindorfer et al. (2005), “We do not pay attention to the end-of-life recovery of materials or energy, nor to proper disposal issues. These green supply-chain issues are important.” To address this issue and implement sustainable CE, new systems and value chains for circular material management are required. Circular supply chains are defined as “the configuration and coordination of the supply chain to close, narrow, slow, intensify and dematerialize resource loops” (Geissdoerfer et al., 2017). This can be aided by the introduction of reverse supply chains, as a way to take back products from customers at EoL and include product collection, reverse logistics, inspection, determining future route, remanufacturing or disposal (Kleindorfer et al., 2005).

Building on the circular supply chain definition, the theoretical concepts of value chains and CE outlined in the previous sections, can be combined as circular value chains. This is explored in a study by Eisenreich et al. (2022), in which a circular value chain framework is developed based on Porters original value chain framework. Eisenreich et al. (2022) concluded that the involvement of external stakeholders in the value chain was the key to successful CE implementation. In their study of circular value chains for plastics, Johansen et al. (2022) concluded that “the transition to the circular economy should be made across the entire plastics value chain in order to ensure circular design, production, use and waste management”. Johansen et al. (2022) also found that LCA should be applied to compare and explore recycling value chains, but that research struggles to do this due to lack of data.

In summary, the term (EoL) circular value chain has been applied in this PhD dissertation, to describe a full industrial system for products reaching their EoL, which is co-created by all stakeholders and includes end-to-end operations and processes with the purpose of achieving and implementing CE principles.

03.05 Circular Economy and the Operational Execution Gap

CE can be implemented both in individual organizations and their supply chains (micro level), industrial systems (meso level) and cities or nations (macro level) (Jackson et al., 2014). At the micro level, organizations will have a large impact and contribute significantly to a successful CE. The role of operations management in CE is evident, and operations management can aid the CE transition by proposing networks for increased collaboration and new business models (Zanjirani Farahani et al., 2022). Yet, research into CE implementation at the micro level is limited (Barreiro-Gen and Lozano, 2020).

Several studies have sought to identify the barriers, drivers, opportunities, and practices for organizational engagement in CE. In this context, Kumar et al. (2019) studied the manufacturing sector, and Bressanelli et al. (2019) conducted a systematic literature review that identified 24 challenges associated with redesigning supply chains. Based on these results, Bressanelli et al. (2019) proposed a framework for practitioners linking challenges to levers to overcome said challenges. Similarly, Govindan and Hasanagic (2018) also presented a multi-perspective framework for the barriers, drivers and practices for CE implementation in supply chains, and Lieder and Rashid (2016) proposed CE implementation strategies. Govindan and Hasanagic (2018) identified general practices for cleaner production including partner collaboration, logistics, and implementing technical equipment and facilities for material handling. However, both studies concluded that legislation and policies will play an important role for future CE transition and lack perspectives of operational execution (Govindan and Hasanagic, 2018, Lieder and Rashid, 2016). Common for CE implementation at the micro level is that organizations tend to focus their efforts only on reducing production waste and recycling materials (Barreiro-Gen and Lozano, 2020). To expand on the many options for CE implementation, Kalmykova et al. (2018) identified 45 different CE strategies and also presented a database of cases for CE implementation.

The CE transition relies on broad alliances between stakeholders such as producers, consumers, policymakers, and scholars, which emphasizes the fact that CE implementation is complex (Kirchherr et al., 2023). Yet, as stressed by Barreiro-Gen and Lozano (2020), there is a clear gap between CE theory and CE practices. To bridge this gap there seems to be a need for increased collaboration with stakeholders. The importance of support from stakeholders is also stressed by Lieder and Rashid (2016), who proposed a CE implementation strategy in an industrial manufacturing context using a concurrent top-down and bottom-up approach.

Most research addresses a strategic level of CE engagement and implementation. Thus, there is a need for exploration of the operations management perspective to address the direct operational implications and challenges when implementing new value chains for recycling and recovery. In other words, for CE to have the desired societal impact, it must be understood how practices are implemented operationally and what their direct impacts and consequences are to the processes and the people involved.

04 Research Design and Methodology

While the thesis outline was introduced in Chapter 1, the general research design and methodology will be introduced in this chapter. Furthermore, the methodology and research designs of the individual papers are described briefly while full elaborations are found in the appended Papers I-VII. Since the applied methods of the individual papers are already described in detail in the appended papers, this chapter will specifically focus on the case study methodology and methods of data gathering as this has been the primary method of empirical data collection. Hence, this chapter describes the overall research design and considerations for this dissertation as a collective piece of research. Finally, the role and impact of the DecomBlades research consortium on the research design is also reflected upon.

04.01 Overall Research Design

This research was designed based on a practice-oriented approach, where the objective was to contribute to knowledge within the research field of EoL management of composites and WTBs (Dul and Hak, 2007). However, theoretical contributions are also achieved through the development of generalizable conclusions, proportions, and frameworks (Dul and Hak, 2007). Research within the field of operations management can have different theoretical purposes including (1) exploration to identify new research areas and needed contributions, (2) theory building to identify and describe contracts, variables and relationships, (3) theory testing to verify developed theories, and (4) theory elaboration and refinement (Voss et al., 2016, Dul and Hak, 2007). This dissertation includes research studies with the purposes of exploration, theory building and theory testing. To achieve this, an inductive research approach has first been adopted (Papers I-III) for exploration, theory building and framework development. Then a deductive research approach has been applied (Papers IV and V) for theory testing of the developed frameworks.

Operations management deals with both physical and human elements in an organization or system (Voss et al., 2002), and consequently a mixed-methods approach can be effective to comprehensively address research topics involving human and physical elements.

The research design of this dissertation consists of a mixed-methods approach utilizing both the method of systematic literature review, qualitative methods including a single case study and a multiple case study, and quantitative methods including mathematical modelling and multi-criteria decision-making. These methods have been applied in the appended papers (I-VI) to fulfil the research objectives and answer the posed research questions. I have found that a mixed-methods approach was especially useful when studying a complex system to provide a multidimensional perspective on processes, decision-making and value chains where different entities including organizations, technologies, and material flows interact.

Figure 3 summarizes the research question, method, purpose, and data collection method of each of the appended papers. In Papers I and II, the future material waste flows and a state-of-the-art roadmap for EoL WTBs have been developed. This has been done through the application of mathematical modelling (Weibull distribution) and systematic literature review (Tranfield et al., 2003). Paper III includes a single in-depth case study for theory building, with the purpose of identifying practices for operational execution, understand the underlying decision-making processes and the relationships between stakeholders (Yin, 2018, Voss et al., 2016). Thus, key constructs and variables are defined and elaborated based on empirical evidence (Dul and Hak, 2007). The propositions and frameworks developed through Papers I, II, and III were then tested and extended by an empirical multiple case study in Paper IV of four representative cases (Dul and Hak, 2007, Yin, 2018). In addition to this work, paper V zooms in on decision-making processes by first developing a framework based on prior literature and then conducting an empirical test and validation of the framework, which both include theory building and testing elements (Voss et al., 2016). Paper VI takes a theory building approach to decision-making by proposing a framework for assessment of future value chain scenarios. The final appended Paper VII includes a study of the researcher's role in the development of new sustainable ecosystems based on focus group interviews with field experts that are analyzed and consolidated (Miles et al., 2018, Saldaña, 2021), leading to the development of a framework for drivers, barriers and required abilities for researchers as a third-party facilitator for new sustainable business ecosystems.

Paper	Paper I	Paper II	Paper III	Paper IV	Paper V	Paper VI	Paper VII
Sub-RQ	RQ1	RQ2	RQ3		RQ4		
Title	Method for estimating the future annual mass of decommissioned wind turbine blade material in Denmark	State-of-the-art value chain roadmap for sustainable end-of-life wind turbine blades.	Circular economy operations for large complex products at end-of-life: The wind turbine case	Value Chains for Recycling End-of-life Wind Turbine Blades: A Multiple Case Study	Sustainability assessment of new technologies using multi criteria decision making: A framework and application in sectioning end-of-life wind turbine blades	Sustainable end-of-life value chain scenarios for wind turbine blades	The operations management researcher's role: The observer or facilitator of new sustainable business eco-systems?
Paper research question(s)	Aim: To predict the yearly amount of decommissioned wind turbine blade material available in Denmark until 2060	1. What is state-of-the-art in the academic literature for EoL Value chains for WTBs? 2. How are fully functional sustainable value chains of EoL WTBs designed and operated from the original site and until secondary products are manufactured?	How is the decommissioning of a large complex product designed and operationally conducted to support the circular economy principles of reuse and recycling?	How are circular value chains for end-of-life wind turbine blades designed and operated, and what are the operational implications?	1. How can a conceptual framework for MCDM ais a sustainable assessment of operational technologies? 2. How can MCDM aid a sustainable assessment and selection of technologies for sectioning of decommissioned WTBs?	Aim: To develop a framework to evaluate the WTB waste recycling scenarios with different levels of TRL in terms of economic, social and environmental aspects.	How can and should the OM researcher engage in research projects for new sustainable business ecosystems where coopetition is involved?
Research methodology	Mathematical modelling (Weibull distribution)	Systematic literature review & meta-analysis	Structured literature review & single case study	Multiple case study	Structured literature review for framework development. Validation through multi-criteria decision-making (MCDM) with waste management company	Structured literature review and scenario development using life-cycle-assessment (LCA)	Expert focus-group interviews
Unit of analysis	Danish WTBs	EoL value chains	EoL value chain	EoL value chains	Assessment process (Company)	Assessment process (value chain)	OM researchers
Empirical data collection	Master data register for wind turbines, Danish Energy Agency	Not applicable	Semi-structured interviews, operations and process data, pictures, direct observations & site visit	Semi-structured interviews, operations and process data, pictures, direct observations & site visit	Workshops + Delphi study approach with WMC Equipment datasheet	Not applicable	Focus groups/round-table discussion
Research Approach /Purpose	Problem quantification (Inductive)	Exploration/Theory building (Inductive)	Theory building (Inductive)	Theory testing (Deductive)	Theory testing (Deductive)	Theory building (Inductive)	Theory building (Inductive)

Figure 3 - Research design and methodology of appended papers

04.02 Systematic and Structured Literature Reviews

The systematic literature review is a methodological approach to literature search, identification, selection, assessment and data synthesis, to ensure a systematic, transparent and repeatable approach to reviewing academic literature (Tranfield et al., 2003). The method ensures that relevant findings and results across existing literature are identified, reviewed, and reported to reach a state-of-the-art of a research field or topic upon which future research can build (Tranfield et al., 2003). Thus, it is often adopted as a stand-alone method for research studies since it is very comprehensive. However, it can also be combined with other research methods. The systematic literature review has been applied in Paper II, where the objective was to create a state-of-art of academic literature within EoL WTBs. In this study, the systematic literature review approach was based on the principles presented by Tranfield et al. (2003). These principles consist of three stages: (1) Planning the review, (2) Conducting the review, and (3) reporting and dissemination. Stage 1 included identifying the need for review, preparing a proposal for review, and developing a review protocol. Stage 2 included identification of research, selection of studies, assessment of study quality, data extraction and data synthesis. The final stage included reporting recommendations and putting evidence into practice (Tranfield et al., 2003).

Besides the systematic literature review approach, structured literature reviews are an integral part of each presented research paper to identify relevant literature, research results and knowledge gaps within the field of research on CE for EoL WTBs. For this purpose, the methodology presented by Hart (2018) and Dekkers et al. (2022) has been applied to create a transparent, objective and repeatable process to literature identification and review, but without the aim of creating a new state-of-the-art of a specific research field or topic. Thus, the comprehensiveness and aim are different from those of the systematic literature review (Hart, 2018, Dekkers et al., 2022). The structured literature review approach was applied in Papers III, V and VI.

04.03 Case Study Research

Empirical research methods based on data from the real world can tie theory and practice together and make important research contributions (Flynn et al., 1990). For this PhD research study, a qualitative empirical study approach has been applied, utilizing the case study methodology. The case study research methodology originates in the social sciences and is frequently applied in operations management. The method allows for a current phenomenon to be studied in its natural setting using multiple sources of evidence and observation of actual practices (Yin, 2018, Voss et al., 2016). The method is suitable when research questions seek to understand complex and complete phenomena and can both be applied in exploration of new research areas, theory building and theory testing (Dul and Hak, 2007, Flynn et al., 1990, Voss et al., 2002) and is particularly suitable for theory building (Eisenhardt and Graebner, 2007). Thus, the method was found to be suitable for the purpose of this research of investigating how the domain of EoL WTB can adapt CE practices adopting a theory building and testing approach.

There are both advantages and disadvantages to utilizing a case study approach. Case studies are a great source of detailed data and provide depth to an emerging topic and can provide unique and important knowledge in a new field where research is yet fragmented or unexplored (Yin, 2018). The limitations pertain to the risk of bias and generalizability pf conclusions. Hence, a detailed and carefully thought-out research design is essential to ensuring that the empirical data will answer the research questions and to overcoming the limitations (Voss et al., 2016).

04.03.01 The research process

‘To create a structured research design, the methodology proposed by Yin (2018) was adapted and used throughout this PhD to conduct multiple case studies. The methodological approach is depicted in Figure 4, and highlights the fact that the **planning** phase, including the identification of a research gap and need for empirical data and case studies, was uncovered as the result of Paper II. This was followed by the **design** phase where case sampling was conducted. A theoretical case sampling approach was taken, meaning that all included cases were selected based on an assessment of suitability to the research question in terms of illuminating and elaborating on the studied concepts on EoL WTBs and CE (Eisenhardt and Graebner, 2007). The assessment of suitability was based on commonality in defined unit of analysis, a variance between cases of defined variables, variance in EoL routes, and accessibility of cases. This was done to ensure that the obtained data would be qualified and valid for answering the research questions. The variables assessed for case sampling were blade geometry and mass, blade quantity, recycling route and technology, blade owner, location, and waste management partner (WMP). All variables are described in appended Paper IV, (Figure 3).

The **preparation** phase comprised the development of a research protocol for data collection and obtaining access and approval to informants. The next phase included data **collection** through multiple sources of evidence, which is further outlined later in this chapter. All cases were studied in real time, meaning that they were current cases that were actively followed. The advantage of this was to get up-to-date data and information in a rapidly changing environment (Voss et al., 2016). Finally, the data was **analyzed** both within each case and between cases. Based on learnings, multiple iterations between preparation, data collection and analysis were implemented to adjust the process to optimize the output and validate information.

The application of the case study methodology outlined above and in Figure 4 resulted in four cases that were analyzed, and results are **shared** in Papers III and IV. First, a single in-depth case study was completed and created the data foundation of Paper III which allowed for new and detailed insights of EoL value chains and operational execution and performance. The single-case approach enabled a high degree of managerial and technical information and data to be gathered. In addition, it allowed for an understanding of the decision-making processes along the value chain and organizational interrelationships (Yin, 2018).

In Paper IV, the design and operation of EoL value chains for WTBs were illuminated by all four cases, since multiple case studies can improve exploration of the research question (Eisenhardt and Graebner, 2007). Thus, this method provided an ideal opportunity for to documenting, assessing, and designing new industrial systems. The challenges and knowledge uncovered through the multiple case study were not unique to the specific cases and thus representative for all WTBs and their EoL challenges. This allows for results to the generalizable (Yin, 2018).

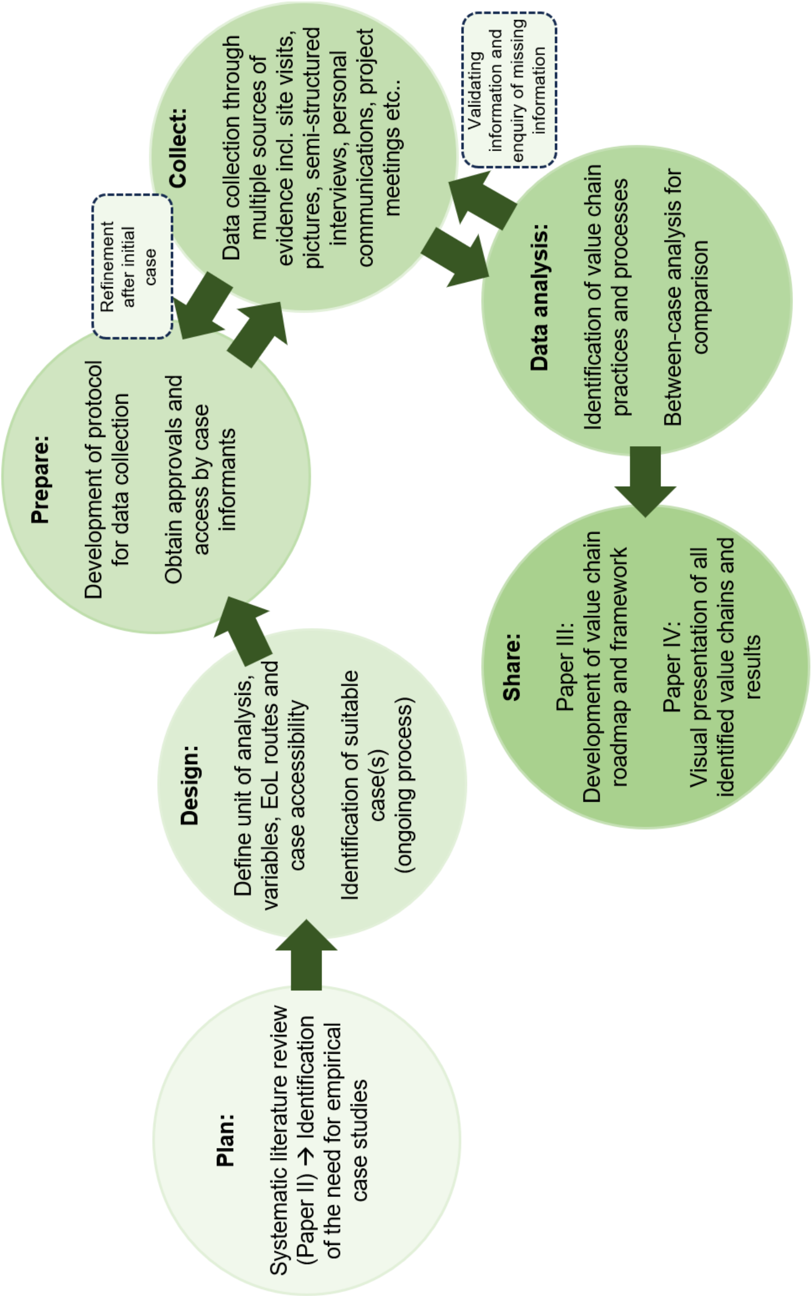


Figure 4 - Case study research methodology adapted from Yin (2018)

04.03.02 Empirical Data Collection and Analysis

During the initial phases of the research period, information was obtained through *meetings, unstructured interviews,* and *personal communication* such as conversations or informal meetings, for instance, bi-weekly co-ordination meetings, project seminars and planned workshops. When working with many industrial partners, a lot of information is shared in informal settings, which is important for the gathering of research data. Retrieving data in this manner was specifically beneficial in the beginning of the research period to get an overview of the industrial setting, identify areas for further investigation and as a PhD researcher to have personal contact with industrial partners. This information was used to inspire the research design and scope of the research project.

In the multiple case study, several sites were investigated, and available information was gathered with as much detail as possible (Flynn et al., 1990). For the case studies, the primary sources of data were semi-structured interviews with key informants involved with the different decommissioning/EoL cases. This involved the WTB owners and their contracted partners such as logistics and waste management companies. For construct validity and data triangulation, multiple sources of data and evidence were used (Yin, 2018), and key informants have in all cases reviewed the results in an iterative process for validation as suggested by Voss et al. (2016). All sources of information from the cases are listed below in Table 1 and will be elaborated in the sections below in more general terms, while the specific data collected, and number of interviews are described in Papers III and IV.

Semi-structured interviews were conducted based on an interview protocol containing the structure of the interview and the included questions that were to be asked of the respondent to ensure a clear connection between the research question, theory and the empirical data (Yin, 2018). This was important to ensure that the data gathered in the interviews and on-site visits would answer the research questions, and that the reliability of the outcome was increased (Yin, 2018). Yet, the interviews also allowed for follow-up questions and for capturing case-specific detail (Flynn et al., 1990). Informants were selected based on their role in the case and their knowledge about the procedures and technologies involved. Examples of questions from the interview guide are found in appended

Paper III, while the number of informants, their title and their respective organization are listed in Paper VI, Figure 4.

Table 1 – Data collection methods

Method of data collection	**Examples**
Unstructured interviews/ personal communication	Conversations Informal meetings
Semi-structured interviews	Interviews with key informants from case companies
Site visits	Physical visits to sites where EoL WTBs were handled
Pictures	Pictures of sites, blades, processes, or equipment
Workshops / meetings	Formal meetings with agenda and minutes of meetings Planned workshops
Written communication	Emails Minutes of meetings External communication Websites
Written documentation and reports	Industrial reports Data sheets Company procedures Official guidelines and procedures

Interviews were conducted during *visits to sites* engaged in processing and material handling. This also allowed for *pictures* to be taken, which were used as a source of information to obtain and document technologies, equipment, practices, or other details. After data collection on site, the obtained data was verified and improved by the informants in a double-looped verification process, which improved data accuracy and validity.

Throughout the project period a large number of *workshops and meetings* were held with DecomBlades partners and with other relevant organizations. The workshops were aimed at several outputs but were overall seeking to align the goals and expectations of the partners and identify common challenges and practices. However, data and case details were also provided through both workshops and meetings, of which minutes were taken made to document what was said and agreed. This ensured traceability and alignment of information obtained between participants.

Other modes of data gathering were utilized which included written communication, written documentation, and reports. *Written communication* included especially emails and written notes from informants. Particularly quantitative data were shared through emails and data sheets cumulated throughout the project. *Written documentation* included internal reports from the industrial companies, invoices, quotes, process descriptions, Excel sheets containing product data etc.

The gathered data was analysed across cases to match patterns and compare differences to ensure external validity and generalizable results (Dul and Hak, 2007). The collected data was analyzed based on a sequential categorization of processes and technologies throughout the EoL value chains. For the in-depth case study in Paper III, the decision-making processes were supported by quotes presented by the interviewees according to the approach by Rockmann and Vough (2023). For the remaining cases presented in Paper IV the focus was on processes and technologies, and quotes were not included.

04.04 Responsible Conduct of Research

Data collected from interviews, observations, and site visits can be biased due to the bias of the interviewee or the interviewer and observer. Such bias can potentially impact the data collected and thus the results and findings (Yin, 2018). Therefore, I have been aware of these mechanisms throughout the process and made sure that measures were taken to avoid any bias on the part of and from partners that could lead to misconduct of research. An important tool is transparency, which is applied through the research design, systematic logging of data and observations, and through data triangulation. This thoroughness is therefore described and presented as part of the research design to assure readers that responsible measures were taken, thus leading to robust findings.

For the sake of validity and replicability, responsible conduct of research is important, but particularly in this research project, misconduct of research could also lead to greenwashing. Greenwashing is a term used to describe companies that try to appear “greener” and more sustainable than they actually are in order to gain economic advantages (de Freitas Netto et al., 2020). As this research project seeks to develop circular value chains for the wind turbine industry, there is a risk that misleading results will contribute to greenwashing. This would not only be misleading for the public but could also lead to future waste solutions that do not fulfil the aim of creating sustainable waste practices for WTBs. Thus, the project setup and the partners involved represent a unique opportunity to make impactful research but with potential pitfalls that must be avoided.

The entire project was managed through a legally binding contract and a non-disclosure agreement between the partners of the DecomBlades research project, meaning that data must be handled accordingly. The data collected consisted of a mixture of qualitative and quantitative data. Because of this, the documentation of data differs depending on the mode of collection, and the data is stored in a secure OneDrive cloud folder solution provided by the university. This solution also provided data back-up and security. However, data files cannot be shared publicly outside the research group at the university.

04.04.03 Research Design in the Context of DecomBlades

Working under the agreement of the DecomBlades project enabled unique access to knowledge and data from highly relevant and engaged industrial and academic partners. However, this commitment has also influenced the research design, which is important to reflect upon. Throughout the three-year PhD period, the overall project had to deliver several milestones and outputs, which to some extent moved the research in a certain direction. The funding of the project by Innovation Fund Denmark implied an expectation of the outcome being somewhat positive and operationalizable. It has therefore been important to consider and reflect on possible conflicts of interest and impacts on research, and on possible bias towards positive findings. Even though access to case studies and data was enabled through the project collaboration, it is believed that the detailed and carefully thought-out research design presented in this chapter clearly conveys the appropriateness and applicability of the chosen methods and the transparency of the data collection and analysis. At the beginning of the project, data sharing was challenged by opposition on the part of the industrial partners to sharing details with other partners. I then experienced how trust was built over time, both between the project partners, and in relations with me as a researcher, which led to greater openness and s satisfactory level of data sharing. This change was crucial for the empirical data collection and reporting, but also demonstrated how my participation in the DecomBlades research project enabled this research.

My involvement in the DecomBlades project has impacted where I started searching for appropriate and suitable case studies. Since a sufficient number of cases were identified by the project partners, I did not need additional cases from organizations outside the project, which could potentially have impacted results. Yet, the cases included in this research were selected based on a protocol, which did exclude some cases from the DecomBlades partners.

It has been a clear priority to me as a researcher to publish as much of the collected data as possible, and the project agreement has not limited my ability to publish. On the contrary, I have found that the agreement allowed access to data that would not otherwise have been obtainable. In the few instances, where data has been considered confidential, normalizing data, or transferring it to another format was found to be a solution. Metadata such as how data was collected, when, where, by whom and from whom etc. was equally important for the validity of the data, and most of the metadata has been shared in this dissertation.

In summary, even though I as a researcher have the freedom to choose the appropriate research methodology, the framing of a project will impact the way we approach research. It is, however, important to emphasize that the research design of this dissertation has not been dictated or influenced by the project partners. However, it is also important to stress that transparency is needed about partner cooperation, data collection and the chosen methodology due to the nature of the project and the project agreements.

Part II

Research Results

05 Circular End-of-life Value Chains for Wind Turbine Blades: Why the Industrial Scale Solutions are Absent

To study how value chains for decommissioned WTBs can be designed, operated, and industrialized according to CE principles, it is essential to understand the reasons why these systems do not already exist. Thus, in this chapter, the barriers to creating circular EoL value chains for WTBs will be identified and analyzed to understand the industrial context and industry-specific challenges influencing blades meeting their EoL. This chapter will therefore answer the first sub-research question:

Sub-RQ1: Why do circular EoL value chains for wind turbine blades not exist today?

To answer the research question, several topics will be analyzed and elaborated based on a European and Danish context. First, the topic and context of landfilling and the current alternatives will be outlined, followed by an analysis of the role of blade ownership and available material information based on a literature review approach. Then, the lifetime of WTBs and expected future waste volumes will be assessed, including a thorough review of existing literature, followed by a presentation of Paper I – Method for estimating the future annual mass of decommissioned wind turbine blade material in Denmark. The key points from the discussion in Paper I are elaborated further in the following section on waste volume uncertainties and implications for EoL value chains. Finally, a review and analysis of grey literature from the public media in Denmark is presented to assess the public perception of wind energy and the EoL issues of WTBs, and how this has impacted the development of new EoL solutions. To summarize findings, a framework – barriers to circular value chains for EoL WTBs – is presented at the end of the chapter. Eight key barriers are identified and collectively answer the posed research question and create a baseline for future efforts to establish circular EoL value chains for WTBs.

05.01 Landfilling and Current Alternatives

The main route for EoL WTBs that have been available on an industrial scale is landfill (Larsen, 2009, Ribeiro et al., 2016). Landfilling of WTBs typically includes pre-processing the blades into sections of 6-8 meters to reduce size and volume before they are taken to a landfill site. A landfill site typically consists of a pit covered with a liner and a collection system for leachate and drainage. Solid waste is then placed in the pit, and once it is full, methane gas recovery systems are installed, and the pit is covered with soil (Nanda and Berruti, 2021).

There are several reasons why landfilling WTB waste is not considered a viable or sustainable waste route: (1) it is estimated that the WTB material will take up to 1 million years to decompose in landfills as it consists primarily of glass (Kumari et al., 2022); (2) The degradation of the material can have a negative impact on the local environment (Ramirez-Tejeda et al., 2017, Halliwell, 2010); (3) Materials are not reused, refurbished or recycled in accordance with SDG12, which contributes to the natural resource depletion crisis (United Nations, 2015b); (4) The embedded value and energy of the material are lost (Ramirez-Tejeda et al., 2017); and (5) The negative public perception of landfill can lead to a decrease in acceptance of wind energy in general (Ramirez-Tejeda et al., 2017). For these reasons, landfilling is considered the least favorable waste management option in a CE (MacArthur, 2013).

Landfill sites are nonetheless largely available globally and used for many types of waste (Nanda and Berruti, 2021). Landfilling is often locally available and cost-effective and has therefore been the most widely available option for WTBs at the EoL (Ramirez-Tejeda et al., 2017). Yet, for the reasons stated above, the Wind Europe association has called for a European landfill ban for WTBs (WindEurope, 2022b) and has investigated the possibilities for implementing alternative waste solutions (WindEurope et al., 2020). In Germany, the Netherlands, Austria, and Finland, bans on landfilling and incineration of composite waste are already in place, while more countries are expected to follow (Chatziparaskeva et al., 2022). Even though Denmark is yet to introduce a landfill ban for WTB’s, operators in the industry, such as Ørsted and Vattenfall, have committed to ending landfill with immediate effect (Ørsted, 2021, Vattenfall, 2021). So far, other regions such as USA and Asia have not made similar calls or introduced legislation. In the study by

Cooperman et al. (2021), it was concluded that landfilling of WTBs would not pose a challenge for landfill capacity in USA in the future.

Back in 2009, Larsen (2009) described how landfilling of WTBs at EoL was on the way out; yet, by 2024 industrial-scale alternatives remain very limited. While WTBs are classified as “non-hazardous waste” recycling their materials remains a challenge due to the difficulty of recycling and the limited infrastructure available (Beauson et al., 2021). Some established alternatives to landfilling exist such as incineration and cement co-processing. Incineration allows for the WTB material to be burned and used for energy recovery. Yet, only the organic material fractions can burn and generate energy, and thus up to 60% of the WTB waste ends up as ash, which is typically landfilled (Jensen and Skelton, 2018). Thus, incineration is not considered a sustainable alternative (Ramirez-Tejeda et al., 2017). The route of cement co-processing is similar to incineration, but the heat generated from burning the material is used to heat the cement kilns, and the glass fiber fractions are used to replace sand and limestone in cement mixtures (Paulsen and Enevoldsen, 2021). This route was originally developed on a commercial scale by Zajonz Logistics GmbH, Holcim Ltd, and Fiberline Composites A/S in 2010 (Sakellariou, 2018). These alternatives are later described and elaborated on in Chapter 6 and Paper II but so far recycling of the WTB material is not cost-effective compared to landfilling (Halliwell, 2010).

05.02 Blade Ownership and Material Information

WTGs are large and costly constructions and, like with other products, responsibility for them rests with the owner. In this context, it means that when the WTG reaches its EoL, the owner is responsible for handling the demolition and waste. WTGs can be owned by private persons, private consortia, municipalities, public energy agencies, private energy organizations and in some cases OEMs. The diversity of ownership is demonstrated in the multiple case study presented in Paper IV. In all instances, the owner must handle the full project including the WTBs or employ one or more partners to do so. This effectively results in a diverse group of owners that must handle WTBs for which no sustainable waste management route currently exists.

To manage the WTBs at their EoL, it is important to know about the blade material composition and geometry. Without this knowledge, it is difficult to design and create a system of sustainable waste management processes. Therefore, it is essential for owners and material recyclers to have access to this information from the OEM. In April 2023, the DecomBlades research project launched a material passport with the intent of this becoming the new standard for the industry (DecomBlades, 2023). The material passport includes a full specification of blade materials and geometry. The level of information shared in the material passports was determined in a collaboration between the OEMs and waste management partners to ensure that the level of detail provided is sufficient to design and implement waste management processes without disclosing any confidential information. Such material passports provide the blade material and geometry information needed to start creating unified value chains to manage WTB waste.

05.03 Legislation and Standards

The role and effect of legislation on the development of new technologies and value chains to handle EoL WTBs have been vividly discussed among stakeholders in the industry, academics, and policy makers. The topic was raised at the End-of-Life Issues & Strategies (EoLIS) conference in 2022, where it was highlighted that the wind industry supports the landfill ban and the design and scaling of new sustainable options. Legislation can be a powerful tool in promoting sustainable behaviors such as recycling (Beauson et al., 2021). However, it is also suggested that this development will not be intensified through the push of legislation even though it might secure more research funding. This comes down to the fact that legal obligations and funding do not necessarily result in the availability of the right competences and efficient processes (Jensen, 2019).

The European Union (EU) has adopted several waste disposal directives, which require monitoring to ensure compliance with environmental regulations. One of the key legislative acts is the Waste Framework Directive (2008/98/EC) (European Commission, 2018), which sets waste management goals for EU member states, and thus directs how waste should be handled. The directive promotes a waste management hierarchy that prioritizes waste prevention, reuse, recycling, and recovery before disposal (landfill). Other legislative acts of relevance to WTB waste include the

Industrial Emissions Directive (2010/75/EU) (European Parliament and Council of the European Union, 2010) and the Landfill Directive (1999/31/EC) (European Parliament and Council of the European Union, 1999), which outline the standards for incineration and landfill in the EU, respectively. Germany has been one of the first movers in establishing a national waste management policy based on CE principles for material handling also referred to as the Circular Economy Act (Kreislaufwirtschaftsgesetz - KrWG) (The Bundestag, 2012). This law implements the EU Waste Framework Directive (European Commission, 2018) and addresses reuse and recycling of waste in production processes and avoidance of waste production. The aim is to ensure sustainable disposal of waste and promote resource efficiency though reuse and recycling. According to paragraph 6, waste management measures must align with the waste hierarchy prioritize: (1) prevention, (2) repairing for re-use, (3) recycling, (4) other recovery (including energy recovery), and finally (5) disposal (landfilling) (The Bundestag, 2012). This means that landfilling is a last resort and should only be used if all other options have been exhausted. This applies also to WTBs, where owners should aim for higher levels of circularity. In 2009, Germany also implemented a ban on landfilling of waste with an organic content higher than 5%, which effectively also covers WTBs due to the resin component being defined as organic (Chatziparaskeva et al., 2022, Cherrington et al., 2012). Other countries have introduced similar policies, e.g. Austria, Finland, and the Netherlands. In the Netherlands, WTB owners cannot landfill WTB waste unless they can document that the alternative is more expensive in EUR per ton. However, at the moment the alternative of mechanical recycling entails higher costs, meaning that effectively WTBs still end up as landfill (Chatziparaskeva et al., 2022).

Another tendency that could potentially lead to a change of EoL management, is the use of non-price criteria in public tendering processes when establishing new WTG sites. Such criteria have recently been introduced in the Netherlands (WindEurope, 2022a) and are qualitative criteria that are implemented to consider aspects other than price when evaluating WTG projects and selecting WTG suppliers. They include initiatives to protect the local environment and the sustainable removal wind farms after EoL (WindEurope, 2022a).

Besides directives and policies, there are standards that OEMs can adopt such as the DIN quality assurance standards. DIN 4866 standard (Deutsche Institut für Normung e.V. (DIN), 2020) on “Sustainable Dismantling, Disassembly, Recycling and Recovery of Wind Turbines” is specifically relevant for EoL WTBs. Developed by a consortium of 25 companies, the standard presents recommendations on how to secure the construction site, on dismantling, and qualifications needed, to comply with occupational health and safety and environmental protection regulations. However, the standard does not provide any environmental or technical r guidelines for recycling but suggests that the highest grade of material re-use or recovery should be applied, and to only utilize energy recovery or landfilling as a last resort.

05.04 Lifetime and Waste Volumes

WTBs have a design life of 20 years for onshore models and 25 years for offshore models according to the IEC 61400 design standards ((IEC), 2019a, (IEC), 2019b). The design life is the minimum time of operation, but many factors affect decommissioning decisions. As part of Paper I, which is presented in the following section, a literature review was conducted to identify research studies projecting the future waste mass from WTBs. An overview of literature that addresses future waste flows, including their applied methodology, geographical area of analysis, assumed lifetime of the WTBs, data gathering approach and timespan for the modelling is presented in Table 2. As shown in the table, numerous articles have studied EoL WTB waste flows in various geographical contexts to predict where and when WTBs must be handled (Andersen et al., 2016, Chen et al., 2021, Cooperman et al., 2021, Deeney et al., 2021, Heng et al., 2021, Lefeuvre et al., 2019, Lichtenegger et al., 2020, Liu and Barlow, 2017, Sommer et al., 2020, Sultan et al., 2018, Tazi et al., 2019).

Common for all the reviewed studies is that it is assumed that the life span of WTBs is close to their design life (i.e. 20 or 25 years). The study by Liu and Barlow (2017) predicts up to 2 million metric tons of WTB waste annually worldwide by 2025. At a European scale, Lichtenegger et al. (2020) estimates that 325 thousand metric tons of waste must be handled annually, also by 2050. While these predictions indicate large waste masses, so far, a relatively low number of WTGs have been decommissioned, and this discrepancy led to the formulation of the research aim for Paper I. Contrary to the reviewed academic publications in Table 2, the Danish National Energy Agency expects onshore WTGs to have an average lifespan closer to 35 years (Energistyrelsen, 2020). Thus, if WTBs are decommissioned later than expected, this effectively influences the actual volumes and waste flows making it less attractive to invest in EoL technologies. Hence, it is important to understand when waste masses will materialize as this will also have implications for the development of new value chains for handling the waste. In the following section, Paper I is presented and addresses the future waste flows of WTBs based on actual decommissioning data from Denmark.

Publi-cation year	Author	Method	Replicability	Geographical area of analysis	Lifetime applied	Predictive/ actual data	Data gathering approach	Timespan for modelling
2016	(Andersen et al., 2016)	Mathematical regression function.	Transparent, can be replicated	Sweden	20 yrs.	Predictive/actual (regression)	Database (VindStats) + prognosis future installations - empirical data for replacement rates for faulty components	2034
2021	(Chen et al., 2021)	Material flow analysis model. Weibull distribution	Transparent, can be replicated	Guangdong, province in South China	14,18 & 21 yrs.	Actual (Weibull distribution)	Dataset from Chinese Wind Energy Association + public development plans. Danish database for lifetime scenarios	2050
2021	(Cooperman et al., 2021)	Not disclosed	Not transparent, cannot be replicated	US, state level	20 yrs.	Predictive	Database (USWTDB) + prognosis of future installations (NREL)	2050
2021	(Deeney et al., 2021)	Integrated GIS and spatiotemporal approach. Kernal density estimation (KDE)	Somewhat transparent, cannot be replicated	Isle of Ireland	20 yrs.	Predictive	Database (the WindPower) + manufacturer specifications	2040
2021	(Heng et al., 2021)	Mathematical modelling Life cycle assessment (LCA)	Transparent	Canada	20,25 &30 yrs.	Predictive	Public datasets & literature data	2050
2019	(Lefeuvre et al., 2019)	Material flow analysis of predicted consumption + 25 yr life span (linear)	Transparent, can be replicated	Worldwide	25 yrs.	Predictive	Literature data	2050
2020	(Lichtenegger et al., 2020)	Linear regression, stochastic distribution on official decommissioning data	Transparent but calculations/functions not disclosed.	Europe, country level	18 yrs.	Actual (regression)	Database of operational wind farms + GIS software + historical data + forecast scenarios	2050
2017	(Liu and Barlow, 2017)	Mathematical function + lifetime scenario generation	Transparent but calculations/functions not disclosed.	Worldwide	18,21 & 26 yrs.	Predictive, 3 scenarios	blade data from manufacturers + database from wind associations + interviews	2050
2020	(Sommer et al., 2020)	Stochastic modelling (stochastic lifetime distribution), simulation study	Transparent, can be replicated	EU-28	17 yrs.	Actual (Stochastic distribution)	Combination of public datasets	2030
2018	(Sultan et al., 2018)	Mathematical modelling. Centre-of-gravity method	Transparent for center of gravity not for waste flow identification	United Kingdom	25 yrs.	Predictive	Literature data (lifetime) + public database	2048
2019	(Tazi et al., 2019)	Material flow analysis (MFA)	Transparent and reproduceable	France, Champagne-Ardenne (CA) region	15 yrs.	Predictive	Public database, industrial and literature data.	2020

Table 2 - Literature overview for WTB waste flow modelling

05.05 Paper I – Method for Estimating the Future Annual Mass of Decommissioned Wind Turbine Blade Material in Denmark

In the following sections the purpose, methodology, findings, contributions, and implications of Paper I are presented. The paper was done in collaboration with researchers from the Technical University of Denmark (DTU) and was published in Journal of Wind Energy in 2024. The lead-author was Asger Bech Abrahamsen, PhD and Senior Researcher from DTU while my contributions were research scoping, literature review and paper review. The full paper is appended.

Purpose – It is essential to estimate the future mass of WTB waste to establish feasible EoL solutions and value chains. Previous literature has assumed that the lifetime of a WTB was equivalent to the design life of the blade. However, data from Denmark indicates that this is not the case. Thus, the purpose of this study is to estimate the future waste mass of EoL WTBs in Denmark based on the master data register from the Danish Energy Agency. Furthermore, the aim is to describe the decommissioning of WTBs in Denmark as a depletion process of the different installation years with one general distribution as a function of time.

Methodology – This research utilizes the “Master data register for wind turbines” provided by the Danish Energy Agency, which holds data on all wind turbines commissioned in Denmark since 1977. The data includes commissioning and decommissioning dates for all WTGs. Based on the data, a model of the evolution of the onshore WTB mass installed in Denmark is proposed. Using a Weibull distribution, the model is based on a general relation between the mass and length of the WTBs, which is established using literature data. The depletion of the WTG fleet is determined as the ratio between the decommissioned turbine blade mass by 2021 and the installed blade mass of a certain installation year. Based on the analysis, an estimate of the future decommissioning blade mass of the Danish onshore and offshore fleet is provided.

Findings – Based on the proposed model using a Weibull distribution and the analysis of the data, it is found that the estimated average time to decommissioning for WTBs in Denmark is 29 years. This is when half of the WTB mass of a given installation year is decommissioned.

Compared to previous studies, which assume the design life of 20 years as the time to decommissioning, the findings of this research show that in Denmark the actual decommissioning time is nine years later. Furthermore, the findings conclude that the WTB mass being decommissioned in Denmark will peak at 2000 metric tons a year in 2028 and again at 5000 metric tons in 2045. Based on the model and Weibull distribution describing the Danish onshore WTG data, only 1.7% of WTBs will be decommissioned at the end of their design life of 20 years.

Novel contribution and research implications – The findings are in significant contrast to previous EoL WTB mass prediction studies as findings suggest that there is a substantial delay between the WTB design life and the decommissioning time of around nine years. This underestimation of the real EoL time for WTBs has important implications for the development and industrialization of recycling value chains, which require a certain amount of WTB material to make a profitable business case. Thus, these results also provide an understanding of why circular EoL value chains for WTBs do not exist today. Future research is suggested where the proposed fleet depletion model of this paper is applied to other European countries to create a total estimate of the future WTB waste mass in Europe.

05.06 Uncertainties in Expected Waste Volumes and Implications for EoL Value Chains

Paper I included a discussion of the potential uncertainties associated with the expected waste volumes. This section will present the main points of this discussion and how this will affect the development of new EoL value chains for WTBs. As presented in a previous section on blade ownership, WTBs are owned by a diverse group of owners, who are responsible for decommissioning the blades. Thus, the owner also determines when the WTB is seen as waste, and several factors can influence when this decision is made.

The global energy crisis starting in 2021 hit hard in Europe and caused the price of electricity to increase (International Energy Agency, 2024b). Thus, keeping WTGs in operation and postponing decommissioning can be profitable when operating and maintenance costs remain below the sales price of the electricity produced. Another source of uncertainty is that even though a WTG or WTB is decommissioned, it does not necessarily mean that it has reached its EoL. Older WTGs can be resold to secondary markets for a second operation period, but it is not documented how large a fraction of decommissioned WTGs are resold. It can therefore not be assumed that the WTB mass decommissioned is equivalent to the WTB mass that must be handled at EoL.

These uncertainties can both lead to a slower depletion of WTBs that must be managed at their EoL. As previously noted, the depletion rate will affect the attractiveness for investments and establishment of EoL value chains and technologies for potential investors and waste management partners. The business case for the organizations that invest in new solutions can be affected negatively without sufficient waste volume, which can cause a lack of profitability and closure of the organization. If waste masses are appearing in a slower rate as suggested in paper I, it can have a positive impact as it provides the industry with more time for developing and scaling EoL technologies and value chains. The negative consequence is that the "burning platform" for establishing new sustainable solutions is less urgent for the owners, ad less attractive for investors of EoL value chains.

05.07 Public Perception of the Wind Energy Sector – a Danish Context

Besides the industry and policy makers, external stakeholders such as the public and the media have an influence on the discourse of the technical developments and how the industry is perceived. Public opinion might lead to further legislation or change in perception of the industry as a whole. Part of the PhD study included a study of the public perception of the EoL management of WTBs in a Danish context. The study aimed to identify the general discourse in Danish media of EoL management of WTBs and how the discourse has developed over time.

A narrative literature review of grey literature published in Denmark was therefore conducted in the Danish national media archives called Infomedia. The search applied a systematic keyword approach and included both printed and digital articles from over 2500 sources published since 1990 (Infomedia, 2022). Furthermore, snowballing was applied to identify other relevant articles such as press releases etc. that were not included in the initial search. Sixty-nine articles were identified, assessed, and classified as either positive, negative, or neutral towards the WTG industry on the topic of EoL WTBs. A full reference list of the sixty-nine articles is found in Appendix IIX and the full assessment can be provided upon request. Yet, this section includes the main findings.

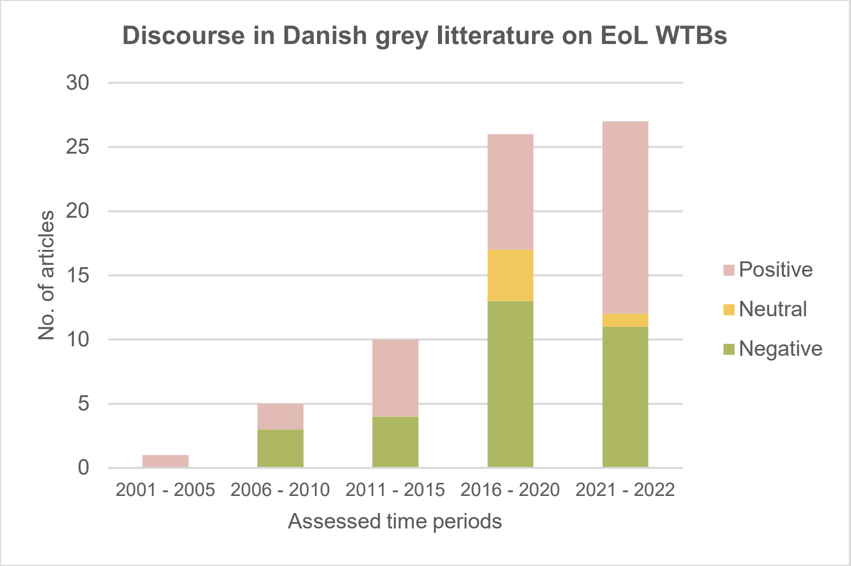


Figure 5 - Public discourse in Danish grey literature on EoL WTBs

Based on this assessment, the discourse was identified for five-year periods from 2001-2022 and illustrated in Figure 5. As the figure illustrates, the general discourse and perspective on EoL WTBs in the Danish media varied over the period investigated. As clearly indicated by the findings, coverage of the topic of EoL WTBs in the Danish news media has increased rapidly since 2001. Between 2000 and 2015 there was an almost equal distribution of positive and negative articles on the topic but with only a small number of articles per period. A shift in the discourse occurred in the period from 2016 to 2020, which marked a turning point for the wind power industry. In this period, the number of publications increased and with only nine of the 26 articles being positive. In the recent years, a significant increase in coverage of the topic can be seen commencing with a range of articles with a negative discourse in the years of 2019 and especially 2020. Yet, in the most recent period from 2021 to mid-2022, a shift in the opposite direction occurred with 16 positive articles out of a total of 27.

At regular intervals, stories on the reoccurring topic of 'wind turbine blades are a waste problem' emerge in different versions. Yet, the overarching topics of the articles have not changed significantly for over 20 years. The main challenges described include: (1) increasing waste volumes, (2) limited end-of-life options, (3) underdeveloped and costly technologies, (4) lack of industrial scale solutions, (5) landfill options are available at a low cost, and (6) a lack of regulation providing no incentive to seek and develop alternative methods. The last point is seen as a negative incentive to find alternative solutions and causing a slow development in overcoming barriers to improve the EoL options. The industry's main response to this argument has been that waste volumes have simply not been significant enough to establish dedicated value chains at reasonable costs. While various projects have been undertaken during the past 20 years targeting EoL for WTBs, recent years have seen a more rapid development in terms of process technologies but also strategic targets, initiatives, and collaborations. This trend has also been evident in Danish media, resulting in a significant increase in coverage in 2021-2022, as illustrated in Figure 5.

The analysis of the Danish media discourse on EoL WTBs shows that the topic has contributed to negative publicity for the wind industry in general. Landfill of decommissioned WTBs has been, and still is, a black spot on the green image that the wind industry seeks to promote of their products and the technology in general. Nevertheless, the articles and stories told by the Danish media not been entirely negative, and positive aspects such as innovation initiatives and collaboration between partners in the industry have been highlighted. This trend has since changed, and the discourse was mainly positive during the years of 2021 and 2022, driven primarily by industry initiatives to end landfill of WTBs. Thus, the study concludes that innovation projects, such as DecomBlades, can change the public discourse.

05.08 Discussion and Conclusion – Barriers to Circular Value Chains for EoL WTBs

To understand why circular EoL value chains for WTBs are not present today, several themes and barriers have been analyzed and outlined in this chapter. The analysis has resulted in the identification of eight main barriers that explain why sustainable EoL value chains for WTBs are not in place. The eight barriers are consolidated in Figure 6 and elaborated on in the sections below and highlight important aspects that must be addressed by research, the industry and policy makers. Even though the challenges of EoL WTBs have been known for years, the **low and unpredictable volumes of waste** have made it difficult to create industrial-scale solutions other than landfill. The results from Paper I demonstrated that simply assuming a standard lifetime of a WTB equivalent to its design life will result in an overestimation of waste volumes. This is a problem for waste management organizations that should invest in the knowledge, equipment, and capacity needed to treat WTB waste, as they would need relatively consistent material flows and volumes to create a business. They have not been available so far.

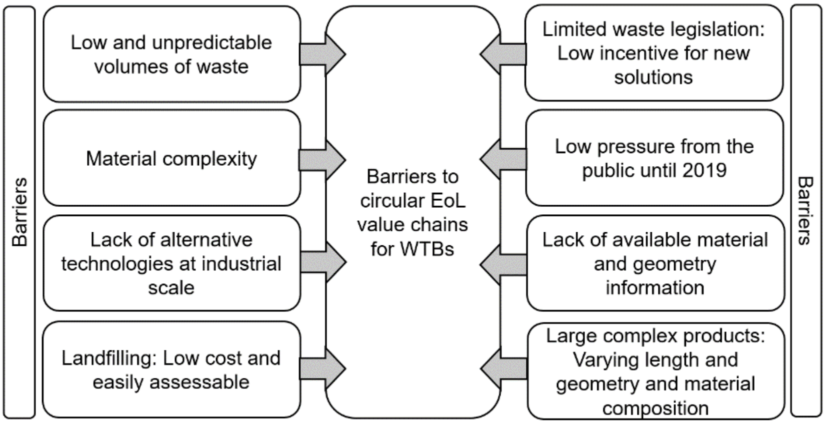


Figure 6 - Barriers to circular value chains for EoL WTBs

While the blade **material complexity** outlined in Chapter 2 constitutes a significant challenge to creating new EoL solutions, the low and unpredictable waste volumes are also found to be impacting the **lack of alternative technologies at an industrial scale**. The use of **landfilling** has therefore been a favorable solution given its wide availability, accessibility, and low cost.

The findings have shown that EoL management has not been a concern until recently due to **limited waste legislation.** However, in the recent years, new international directives and national landfill bans have increased the motivation to solve the challenge of WTBs at their EoL. Furthermore, the findings also show that there was a **low pressure from the public** until around 2019, since when the topic has attracted increasingly negative attention. This tendency is also highlighted in Paper II presented in Chapter 6, where findings show that academic literature on the topic vastly increased from 2017.

WTBs are **large complex products** of varying lengths, geometries, and material compositions. These variations are barriers to designing circular waste solutions with standardized operations. Thus, to create such solutions, waste management organizations must also have access to sufficient **material and geometry information** to manage EoL operations and sell the secondary materials for new applications. This information has not been readily available so far, and the recent launch of the product material passport is therefore an important contribution to overcoming this barrier.

Even though the findings presented in this chapter emerge primarily from a Danish context, they are still considered to be generalizable across Europe to some extent. National differences, for example within legislation, public perception, knowledge etc., can influence the extent and effect of a given barrier. The barrier of low and unpredictable volumes of waste can also vary since WTG fleet depletion rates are influenced by national factors such as incentives to upgrade existing WTG with new blades, as seen in France (Tazi et al., 2019), or high energy prices, leading to WTGs operating for longer. However, barriers to do with material complexity, lack of industrial-scale technologies, ease and cost of landfilling, operational issues of large complex products and lack of material and geometric information are considered general across markets, since these pertain to the technical development and the nature of the WTBs.

In conclusion, the answer to the research question is multi-faceted as findings show at least eight main barriers to creating sustainable value chains for EoL WTBs. As Figure 6 highlights, there are essential barriers that must be overcome to facilitate the design, operation, and industrialization of circular value chains for WTBs. However, some of the barriers are already being addressed. The need for collaboration and the lack of available technologies are addressed by the many collaborative industry and academic research projects on the topic which will be analyzed in Chapter 6. The pressure from the public has increased since 2019 with negative press, but in recent years, positive stories on new technological developments have appeared. The lack of available material and geometry information has been addressed by the introduction of the material passport standard, and finally, the low incentive to exclude landfill is addressed by owners self-imposing landfill stops and the introduction of non-price criteria in tender processes for new WTG sites. In other words, progress is happening but there are still barriers to tackle.

06 Development of Roadmap for End-of-life Wind Turbine Blades

In Chapter 5 it was established why sustainable industrial-scale value chains for EoL WTBs are not in place today. Furthermore, based on results from Paper I, it was concluded that even though future waste volumes of WTBs might be delayed, a significant increase in waste is still to be expected in the coming decades. Thus, with vastly increasing waste volumes and a lack of industrial-scale EoL solutions, there is a clear problem to be solved. In this chapter, technologies and processes that could be potential solutions for EoL WTBs are therefore explored, by adopting a value chain perspective to answer the following research question:

Sub-RQ2: Which EoL value chain routes are potential end-to-end solutions for wind turbine blades, and what technologies and processes are included in the design of these solutions?

To answer this research questions, two studies will be presented and elaborated on, followed by a consolidation of the results from each study as outlined in Figure 7.

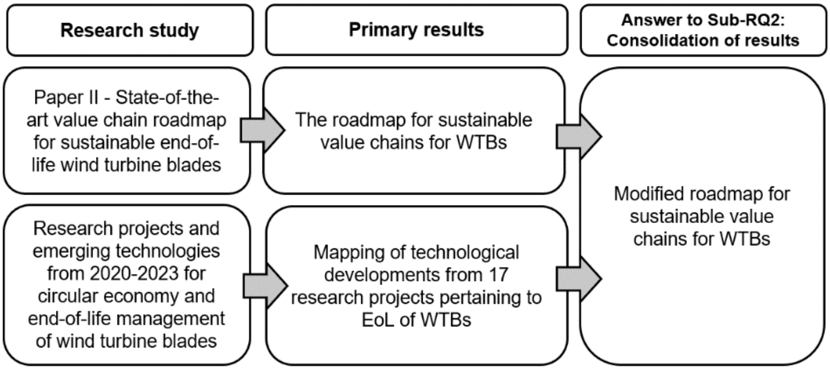


Figure 7 - Outline of method for consolidation of research results.

First, Paper II titled: 'State-of-the-art value chain roadmap for sustainable end-of-life wind turbine blades', is presented. Paper II adopts a systematic literature approach and includes a review of 61 publications pertaining to the topic of EoL WTBs identified through academic literature. Through a meta-analysis of the publications, all findings are mapped in the roadmap for sustainable value chains for WTBs. The findings of Paper II do not include results or themes that have not yet been published in academic literature. Thus, to understand the newest developments on the topic, a second study was developed and completed. The study is titled 'Research projects and emerging technologies from 2020-2023 for circular economy and end-of-life management of wind turbine blades'. This study consisted of a review of 17 ongoing research projects on EoL management of WTBs. The project characteristics were mapped, including new emerging research fields and technologies. The findings from the study were discussed and validated by key academic and industrial experts. Finally, to answer the second sub-research question, the findings of the two studies were consolidated and elaborated on in a modified roadmap for sustainable value chains for WTBs. The modified framework was shared, evaluated, and discussed in a focus group interview, where seven industrial stakeholders representing EoL value chains processes were included.

06.01 Paper II – State-of-the-art value chain roadmap for sustainable end-of-life wind turbine blades

In the following sections, the purpose, methodology, findings, contributions, and implications of Paper II are presented. The paper was published in Journal of Renewable and Sustainable Energy Reviews in 2024. For full paper, see Appendix II:

Purpose – The purpose of this research study was to identify and map complete state-of-the-art value chain routes for EoL management of WTB waste, including the technical, operational, and logistical-processes needed to establish fully functional value chains for EoL WTBs. The study aim was two-fold as it first examined the state-of-the-art in the academic literature for EoL WTB value chains for to determine the topics and themes addressed in research so far. Secondly, the study examined how fully functional sustainable EoL WTB value chains are designed and operated from the original site and until secondary products are manufactured.

Methodology – The study adopted a systematic literature review methodology to identify all relevant academic literature and provide a reproduceable and transparent state-of-the-art analysis of the research field. A literature search strategy including six steps was developed leading to the identification of 61 publications that were included in the review. The publications were screened based on a pre-defined protocol consisting of four themes that represent the processes and activities required for EoL value chains for WTBs. Under the four themes, 16 research topics were identified, and each publication was screened and coded according to the topics that it addressed. The publications were also coded according to publication year, applied research methodology and geographical origin. A meta-analysis of the findings across the reviewed publications was conducted, which resulted in a presentation of the state-of-the-art of academic literature and the development of the roadmap for sustainable EoL value chains for WTBs.

Findings – The study presents an overview of academic literature according to four research themes of: (1) planning and assessment of EoL value chain projects, (2) EoL value chains and operations, (3) R-technologies, and (4) material properties and application. The findings showed that 50% of the reviewed publications consist of literature reviews, 25% were lab-studies of R-technologies, while the remaining 25% were a mix of various data modelling approaches and a few case studies. The study showed that research has predominantly been conducted in the USA and Northern Europe. A key finding was that no empirical case studies of full EoL WTBs projects were documented in literature, which leaves a knowledge gap. Empirical cases and data are important for the development and design of new EoL value chains and to identify and research solutions of operational challenges. The study also showed that R-technologies for WTBs is the research theme that has received the most attention. The research topic of operations and logistics, such as blade sectioning, transport, and pre-processing of WTB material, has been almost absent. Thus, it is concluded that a clear knowledge gap exists regarding the research theme of EoL value chains and operations. Research on partner collaboration, future waste masses, the environmental impact of R-technologies and the impact of legislation was also found to be scarcely addressed in academic literature. Secondly, the study presents a novel framework: the roadmap for sustainable value chains for WTBs depicted in Figure 8. The roadmap presents six EoL routes, each representing a potential EoL solution and R-technology pertaining to the circular strategies of material repurposing, recycling, or energy recovery. The routes include all the necessary value chain process steps of (1) dismantling and preparation, (2) sectioning of blades for transport, (3) 1st preprocessing, (4) 2nd preprocessing, (5) material processing (R-technology), and (6) final product or application. Within each value chain, the potential technology and equipment that can be applied are listed.

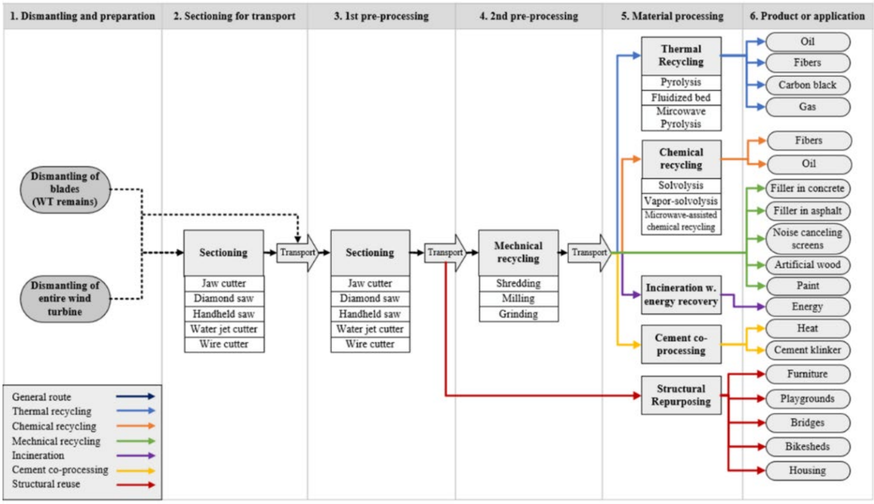


Figure 8 - The roadmap for sustainable value chains for WTBs from Lund and Madsen (2024)(From Paper II, Appendix II)

Novel contribution and research implications – The study provides two novel contributions to the field of EoL WTBs. First, it provides the first comprehensive systematic review and value chain perspective in academic literature on EoL WTBs and highlights important knowledge gaps for future research. Second, it presents a novel roadmap for sustainable value chains for WTBs. The roadmap provides a complete state-of-the-art value chain overview, which both academics and practitioners can adopt to design, operationalize, and scale future waste solutions. Thus, the study findings have important implications for both industrial organizations wanting to contribute to future EoL value chains as well as WTB OEMs and owners seeking to improve their level of material circularity and thus their environmental impact.

06.02 Research Projects and Emerging Technologies from 2020-2023 for Circular Economy and End-of-life Management of Wind Turbine Blades

The purpose of Paper II was to assess the state-of-the-art in the academic literature. However, research results take time to be published and not all technical developments are necessarily reported in the academic literature. Thus, a research study was developed and conducted with the aim of identifying and assessing research projects currently in progress. The focus was on the project descriptions and reported findings to evaluate how these results could influence the current state-of-the-art presented in Paper II. The study provides an overview of 17 collaborative research projects that have been initiated since 2020 (after the start of the DecomBlades research project) on the topic of circular EoL composites and WTBs. The 17 research projects were presented and described, including partners, funding, research aims, and aspects of the value chain for EoL WTBs addressed. Key research findings from the projects were identified and reported, and finally it was explained how these findings influence future research agendas for EoL management of WTBs to achieve a higher level of circularity.

06.02.01 Methodology

The study presented in this section was developed based on two combined approaches. First, a comprehensive list of research projects developed by the project members of the IEA Wind Task 45 obtained from the Technical University of Denmark was used as a data base (International Energy Agency, 2024a). The list included all identified research projects pertaining to WTBs and the repurposing, recycling, or prevention of waste. The list was screened, and research projects initiated at the same time or after the start of DecomBlades were included (2020-2023) to capture information that had not been part of the assessment made prior to starting the project. The identified research projects were investigated based on available online project information as most of the projects had not yet published any results. To standardize the assessment, all the research projects were screened based on: Name of project, kick-off year, external funding agency, external funding amount, technologies investigated, included partners, original project description and value chain steps addressed. Following this process, the findings from the analysis were grouped according to themes and the results were elaborated on.

Solvolysis was found to be the technology that had seen most research progress in the period, and it has therefore been addressed in a dedicated section.

The second approach was to assess and validate the results. First, the research findings were peer-reviewed and discussed with two senior researchers from the research field for further insights and a validation of the results. Second, the technical details and developments of the solvolysis technology from the CETEC project were validated through a structured interview (Flynn et al., 1990) with the Senior Specialist – Sustainability and Advanced Materials from the OEM who was a part of the CETEC research project group.

The scope of this study was to provide technological insights and to identify new initiatives in the three-year period. The method for this study was not exhaustive, and there might be projects or developments that were not included. However, the approach, the number of identified projects and the subsequent triangulation process are deemed sufficient for the study aim. Finally, the study did not include an assessment of TRL or direct recommendations of technologies or processes for future value chains. This was because it was found almost impossible given the (lack of) available information from the research projects in progress and the current TRL of the technologies.

06.02.02 Analysis and Results

Table 3 presents the 17 projects including their main project characteristics. In the following sections, the main findings will be presented.

Project name	Kick-off year	External funding agency	External funding amount (EUR)	Classification of research focus	Primary technology researched	No. of partners	Value chain steps addressed
Blades2Build (European Commission, 2023a, Blades2build, 2023)	2023	EU - Horizon	€ 12,362,239.68	Recycling	Cement, structural reuse	14	Not clearly described
EoLO-HUBs (European Commission, 2023b)	2023	EU - Horizon	€ 9,994,682.38	Recycling	Solvolysis and Pyrolysis	15	Steps 1-6
REFRESH (European Commission, 2023f)	2023	EU - Horizon	€ 11,462,602.00	Recycling	Mechanical recycling and pyrolysis	11	Steps 1-6
Project from University of Sydney (Williamson, 2023)	2023	NA		Recycling	Pyrolysis	NA	Step 5 - Pyrolysis
TURBO (European Commission, 2023g)	2022	EU - Horizon	€ 6,813,734.00	Prevention	Reduce production scrap	9	NA
Wind Value (Wind Value, 2023)	2022	Irish Research Council	NA	Decision support	NA	3	NA
RECREATE (European Commission, 2023e)	2022	EU - Horizon	€ 8,358,044.00	Recycling / prevention	Green solvolysis and electro fragmentation	21	Focus on steps 5 and 6
ESTELLA (European Commission, 2023c)	2022	EU - Horizon	€ 4,966,474.00	Prevention	New resin	13	NA
CIRCUBLADE (Chalmers Industriteknik, 2023)	2022	Vinnova	€ 301,724.14	Repurposing	Structural reuse	9	Steps 1-6
REKOVIND2 (RISE, 2023)	2022	Swedish Energy Council	€ 103,448.28	Repurposing/ recycling	Solvolysis, pyrolysis, mechanical recycling.	NA	Not clearly described
EuReComp (European Commission, 2023d)	2022	EU - Horizon	€ 8,903,632.50	Recycling	Recycling - not specified	20	Not clearly described
CETEC (Ahrens et al., 2023, CETEC, 2023)	2021	Innovation Fund Denmark	€ 1,409,395.97	Prevention	Chemical processing: solvolysis	4	Step 5 - material processing
WindLEDeRR (MaREI, 2021)	2021	Sustainable Energy Authority of Ireland		Repurposing	Repurposing - specific purposes	7	Not clearly described
VIBES (European Commission, 2023h)	2021	EU - Horizon	€ 4,224,039.25	Recycling	Chemical process - Solvolysis	13	Step 5 - Material processing
SUSWIND (National Composites Centre, 2021)	2021	NA - possibly the National Composites Centre		Recycling	Mechanical recycling and cement co-processing	13	Steps 1-6
ZEBRA (LM Wind Power, 2023, JEC Composites, 2022)	2020	Unclear	€ 18,500,000.00	Prevention	New resin	7	NA
CARBO4POWER (European Commission, 2020a)	2020	EU - Horizon	€ 6,996,860.75	Prevention	New material systems	19	NA

Table 3 - Research projects on EoL of WTBs initiated in 2020-2023

06.02.03 Funding and Partners

Thirteen of the 17 projects involve seven or more partners. Common for most of the projects is that partners include a mix of universities, research institutions, blade producers, blade owners and material or technology providers. Most projects include a WTB OEM, but none of the projects include multiple OEMs. Nine out of 17 projects are funded by the EU through the EU Horizon program. Besides it being a significant number of projects receiving funding from EU, they all consist of 9-21 partners and have received a total of EUR 74 million in direct funding. Most projects involve a relatively low investments by the participants compared to the funding received. The projects that received the most funding are Blades2Build and REFRESH, both started in 2023 and have received EU horizon funding of EUR 12.3 million and EUR 11.4 million, respectively. From this brief financial overview, it can be concluded that there are significant funding possibilities through the EU Horizon program and that there is a growing interest and willingness to address and invest in solutions for EoL WTBs and material circularity.

06.02.04 Research Focus and Technologies

The 17 projects address various aspects of EoL management of WTBs, from prevention initiatives to recycling technologies. The research focus of the projects varies: Two projects, Blades2Build and SUSWIND, address cement co-processing. REFRESH, REKOVIND2, and SUSWIND focus on mechanical recycling. Four projects, EoLO-HUBs, REFRESH, REKOVIND2 and the (unnamed) project by University of Sydney, focus on pyrolysis. Three projects research new resin material systems for future blade production. The three projects are ESTELLA, ZEBRA and CARBO4POWER. Five projects, EoLO-HUBs, RECREATE, REKOVIND2, CETEC, and VIBES, all do research into solvolysis. Finally, one project is focusing on structural reuse, being the project of CIRCUBLADE. The TURBO project focuses on reduction of scrap in initial blade production, while the Wind Value research project seeks to provide support for decision makers.

By categorizing the projects by their research focus, it becomes clear that solvolysis (chemical recycling) followed by pyrolysis (thermal recycling) are the technologies receiving the most attention. Common for both pyrolysis and solvolysis is that the TRL is currently low at levels 7 and 5, respectively (Paulsen and Enevoldsen, 2021). Yet, with the current investments and research focus on these technologies, significant progress could be made in the coming years. This is supported by the development of the pyrolysis process achieved by the DecomBlades project which is reported in appended Paper IV, and by the development of solvolysis announced in 2021 by Siemens Gamesa Renewable Energy with the recyclable blade (Siemens Gamesa Renewable Energy, 2021) and by Vestas and the CETEC project in 2023 (CETEC, 2023). Both projects are described further below.

06.02.05 Value Chain Design

The roadmap for sustainable EoL value chains for WTBs developed in Paper II (Figure 8) identified six main routes that a WTB can go through at its EoL, including six overall process steps. As part of the current study, it has been assessed which of these value chain steps each research project contributes to (if any), and results are listed in Table 3.

Based on the project descriptions, it was found that Blades2Build, EoLO-HUBs, REFRESH, CIRCUBLADE and SUSWIND are taking a value chain approach by addressing steps 1-6, meaning operations on site, pre-processing, and logistical processes, as a part of the research project. This implies an acknowledgment of the need for value chain design of all involved processes, and of the fact that more and more projects include these aspects in their project objectives and scope. However, several of the projects also deep-dive into *step 5 – material processing* for solvolysis and seek to develop this further, including RECREATE, CETEC, and VIBES.

06.02.06 Main Developments Since 2020

Besides the 17 projects reviewed in this study, three major technical developments were announced during the period. First, in 2021, Siemens Gamesa Renewable Energy announced the launch of a new recyclable blade as the first OEM in the industry (Siemens Gamesa Renewable Energy, 2021). The development was a new resin system that allowed blades made with a modified resin to be recycled in the future through a chemical recycling process. The fact that the blade could be recycled marked a new beginning for recyclable resin systems. Other projects have been identified that aim to achieve similar results such as

CARBO4POWER (European Commission, 2020a) and ESTELLA (European Commission, 2023c).

Second, in 2022, the ZEBRA project announced that they had succeeded in making the world's largest thermoplastic blade using a new resin technology. The blade was produced by LM Wind Power and served as a prototype for the project to test the recyclability of the materials (JEC Composites, 2022). Common for both these technological developments is that they are based on new resin technology and that the advantage of recyclability cannot be achieved until the blade reaches its EoL. These results do therefore not influence already existing blades and their recyclability.

The third announcement was made by Vestas and the CETEC project at the beginning of 2023 (Hill, 2023). The project announced that they had successfully separated cured epoxy resin from the remaining material fractions in Vesta's epoxy blades using a chemical solution. The difference between this and the other identified projects is that the method enables separation of materials in existing blades. Thus, this technological development could have implications for EoL value chains for WTBs. For this reason, the results from the CETEC project will be further described in the next section.

06.02.07 Solvolysis Results from the CETEC Project

To obtain more information on the CETEC project, an interview was made the Senior Specialist in Sustainability and Advanced Materials from Vestas who participates in both the CETEC project and a follow-up project. The information and findings from the interview are summarized here below and have been verified by the informant (Senior Specialist – Sustainability and Advanced Materials, 2023).

The initial CETEC project was finalized in early 2024, but a two-year follow-up was already started in 2023 by project partners Vestas, Stena Recycling and Olin. The aim of this project is to mature the solvolysis technology from its current stage of test runs of 100-1000g of material to a TRL of 6, with a test amount of 1 ton. The objective of the project is to reach a point where it can confidently be decided what a facility and setup for the processes should look like, and whether it is feasible to build or not. The project will be concluded in 2025. The developed solvolysis technology includes a two-step process for separating the resin fraction of WTBs from the remaining materials. The process can run on both full WTB sections and grinded WTB material. Besides EoL WTBs, composite production waste can also undergo this process.

The first step is to submerge the WTB material into a solvent catalyst fluid, which transforms the cured epoxy resin material into a powder. The powder can then be fully separated from the remaining material fractions in the WTB. Since the solvent just acts as a catalyst, solvent consumption of is minimal. The solvent used is not disclosed but is said to be a standard chemical material currently procurable. Step two is a chemical recycling process whereby the epoxy powder is processed through an extra process step at the epoxy manufacturing facility, transforming the epoxy resin into what is chemically the same as virgin material and which can be used at the same level, thus substituting virgin materials (Ahrens et al., 2023).

The solvolysis process developed by the CETEC project does not address EoL management of WTBs in terms of on-site operations, logistics or pre-processing (value chain steps 1-3). Furthermore, the CETEC project has not investigated how the developed solvolysis process influences the quality or the cleanliness of the glass or carbon fibers. Nor does it address the recycling of glass fibers, wood, PET foam or any composites made with polyester, vinyl ester etc. from the blades. The process is tested only on the epoxy system used by Vestas and on no other epoxy variations. Thus, to summarize, there is still a great need for the value chains presented in Paper II to be addressed. However, this development is a positive step forward in that the solvolysis process can be used as a separation process (value chain step 4) followed by further material processing through other technologies such as remelting of the glass fibers.

06.02.08 Sub-conclusion – Research Projects and Emerging Technologies from 2020-2023 for Circular Economy and End-of-life Management of Wind Turbine Blades

Seventeen research projects in progress and initiated since 2020 have been classified according to project focus, primary technologies researched, number and nature of partners, and how they link to the value chains needed for processing EoL WTBs. Common for the projects are that most projects is cross-collaborative and include multiple partners.

The projects are mostly based on external funding with the EU Horizon program being the primary funding agency. A total of EUR 74 million has been received from EU Horizon across nine projects between 2020-2023. The main research focus of the projects is on solvolysis and pyrolysis, indicating a growing interest in the potentials of these technologies. During the period, the main technological developments are within recyclable resins, solvolysis, and pyrolysis. It is also acknowledged that for full value chains to be realized, additional steps of product refinement must be explored.

06.03 Modified Roadmap for Sustainable Value Chains for End-of-life Wind Turbine Blades

Paper II presented a roadmap for sustainable value chains for end-of-life wind turbine blades in Figure 8, which was derived from the state-of-the-art in academic literature. The roadmap consists of six value chain steps and six potential EoL routes for WTBs. However, as shown in the second study on research projects and emerging technologies presented in this chapter, recent technical developments have occurred that must be considered. In addition, the proof of concept (PoC) for the pyrolysis route developed in the DecomBlades project, described later in Paper IV and Chapter 7, has also led to additional insights and findings as regards the pyrolysis route. These additional findings are important to answer the research question of which EoL value chain routes are potential end-to-end solutions for WTBs and what technologies and processes should be included. Thus, based on a consolidation of the findings from the two presented studies, a modified version of the roadmap presented in Paper II has been developed. The research findings and modified roadmap have been shared, evaluated, and validated through a focus group interview, where seven industrial stakeholders representing both OEMs and the thermal, chemical, and mechanical recycling routes were included. Based on this evaluation, a few adjustments were made, resulting in the roadmap presented in Figure 9. The roadmap was found to be accurately presenting the challenges pertaining to creating full-scale value chains for EoL WTBs. The feedback from the focus group interview included the importance of the addition of steps 6 and 7 to the roadmap and the fact that research and development is still needed on the output materials to reach commercialization.

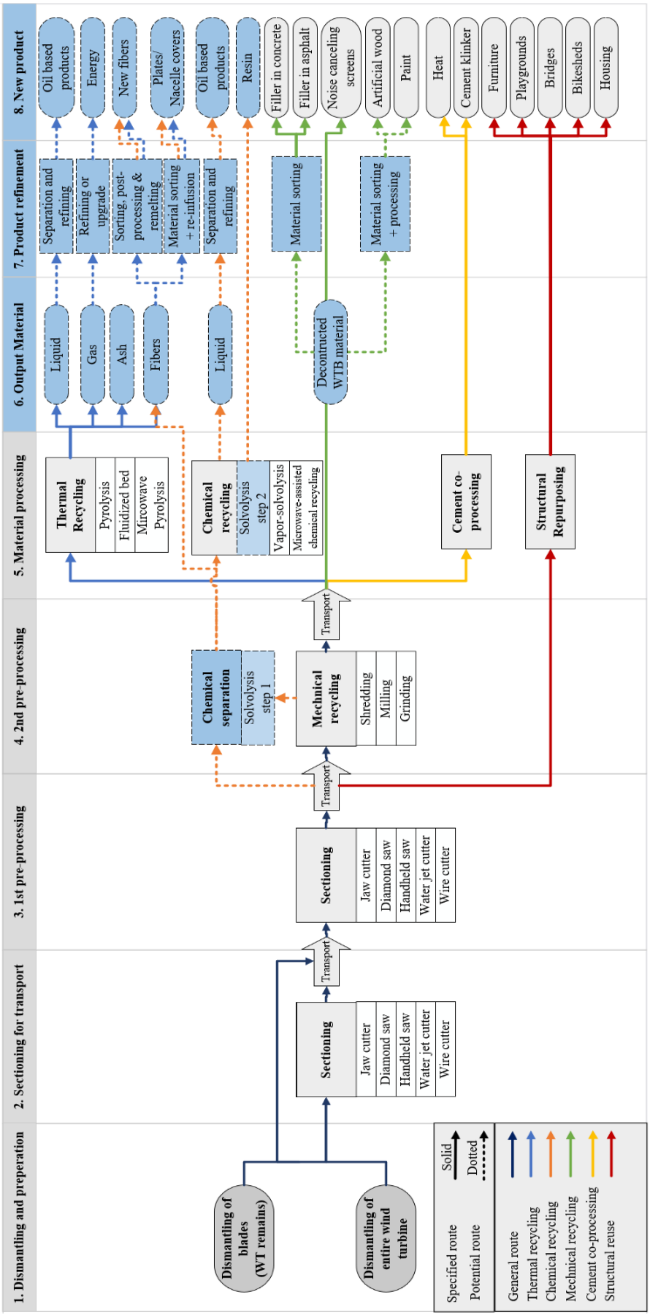


Figure 9 - Modified roadmap for sustainable end-of-life value chains for WTBs

The findings and their prospective impact on future value chains for EoL WTBs are visualized in the modified roadmap in Figure 9. All the modifications to the roadmap in the form of additional value chain steps, new technologies, new process steps and new products are marked in blue. The additional or modified EoL routes are presented with dotted lines/arrows.

Besides two additional value chain steps, the findings particularly on the solvolysis and pyrolysis processes have resulted in modifications. These include the use of solvolysis as a 2nd pre-processing step that future value chains could utilize for material separation even for large sections of WTB material. The two steps of solvolysis conducted in the CETEC project are also depicted, including the resin as a new product. The route of thermal recycling, i.e. pyrolysis, has also been modified to take account of the findings and learnings from the DecomBlades PoC. The PoC resulted in learnings of (1) the need for product refinement, (2) remelting of recovered glass fibers substituting virgin materials, and (3) the use of recovered fibers directly in plate production for new nacelle covers (Chapter 7 and Paper IV). The main modifications between the original roadmap in Figure 8 and the modified roadmap Figure 9 are listed and explained here according to the value chain steps:

- Incineration with energy recovery: The route of incineration is only slightly above landfill in the waste hierarchy because of the lack of circularity and low utilization of resources (MacArthur, 2013). For this reason, this route is not considered as a circular solution and should be avoided if other routes are available. It has therefore been removed from the roadmap.

- Steps 1 to 3: Based on the findings, no modifications were needed.

- Step 4: Addition of chemical separation process. For the route of chemical recycling, chemical separation – solvolysis step 1 – has been added to as a 2nd pre-processing technology. The chemical separation process can be applied to both WTB material sections as well as mechanically recycled material.

- Step 5: Addition of chemical recycling process. For the route of chemical recycling, solvolysis step 2 has been added as a material processing step in accordance with the findings of the CETEC project.

- Steps 6 and 7: These new value chain steps – Output material and product refinement – have been added to the roadmap as findings show a need for an improved understanding of refinement of output materials from the material processing in step 5. Step 6 describes the material coming from the material processing step that is yet to be further refined to be of value for potential customers. Step 7 describes the specific refinement processes needed to turn processed materials into new products.

- Step 6: Addition of six output materials. In the thermal recycling route, the output materials of liquid, gas, ash, and fibers have been added to represent the material that must be further refined. In the chemical recycling route, the output material of liquid has been added since, findings also show that this must be further refined into oil-based products. In the mechanical recycling route, the output material of deconstructed WTB material has been added to highlight the possible need for further refinement depending on the final new product application.

- Step 7: Addition of seven product refinement processes. For the thermal recycling route, four refinement processes have been added to illustrate the respective refinement processes of the output material from the pyrolysis process. For the chemical recycling route, a separation and refinement process of the liquid is added, and for the mechanical recycling route, material sorting, and processing are added depending on the final new product application.

- Step 8: This step was previously referred to as step 6. In this step six new output products have been added to illustrate the research findings concerning, in particular, the chemical and thermal recycling routes.

06.04 Implications and Further Research

The modified roadmap for sustainable value chains for of end-of-life wind turbine blades illustrates the potentials of future EoL value chains given current and expected future developments. However, the roadmap should not be considered as the final solution, but rather as input for exploration and future research.

Based on a systematic literature review, Paper II showed that no case studies of EoL value chains have been reported in literature so far. Thus, further research is suggested to include such case studies of EoL WTB projects, to obtain further details and operational insights, and to validate the roadmap in an empirical context. What is illustrated by the research findings is that there are several technical solutions to facilitate circular EoL management of WTBs. Currently, the routes of structural repurposing, cement co-processing, and mechanical recycling are technically feasible. In other words, no evidence is found to suggest that these routes cannot be performed with the current technologies, thus suggesting that scaling of these solutions is a question of knowledge, collaboration, and investment – and not of technical feasibility.

The results have several implications. First, the roadmap provides an overview of the state-of-the-art and highlights where more research is needed. The roadmap is the first of its kind to utilize a value chain approach to map end-to-end routes for EoL WTBs. The six identified routes and their subprocesses provide practitioners and owners with an overview of available routes, including processes and technologies, for their EoL WTBs. Thus, with the roadmap, it is simpler for owners to sustainably manage their EoL WTBs. Second, the roadmap provides both owners and potential waste management partners with a tool for collaboration and co-creation of new EoL value chains. This implication also raises the need for more research into how owners and waste management partners are collaborating to facilitate such value chains. Third, the findings have implications for the development of chemical and thermal recycling, but further research is necessary for these routes, especially steps 6 and 7 (output materials and product refinement). However, findings from the assessment of research projects in progress also show that these routes are the ones receiving the most attention and funding, indicating that developments for these routes are likely in the near future. Fourth, the findings also show that all routes must go through value chain steps 1 – 4, and yet results from Paper II show that little attention has been given to these processes. Thus, there is a need for research to identify best practices in these processes, especially since they are complex due to the nature of the blades being large complex products with varying lengths, geometries, and material compositions. Finally, it should be noted that the roadmap does not indicate which route is better in terms of levels of circular principles. However, the findings and conclusions of this chapter constitute an important baseline for future research, and it is suggested that assessments of the different EoL routes be conducted, including their TRL, level of circularity, environmental impact, and cost.

06.05 Conclusion

This chapter set out to investigate which technologies and processes are potential solutions for EoL value chains for WTBs. Paper II addressed this research aim through a systematic review of academic literature on EoL WTBs. The findings of Paper II included a full assessment of all the technologies and processes that may work as potential solutions for EoL WTBs. The study proposed a roadmap for sustainable value chains for EoL WTBs, including six potential routes. Second, to investigate recent technological developments not yet documented in academic literature, a study of research projects and emerging technologies from 2020-2023 for CE and end-of-life management of WTBs was conducted. The study concluded that there is an increased research focus on the technologies of solvolysis and pyrolysis, which is demonstrated by the number of research projects in progress and recent announcements of research findings. These developments have been compiled with the findings from Paper II in a modified version of the roadmap for sustainable value chains for end-of-life wind turbine blades. In conclusion, the modified roadmap combines the state-of-the-art with the newest technological developments and thus specifies in detail how future EoL value chains for WTBs can operate and which technologies and processes are potential solutions for EoL value chains for WTBs.

07 Design and Operation of Fully Functioning Value Chains for End-of-life Wind Turbine Blades

This chapter builds on the research outcomes of Chapter 6 which identified potential EoL routes for WTBs. The outcome resulted in a roadmap for sustainable value chains for WTBs that was developed based on a meta-analysis and consolidation of literature findings that did not include any empirical cases of EoL WTBs. Hence, to build on these findings and move the research field forward, further technical and operational insights must be obtained through empirical studies to validate and elaborate on the findings from Chapter 6. This chapter will therefore include empirical findings from four cases to shed more light on the design and operations of fully functioning value chains for EoL WTBs. This chapter will therefore answer the following research question:

Sub-RQ3: How can fully functioning value chains for end-of-life wind turbine blades be operated at an industrial scale to support a circular economy?

First, the chapter briefly outlines the literature on EoL management for large complex products (LCPs) in general. It then builds on the findings and implications of Papers III and IV. Paper III will be presented to answer how decommissioning of LCPs is designed and operationally conducted to support the CE principles of reuse and recycling. Paper III adopts an in-depth single case study methodology and studies a full EoL value chain for 21 WTBs destined for either reuse or recycling in cement co-processing. The study focus is on practices, challenges and decision-making behind the design and operational execution.

Next, Paper IV is presented, which answers the research question of how fully functioning recycling value chains for EoL WTBs can designed and operationally executed to support the CE. The paper adopts a multiple case study approach, and four different EoL recycling value chains are investigated. Paper IV builds on the learnings from Paper III and adds three additional empirical case studies, each of which documents all the value chain processes applied for EoL solutions following CE principles. However, in this study the focus is on similarities across cases for standardization of future industrial-scale value chains. Finally, findings across Paper III and IV are briefly discussed and concluded on.

07.01 Circular Economy in Decommissioning of Large Complex Products

Zooming out from the domain of WTBs, other types of LCPs meeting their EoL are found to present similar challenges. LCPs such as aircrafts (Keivanpour et al., 2015), offshore oil and gas platforms (Vidal et al., 2022) or constructions (Yu et al., 2021, Ghaffar et al., 2020, Knoth et al., 2022) are considered highly complex since they contain high material volumes, complex material compositions and fragmented waste sources, making circular EoL management difficult and resource-intensive (Yu et al., 2021, Ghaffar et al., 2020). To achieve CE in this context, it is essential that CE principles such as reuse or recycling of materials are established at the highest possible level to secure materials and their value for new secondary applications (Potting et al., 2017). However, decommissioning methods covering project management, decision-making, and operational processes are scarcely addressed in the existing literature (Topham and McMillan, 2017).

Studies from the construction industry find that to introduce circular waste practices, continuous interlinked processes are required. This includes waste identification, source separation, pre-demolition audits, robotic sorting, mobile on-site operation, manufacturing processes onsite and off-site, quality management, policies, and regulations (Yu et al., 2021, Ghaffar et al., 2020). Vidal et al. (2022) develops a conceptual framework for decommissioning of offshore gas and oil platforms and finds that decommissioning projects are complex and must involve several stakeholders such as governments, operators, and engineers.

The results from Knoth et al. (2022) indicate that barriers to material circularity include limited infrastructure, a lack of pilot projects, lack of collaboration throughout the value chain, stagnant regulations and finally a lack of training in the circular design processes. Therefore, studying empirical cases of decommissioning projects and their value chains, collaborations, practices, and challenges can address the current gaps in literature and practice. This research gap will therefore be addressed by Papers III and IV, which include four empirical case studies of full decommissioning projects.

07.02 Paper III – Circular Economy Operations for Large Complex Products at End-of-life: The Wind Turbine Case

In the following sections, the purpose, methodology, findings, contributions, and implications of Paper III are outlined and presented. An earlier version of the paper was presented at the European Operations Management Association conference in Leuven, 2023 (EurOMA 2023). After this, the paper was further developed through a three-month research stay at University of Cambridge, Institute for Manufacturing, in close collaboration with Associate Professor, Dr Veronica Martinez. At the time of submission of this dissertation, the manuscript had been submitted for journal publication. For full paper, see Appendix III.

Purpose – LCPs including wind turbines and their blades present complex challenges at their EoL due to material variations, volumes, and complexity. Therefore, it is critical to establish circular EoL routes for LCPs aligning value chain operations with CE principles. Even though CE implementation has gained increasing attention, research studying the role of operations management in implementation of CE is scarce. Thus, this research aims to study how decommissioning of LCPs is designed and operationally conducted to support CE principles, particularly reuse and recycling, through identifying the operational processes and building blocks for CE implementation.

Methodology – First, this study includes a structured literature review to identify the phases of decommissioning and understand the building blocks for operational execution and performance in EoL management of LCPs. Based on a meta-analysis of current literature, themes and practices have been synthesized into a framework for material circularity in decommissioning of LCPs. The findings from literature particularly identified the third project phase of operational execution as a knowledge gap. Thus, the second part of this study applied an in-depth empirical case study method to study operational execution practices for CE. The case included the end-to-end decommissioning process of 21 WTBs in Finland that were going to be reused or recycled. Data was collected through semi-structured interviews with informants, a site visit, technical data, and pictures that went through a double-looped verification process with the informants. The case study systematically documents the operational and logistical processes involved in project execution, and findings were consolidated in a framework for decommissioning of LCPs and discussed in relation to existing literature.

Findings – First, the findings from the literature review identified four main decommissioning project phases, each including a number of activities. The four phases were: (1) overall planning, (2) preparation for decommissioning, (3) operational execution, and (4) post-decommissioning. These findings were consolidated in a framework for CE in decommissioning of LCPs. However, in particular the third project phase of operational execution was found to be scarcely addressed in the literature while identified as being a crucial part of CE implementation. The results from the in-depth case study specifically addressed the operational execution phase of a decommissioning project for EoL WTBs. The case study included the CE principles of reuse and recycling and a total of seven main activities for operational execution of LCPs were identified. The activities were elaborated on and outlined in the framework for CE in decommissioning of LCPs. They were (1) on-site demolition, (2) sectioning material into transportable sizes, (3) transportation to pre-processing and material reuse, (4) material pre-processing for recycling, (5) transportation to recycling facilities, (6) material recycling, and (7) material refining and secondary application. The framework provides practitioners and researchers with a step-by-step project management approach focusing on the operational implications of decommissioning of LCPs. The study results also illustrate the complexity and challenges faced in decommissioning operations but highlight the importance of operational execution for successful material circularity. Finally, it was confirmed that complex decision-making is needed and involves tradeoffs between safety aspects, environmental factors, social aspects, cost, technological feasibility, and political factors.

Novel contribution and research implications – This research has several important implications. The detailed insights provided by the in-depth case study and the developed framework can provide academics and practitioners with knowledge on the operational processes needed for EoL projects of LCPs. In particular, the findings will support future research and projects pertaining to increased material circularity for EoL products. The results elaborate the decommissioning phases of the LCPs, which have been missing from theory and practice. Thus, the novel contribution of this research concerns the impact and role of operations management on CE implementation. The case study is the first to be documented in academic literature concerning a full end-to-end value chain for a WTB case, and thus addresses the call for empirical data specifically in this research domain, which makes an important contribution to the wind power industry.

07.03 Paper IV – Value Chains for Recycling End-of-life Wind Turbine Blades: A Multiple Case Study

In the following sections, the purpose, methodology, findings, contributions, and implications of Paper IV are presented. The paper is based on four empirical case studies. The paper is single-authored and at the time of submission of this dissertation, the manuscript had been submitted for journal publication for review. For full paper, see Appendix IV:

Purpose – A previous research study (Paper II) found that the academic literature on EoL management of decommissioned WTBs is dominated by literature reviews, and that data and knowledge on industrial-scale solutions for circular waste management are lacking. Especially empirical data and real EoL WTB following circular pathways are absent in the literature. Thus, there is a knowledge gap in terms of investigating how full value chains can be designed and operated at an industrial scale and including all planning, operational, and logistical processes. This knowledge is required to understand how full value chain systems can be designed and industrialized to support the vastly increasing number of EoL WTBs blades. Hence, this study answers the research question of how fully functioning recycling value chains for EoL WTBs can be designed and operationally executed to support the CE.

Methodology – This study adopts a multiple case study methodology to study four empirical cases of end-to-end recycling value chains for EoL WTBs. To study how variables may influence the design and operational execution for material recycling, the case sampling was based on a carefully designed approach considering six variables: (1) blade geometry and mass, (2) blade quantity, (3) recycling route and technology, (4) blade owner, (5) blade location, and (6) waste management partner. Four cases were identified, and all involved EoL value chains pertaining to the CE principle of recycling and represented variance within the six defined variables. The recycling technologies were all at a minimum TRL of seven, and included pyrolysis, cement co-processing and mechanical recycling. In all cases the data was gathered through semi-structured interviews completed with key personnel from the blade owners and the waste management partners involved in each case. First, the data was analyzed for each individual case and mapped according to the sequence of value chain processes described. This included the responsible organization and applied technologies and equipment. Next, the results across the cases were grouped and aligned according to their operational activities for cross-case comparisons. The findings were consolidated in detailed case descriptions followed by a complete value chain roadmap for all four cases.

Findings – The study findings include the identification, documentation, and analysis of four recycling value chains that can be completed at an industrial scale for WTBs reaching their EoL. Findings show that to design and operate an industrial-scale recycling value chain, up to eight different process steps are required. These are identified as: (1) on-site demolition, (2) sectioning for transport, (3) first pre-processing, (4) landfilling of non-recyclable parts (if applicable), (5) second pre-processing, (6) material recycling, (7) post-processing, and (8) material refining and application. In addition, four different steps of transportation can be necessary. The results conclude that the variables of blade model, geometry, quantity, weight, owner, waste management partner, and recycling technology influence the number of applied process steps in the EoL value chain. However, multiple processes are recurrent across cases and not dependent on the material recycling technology. These value chain steps include on-site demolition, sectioning of the blades for transportation, pre-processing of material, and mechanical shredding. It is thus suggested that these processes are standardized and automated for improved efficiency. Through this study, it was found that to implement CE principles, such as recycling, a full value chain setup is required. This includes multiple complex operations, transportations, and organizations, which illustrates that recycling involves more challenging and extensive operations than is indicated by the existing literature. Challenges associated with finding suitable equipment, ensuring a good working environment, working outdoors, pollution and cleaning are emphasized. Nevertheless, it is concluded that the design and operational execution of recycling value chains for EoL WTBs is indeed feasible from a technical and cross-sector collaborative point of view.

Novel contribution and research implications – This study is one of the first to document multiple end-to-end recycling value chains for WTBs at EoL. The lack of empirical data has been well-documented in previous studies, and thus the data and detailed case descriptions presented are a novel contribution with implications for both academia and practitioners seeking to establish industrial-scale recycling systems. Findings demonstrate that planning and execution across multiple geographical locations and partners is necessary, which results in highly complex value chain design and management. Hence, present and future value chain partners can benefit from the contributions of this research when establishing full industrial recycling solutions. Data and results can also be applied in future research seeking to assess the environmental impact of recycling value chains for blades. A novel theoretical contribution is made to the literature on operations management and value chain design for on implementation of CE. Particularly, the study showcases the fact that CE is not as clean as the concept; rather it is difficult and actual hands-on work that calls for practical and technical solutions.

07.04 Discussion

The results presented in this chapter showcase four diverse full-scale EoL value chains and address the lack of empirical studies of EoL WTBs in academic literature. This knowledge is needed to move the research field forward and facilitate industrial-scale adoption, as emphasized by the results of Paper II. The findings in this chapter make a practical contribution to CE literature, and address the knowledge gap between CE theory and practice highlighted by Barreiro-Gen and Lozano (2020).

The empirical case studies from Paper IV expand on the modified value chain roadmap developed in Chapter 6 (Figure 9) by testing the thermal recycling, mechanical recycling, and cement-co-processing routes. In addition, the in-depth case study from Finland of 21 WTBs shows the application of the CE principle of reuse. First and foremost, the empirical data from the case studies validates the eight value chain steps proposed in the value chain roadmap (Figure 9), which are (1) on-site demolition and dismantling, (2) sectioning for transportation, (3) 1st pre-processing, (4) 2nd pre-processing, (5) material processing (recycling), (6) & (7) product refinement of output materials, and (8) new product application.

The results do, however, provide a more detailed picture of the operations involved in the various recycling routes and the decision-making behind. Thus, the value chain routes are documented and validated in an industrial setting. It demonstrates that no matter which of the three tested recycling routes are followed, some level of WTB sectioning and pre-processing is required and that several transportation steps are involved. Mechanical shredding is also applied in all cases, which was also suggested by the value chain roadmap in Chapter 6. Case D from Paper IV also validates the pyrolysis route and the potential for glass re-melting suggested in Chapter 6. In case D, the pyrolysis technology was demonstrated at an industrial scale, and materials underwent several processes and post-processing for product refinement. This has important implications for the development of future value chains utilizing the pyrolysis technology and glass-remelting, and it documents the value chain system that must be in place for this to work at an industrial scale.

Across the two presented papers, successful material recycling was found to be dependent on well-designed value chains aligned both upstream and downstream with suppliers. This means that the initial processes of sectioning and pre-processing are designed according to the specifications of the subsequent material recycling processes and the desired secondary product. This emphasizes that future recycling solutions for EoL WTBs must be seen as full value chain systems with processes, technologies, logistics and multiple partners involved. This finding supports the findings by Govindan and Hasanagic (2018) on the importance of partner collaboration, logistics and implementing technical equipment and facilities.

The study findings from Paper III also provided a clear framework for decommissioning of LCPs, addressing the call by Topham and McMillan (2017) for more detailed planning of decommissioning processes. Even though this study focusses mainly on EoL WTBs, the study findings also align with the previous research conducted in the construction sector, where circular waste management requires continuously interlinked processes such as source separation, sorting and processing, remanufacturing processes onsite and offsite, and quality management (Ghaffar et al., 2020).

In addition, the findings from the four cases show that the initial value chain processes are the same across recycling value chains. Thus, processes can be standardized and optimized as they are not found to be dependent on WTB model, size, or material composition. Hence, if operational practices can be standardized, they can become more efficient or automated, and as proposed by Ghaffar et al. (2020) this could include robotic sorting or mobile on-site operation.

The study results demonstrate the importance of overcoming barriers to material circularity such as the lack of pilot projects and collaboration in the value chain (Knoth et al., 2022). In this regard, the results of Paper III show how to ensure collaboration in the design and operation of decommissioning projects, and Paper IV showcases four projects for material circularity.

07.05 Conclusion

The two studies of Papers III and IV combined answer the third sub-research question. The research results have been established based on a detailed empirical data set of four case studies documenting how fully functioning circular value chains for EoL WTBs can be designed and operated. In conclusion, to design and operate fully functioning value chains for EoL WTBs in accordance with CE principles, the following points apply:

- All phases of decommissioning/EoL must be designed in alignment based on a value chain approach and CE principles.
- A full decommissioning project should consist of four phases: (1) overall planning, (2) preparation for decommissioning, (3) operational execution, and (4) post-decommissioning.
- In the third phase of operational execution, up to eight separate process steps and four separate points of transportation may be required.

All steps in the EoL value chain must be designed as a single complete system in which all processes are developed and aligned in accordance with the specifications of the desired secondary product made from the WTB waste. Partner collaboration upstream and downstream in the value chain is found to be essential to designing and operating successful EoL value chains, in order to obtain data, knowledge and utilize expertise within technologies and waste handling. Finally, all four cases demonstrated fully functioning value chains for EoL WTBs in accordance with CE principles, concluding that all three recycling routes are technically and practically feasible.

08 Evaluation of Circular Value Chains for End-of-life Wind Turbine Blades

The previous chapters have answered the question of how to design and operate different value chain routes for EoL WTBs pertaining to the circular principles of reuse, repurposing, and recycling of materials. A question that remains to be answered is how to compare and evaluate the impact of the different technologies and EoL routes, and which variables should be considered when making this assessment. As demonstrated in Paper IV, Figure 2, the different EoL routes are at different levels of circularity and TRL. Furthermore, the aspect of cost for investments and operations are also to be considered. This chapter will therefore answer the following research question:

Sub-RQ4: How can it be evaluated which circular value chains for end-of-life wind turbine blades should be industrialized and what variables influence this decision?

To answer this research question, two separate studies will be presented. First, Paper V looks at decision-making from an operational perspective by zooming in on a single value chain process. A Three-Stage Framework for Sustainable Decision-Making (3-SuDeM) was developed and adopted a multi-criteria decision-making methodology. The framework was tested and validated with a waste management company to identify which equipment was preferred for sectioning WTBs in future industrial-scale value chains. Next, Paper VI studies how future value chains for EoL WTBs can be assessed and evaluated through a combination of life cycle assessments (LCA) and multi-criteria decision-making (MCDM). In Paper IV, a framework for this assessment was developed to consider future EoL scenarios for WTBs characterized by different TRLs and levels of economic feasibility, environmental impact, social impact, and circularity. The findings of both studies are consolidated in Figure 10 to provide an overview of the variables identified as influencing the assessment of value chain scenarios. Finally, the results of this chapter are briefly discussed and concluded on to answer the posed research question.

08.01 Paper V – Sustainability Assessment of New Technologies using Multi-Criteria Decision-Making: A Framework and Application in Sectioning End-of-life Wind Turbine Blades

In the following sections the purpose, methodology, findings, contributions, and implications of Paper VI are presented. The article was written in collaboration with two co-authors and published in Renewable and Sustainable Energy Reviews in 2023. For full paper, see Appendix V:

Purpose –Research has so far primarily addressed EoL technologies for WTBs, and a knowledge gap is identified pertaining to operations and logistical practices prior to recycling, including cutting and sectioning operations needed in complete EoL value chains. Several practices and technologies have been identified as potential solutions for sectioning operations for WTBs. However, it remains unclear how to evaluate which of the different technological options for cutting is preferred and which criteria should be included in this evaluation. Therefore, the purpose of this study was to develop and validate a full framework that can aid the sustainability assessment of technologies.

Methodology – First, this research adopted the approach of a structured literature review. Literature was reviewed with a focus on assessment aims, research domains and applied assessment framework and/or methodology to identify relevant methods for sustainability assessment of technologies. The analysis led to the identification of MCDM as the most suitable method for assessment. Next, based on a consolidation of key literature findings, a complete step-by-step framework for sustainability assessment using MCDM analysis was developed. The developed framework was then tested for validation in cooperation with a waste management company with practical experience in sectioning WTBs. Through this process, four relevant alternatives of technologies for sectioning WTB were first identified and discussed. This was followed by an evaluation grounded in a 3BL approach including environmental, social, and financial criteria. Criteria for evaluation were identified through literature and through workshops with the company. The criteria were then ranked through a Delphi study approach to reach consensus between the participants, concluding the global and local weighting of all criteria. Data for each criterion was retrieved from suppliers, product specifications of each technology, literature, and experts in the company. The MCDM method of Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was then applied to complete the evaluation. To validate and discuss the results, two separate sensitivity studies were completed.

Findings – The findings from the literature review concluded that the MCDM evaluation method was the most accepted method for sustainable decision-making since it allows for multiple criteria to be covered, but with different importance being given to each criterion. Literature findings were consolidated in a conceptual framework named the Three-Stage Framework for Sustainable Decision-Making (3-SuDeM). The 3-SuDeM framework addresses the identified research gap by proposing a systematic step-by-step approach to sustainable decision-making by considering multiple criteria. Stage 1 includes the definition of the main goal of decision-making and the identification of: alternatives for evaluation, sustainable criteria, data input and weightings of criteria. Stage 2 includes the problem analysis, selection, and completion of the MCDM method. Stage 3 includes the problem resolution, including a sensitivity analysis, leading to a final stakeholder evaluation of the most sustainable solution against the originally defined goal. The findings from the 3-SuDeM case application with the waste management company included the identification and inclusion of four technological alternatives for blade sectioning, and 15 assessment criteria pertaining to the 3BL. Findings based on the analysis indicated that the preferred technology for sectioning WTBs was an excavator with a saw blade fixture. This caused the waste management company to consider this option instead of a fuel-powered handheld saw that they had previously used, and to justify investing in the excavator with a saw blade fixture as a long-term investment. Nevertheless, the results are based on a single application, including the priorities of the specific organization and a set of assumptions for the data collection. Thus, the result should be considered as a preliminary guideline for other organizations.

Novel contribution and research implications –The implications of this study are twofold. First, the 3-SuDeM framework proposed and applied in this research provides an important contribution to literature on MCDM and industrial sustainability implementation by providing a structured three-stage approach to complex decision-making. Secondly, the results have implications for practitioners and provide a method and demonstration of how to evaluate and select sustainable technologies in future value chains. The framework makes sustainable decision-making approachable and manageable directly in industrial settings. The findings particularly support the development of EoL value chains for WTBs by identifying an excavator with a saw blade fixture for cutting operations. This technology can be applied in full industrial value chain solutions that consider cost, environmental, and social aspects of those value chains.

08.02 Paper VI – Sustainable End-of-life Value Chain Scenarios for Wind Turbine Blades

In the following section, the purpose, methodology, findings, contributions, and implications of the Paper VI will be presented. The paper is found in Appendix VI and has been presented at the WindEurope Annual Event in Copenhagen 2023. Afterwards the paper was published in Journal of Physics, the Conference Series. The paper was written in collaboration with colleagues from the Institute of Green Technology and University of Southern Denmark. My contributions were to the research scoping, data collection, literature review, and paper review.

Purpose – Sustainable recycling value chains for EoL WTBs are yet to be commercialized and become widely available to provide a feasible alternative to landfilling or incineration. Yet, research assessing the sustainability of future EoL solutions for WTBs based on a full value chain approach and empirical data has so far been absent. To conduct such assessments, trade-offs between the environmental, economic, and social impacts should be considered including the value and circularity level of potential secondary products. However, the literature review did not identify any established framework for sustainability assessment of emerging recycling scenarios. Thus, the purpose of this research was to develop a framework that can be used to evaluate different future EoL value chain scenarios at different levels of technological readiness, economic feasibility, environmental impact, social impact, and circularity.

Methodology – Based on a value chain approach to full EoL scenarios of recycling technologies for WTBs, a framework was developed and proposed. These scenarios included mechanical recycling, pyrolysis and cement co-processing that are at different TRL due to various technological barriers. A landfill scenario was also included as a baseline scenario. The scenarios were developed and defined based on workshops and meetings with industrial organizations with expertise and experience in EoL operations and with WTB OEMs that provided blade data and specifications. Data was then compiled and analyzed through the application of material flow analysis and LCA. Initial results highlighted that the assumptions made concerning avoided products in trade-off accounting had a high impact on results. To account for these challenges, future versions of each recycling scenario were developed based on the shared socio-economic pathways (SSP) for 2030, 2040 and 2050 developed by the Intergovernmental Panel on Climate Change (IPCC). For each pathway, best, middle, and worst-case scenarios were considered. Finally, findings including case descriptions, proposed assessment methods and future scenarios were combined into a proposed framework.

Findings – The study results include the development and alignment of four different recycling value chains: mechanical recycling, pyrolysis, cement co-processing and a baseline landfill scenario. A number of technological options were applied as part of the value chain assessment, such as equipment for shredding, size and specification of shredding blade material fractions, transportation modes and post-processing options. Each recycling value chain was aligned with three SSP scenarios, i.e. SSP1, SSP2 and SSP5, and three timeframes for 2030, 2040 and 2050. Five assessment methods were identified as suitable for evaluating the different value chain scenarios. Yet, the key challenge was that these methods do not consider (1) the differences in TRL and circularity levels, (2) a non-weighted evaluation of environmental, economic, and social sustainability, and (3) the acuteness of increasing waste volumes from EoL WTBs. Thus, to address these challenges, the framework of emerging-scenarios assessment was proposed. The framework is based on the integration of LCA and MCDM for decision-making. The framework includes five main steps for assessment: (1) prospective LCA, (2) shared socio-economic pathway scenarios, (3) developing aligned scenarios, (4) applying MCDM method, and (5) considering EoL scenarios over time.

Novel contribution and research implications – The assessment framework proposed in this study can serve as the basis for evaluating and comparing the impact of future EoL value chains for WTBs. The novel framework addresses the complexity of evaluating technologies at various levels of circularity and TRL, while also considering the future development of these technologies, which has been overlooked in literature so far. Thus, this research has implications for academics and practitioners involved in the design and implementation of future EoL value chains for WTBs as it outlines a method for evaluating emerging technologies that have not yet been implemented, and thus provides managerial insights for a timeframe up until 2050. This approach can also be adapted to other industrial domains where similar challenges are faced.

08.03 Discussion

The results and implications of the respective studies are discussed separately in each of the appended papers. In this section, the combined results are discussed in connection with the fourth sub-research question posed at the beginning of the chapter. In relation to EoL management and technologies for WTBs, other studies have applied the LCA methodology (Morini et al., 2021, Ratner et al., 2020, Sakellariou, 2018) or an MCDM methodology (Deeney et al., 2021, Delvere et al., 2019). Hence, the approaches are not unknown in literature. Nonetheless, Paper V is the first to apply this method directly for selecting technologies for EoL value chains. The results show how MCDM methods such as TOPSIS can assist single organizations in decision-making for sustainability.

Paper VI is the first to propose an assessment framework using a combined prospective LCA and MCDM approach that can address the complexity of evaluating technologies and value chains yet to be developed. The prospective LCA method can be applied for full value chains and requires data from several organizations and background systems. This can assist the assessment of new industrial systems outside single organizations. LCA studies are increasingly used, in both academia and by industry and policymakers, to document and assess the environmental impact of products, value chains or systems (Jegen, 2023). However, a standard LCA method does not consider other variables such as cost, social responsibility, TRL levels etc. Therefore, the contributions of Papers V and VI are important as they highlight the necessity of combining the LCA approach with more variables for assessment, which can be done through the application of a MCDM method. This applies especially when evaluating future scenarios where data is limited.

Several variables were identified by the two studies as influencing decision-making for selecting and scaling specific processes and technologies (Paper V) and entire value chains (Paper VI). The variables for decision-making have been merged in Figure 10 to present a complete overview of variables that should be considered in future decision-making when comparing and assessing EoL technologies and value chains.

Figure 10 has direct implications for future research and for practitioners as it provides a novel overview of variables that influence decision-making and which assessment methods to apply.

The findings from the two studies highlight the complexity in evaluating very different variables and how this can influence decisions. The trade-off between cost, environmental performance, level of circularity and TRL is a particularly complex task to assess. This dissertation does not include LCA assessments of future value chain scenarios as this is outside of the research scope. However, future research is suggested where the data presented in Chapter 7 is applied to the assessment methods proposed here in Chapter 8. It is therefore important to stress that the results of the presented studies merely answer the question of which methods can be used for decision-making and determine which variables should be considered, while demonstrating how to apply these methods. However, the results do not determine which are the preferred future value chains or technologies for EoL WTBs. So far, the weight and impact of the variables still depend on the priorities of the organizations involved. This could be impacted in the future through changes in legislation, standards, or non-price criteria in tender processes, which will be discussed further in Chapter 9.

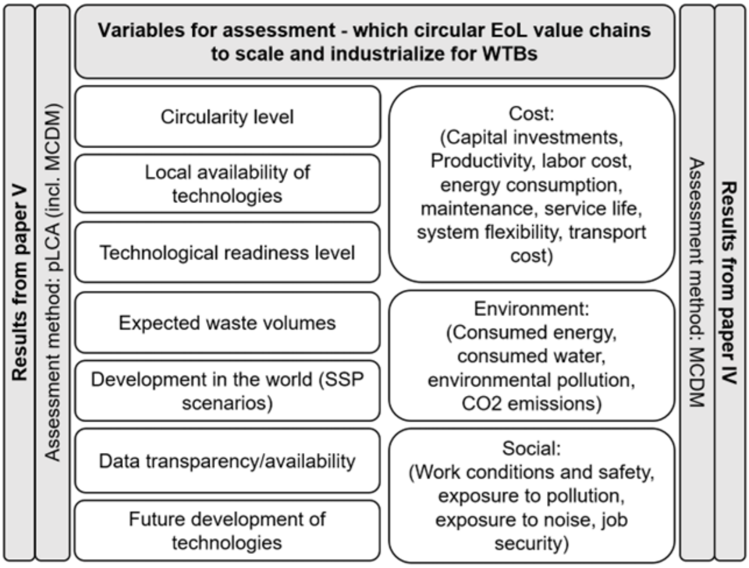


Figure 10 - Variables for decision-making.

08.04 Conclusion

In this chapter, two studies are presented and elaborated on to answer the question of how to evaluate which circular value chains for EoL WTBs should be industrialized and what variables influence this decision. In Paper V it was found that the most widely applied method for sustainable decision-making is the MCDM method. A complete Three-Stage Framework for Sustainable Decision-Making (3-SuDeM) was developed and successfully tested with a Danish waste management partner to assist the selection between four different technologies for WTB sectioning. The method was found to positively aid the decision-making process, making sustainable decision-making approachable and manageable. Paper VI proposed a five-step framework of emerging-scenarios assessment that integrates a prospective LCA approach and MCDM methodology. The framework considers the challenges of acuteness of increasing waste volumes, the differences in TRL and circularity levels, and the lack of weighted environmental, economic, and social sustainability variables. The framework also aligned the assessment of each future recycling value chain scenario with SSP scenarios and different timeframes up until 2050. The developed framework may work as a platform for evaluating and assessing future scenarios of circular value chains and can provide managerial insights for decision-making as to which value chains should be industrialized over time. Hence, to evaluate which circular value chains for WTBs should be industrialized the assessment methods of MCDM and prospective LCA can be applied. Findings across the two studies highlighted that a complex set of variables should be considered in the assessment. These include circularity levels, local availability of technologies, TRL, expected waste volumes, SSP scenarios, data availability, future technical developments, cost, environmental, and social aspects.

Part III

Discussion and Conclusion

09 Discussion

Research on circular waste management in the domain of the wind turbine industry is attracting increasing interest both in academic literature, in popular media and among practitioners. Particular attention has been paid to WTBs made from complex composites materials as they are currently landfilled, and the challenges of designing, implementing and operating circular supply chains have been almost absent. Hence, this PhD research dissertation set out to study "how value chains for end-of-life wind turbine blades could be designed, operated, and industrialized in accordance with a circular economy?".

To answer this research question, four sub-research questions were defined and answered separately in Chapters 5-8: (1) Why do circular end-of-life value chains for wind turbine blades not exist today? (2) Which end-of-life value chain routes are potential end-to-end solutions for wind turbine blades, and what technologies and processes are included in the design of these solutions? (3) How can fully functioning value chains for end-of-life wind turbine blades be operated at an industrial scale to support a circular economy? And (4) how can it be evaluated which circular value chains for end-of-life wind turbine blades should be industrialized and what variables influence this decision?

In this chapter, the results and contributions of this dissertation as a collective piece of research will be synthesized and discussed in accordance with existing literature and in relation to the research objectives. The discussion is divided into four sections: (1) Recycling technologies and solutions, (2) Future end-of-life value chains for wind turbine blades, (3) How to overcome barriers for EoL value chain industrialization, and (4) Implementation of CE through operations management.

As stated in Chapter 4 on methodology, this dissertation takes a practice-oriented approach, meaning that the main contribution is focusing on practice and knowledge. That said, the research results have also included important results for CE literature and theory, and thus the final part of this discussion addresses the research results in relation to CE literature and the theoretical contributions of this research.

09.01 Recycling Technologies and Solutions

Across the study results presented in this PhD dissertation, six EoL value chain routes were identified as alternatives to landfilling and were all found to be feasible solutions for WTBs. The routes include incineration with energy recovery, cement co-processing, mechanical recycling, thermal recycling, chemical recycling, and structural repurposing. The routes were first derived from a synthetization of literature findings based on a systematic literature review in Paper II, which resulted in a state-of-the-art value chain roadmap. The recycling value chain routes were then tested through one in-depth case study (cement co-processing) in Paper III and further elaborated on in an additional three case studies in Paper IV (cement co-processing, pyrolysis, and mechanical recycling). Common for the identified routes is that they can all be implemented from a technical, operational, and logistical point of view. In addition, they include many similar operational and logistical processes that could be streamlined and standardized across the various routes. The following sections will discuss the key findings pertaining to recycling routes, excluding incineration and structural repurposing.

09.01.01 Mechanical Recycling

The process of mechanical recycling was both found to be a scalable solution in its own right, and to work as a pre-processing method for the other recycling routes. Mechanical recycling was found to be the most common recycling solution mentioned in academic literature (Paper II), with a high TRL level (Paulsen and Enevoldsen, 2021), and with numerous secondary applications demonstrated (Fonte and Xydis, 2021, Rani et al., 2021, Jensen and Skelton, 2018, Rahimizadeh et al., 2019).

The results of this study confirm that a feasible circular value chain designed around mechanical recycling can be operated and industrialized, which was demonstrated fully by case B in Paper IV. In addition, the process was found to be utilized for pre-processing in the value chains for cement co-processing, pyrolysis, and solvolysis, which was demonstrated in cases A, C and D in Paper IV, and which is consistent with notions made by Rani et al. (2021) and Mishnaevsky (2021). Thus, an interesting finding is that the mechanical recycling process is strongly expected to be part of all future recycling value chains. This means that the development and scaling of this technology is important for future EoL solutions. It can therefore be argued that research, investments, and efforts to develop and standardize this technology are needed in all cases.

Because of the TRL, maturity and accessibility of the mechanical recycling technology, it is arguably the preferred route for EoL WTBs at the time of writing this dissertation. Previous studies have also found it to be the preferred option in terms on environmental impact (Delvere et al., 2019, Liu et al., 2019). However, depending on the secondary applications of materials derived from mechanical recycling, circularity levels can vary significantly. The secondary product applications will also have an EoL, where recycling through solvolysis and pyrolysis is an option. Yet, the EoL routes for secondary application products remain unknown. In terms of timelines the mechanical recycling route can be an appropriate solution in the short term and until alternative routes have been further developed. In the medium and long term, mechanical recycling will still be required as pre-processing for the remaining routes.

09.01.02 Cement Co-processing

Besides mechanical recycling, cement co-processing was found to be the only technology that is currently available at an industrial scale with facilities in Germany and Finland (Sakellariou, 2018, Kuusakoski Recycling, 2022). Yet, in this PhD study, it was also found to be the least favorable option in terms of material circularity level. The route is less commonly referred to in literature compared to the remaining recycling routes (Paper II), but cement co-processing is reported to be a potential solution for WTBs and composite material, among others by Sakellariou (2018) and Paulsen and Enevoldsen (2021) noting that it is at the highest TRL level. The recycling value chain design was defined and validated in Chapter 5, while it was documented, assessed, and analyzed in cases A and C in Papers III and IV. Because of the nature of cement co-processing, where the resin fraction is incinerated for heat in the cement kiln, the level of material circularity is the lowest out of the assessed recycling technologies (Figure 2, Paper IV). Results from Paper VI also showed that the environmental benefits associated with the cement co-processing route are highly dependent on the fuel type substituted in the cement plant. Hence, the potential environmental gain of the process must be analyzed based on the fuel type used in each facility and their geographical circumstances. Based on these findings, cement co-processing has been found to be technically feasible and scalable while the value chain processes supporting the route were defined and operationally conducted. Yet, it is also the least favorable route in terms of material circularity, and it is therefore recommended that the route be used in a short term until routes with higher circularity levels have been further developed.

09.01.03 Pyrolysis

In this PhD study, the results include a full documentation of a value chain for pyrolysis (case D, Paper IV), and the results demonstrated that this route was feasible at an industrial scale. Pyrolysis has been described in literature as a potential solution but also as a complex process at a low TRL (Paulsen and Enevoldsen, 2021), as having no current facilities (Naqvi et al., 2018) and as being and energy-intensive process (Ramirez-Tejeda et al., 2017). To address these findings, the PoC project reported in case D, Paper IV, was the first project to present an end-to-end value chain design and execution of the pyrolysis process for two full WTBs i.e. of 10 metric tons of materials. The project focused on the glass fibers and demonstrated that fibers recovered from EoL WTBs could be remelted to make new fibers by substituting up to 2% virgin raw materials in glass fiber production. Thus, if the results from the PoC project are further developed and scaled, the value chain will be fully circular for the glass fiber fraction of WTBs, where recovered glass fibers directly replace virgin materials. So even though the pyrolysis process uses energy in the recovery process, the final material substitution may be at a higher level in terms of circularity. This raises the question of whether recycling technologies with higher energy consumption can be justified by the higher level of material circularity achieved and the impact of avoided virgin raw materials. This can be evaluated using the LCA-method, which was found to be applied by both Ratner et al. (2020) and Sakellariou (2018) to evaluate EoL solutions for WTBs. In Paper VI, a framework was suggested for prospective LCA analysis which considers these aspects, but which also considers the future development of the surrounding systems based on the SSP scenarios.

This dissertation does not aim to conduct an environmental evaluation of the identified value chains but points out, however, that this is required from the point of view of assessment and decision-making. The presented value chain roadmap (Figure 9) and the PoC project (case D, Paper IV) collectively present how a full end-to-end industrial value chain for pyrolysis can be designed and executed at an industrial scale. This is considered to be the first step towards improving the TRL level for pyrolysis and towards creating full value chain solutions based on this technology in the future. Given the high level of material circularity and the successful outcome of the PoC, pyrolysis is deemed to be a realistic and feasible solution for EoL WTBs once further research and development has been done.

09.01.04 Solvolysis

The solvolysis technology is found to be the least mature recycling technology and is thus not considered to be a potential solution in the short term. The process was frequently mentioned in literature such as in Mattsson et al. (2020) or Ribeiro et al. (2016), but remains at a low TRL of 5-6 (Paulsen and Enevoldsen, 2021). Since the technology requires little or no heat in addition to a chemical solution, the energy consumption is lower than for the pyrolysis process. The composite fractions of fibers and resin are still separated and can be refined and reused separately for new purposes. Given the low TRL, solvolysis has not been included in the empirical case studies, but other research projects have aimed at maturing this technology, including the CETEC project (CETEC, 2023), where positive results and chemical processes were demonstrated in Ahrens et al. (2023). However, the CETEC project focused only on epoxy-based resins and not polyester or vinyl ester. Findings from Chapter 6 showed that further research into the industrialization of the solvolysis process has already started. In addition, five collaborative research projects were also identified, such as VIBES (European Commission, 2023h) and EoLo-HUBs (European Commission, 2023b), that are targeting the development of the solvolysis technology. This could lead to an improved TRL in the coming years and thus the possibility of scaling and industrializing solvolysis as an EoL solution. This finding was included in the modified roadmap framework in Figure 9, which consolidated findings in Chapter 6 and demonstrated that the solvolysis recycling technology could be a future solution for EoL WTBs. Thus, if the development efforts are successful and results in increased TRL, the solvolysis route and the associated value chain can be scaled and industrialized and present a feasible EoL solution for WTBs. Yet, findings of this research indicate that this route will require further development and testing to reach maturity, making it a long-term solution compared with the other recycling routes.

09.02 Future End-of-life Value Chains for Wind Turbine Blades

09.02.05 The Value Chain Perspective

Perhaps one of the most important contributions from this research is the value chain perspective to material and waste management at EoL for WTBs. The results of Paper II showed that the academic literature has not been researching the required value chains and technologies to support material recycling. Few studies, like Liu et al. (2019) and Rentizelas et al. (2021), have adopted a value chain perspective, but as a means to other research ends, and not based on empirical data. Krauklis et al. (2021) also included some processes like disassembly, material selection and recycling but did not systematically study these processes. Beauson et al. (2021) developed a model for an EoL WTB value chain but focused on key decision-making points and the criteria to be included in the assessment. However, the framework presents the routes of reuse, repurposing, recycling, and recovery, but does not outline the associated value chains. Thus, the findings of this research contribute to the work by Beauson et al. (2021), Rentizelas et al. (2021) and Krauklis et al. (2021) by expanding on each of the operational and logistical steps of the circular value chains. In Chapter 5, the review of collaborative research studies in progress targeting EoL WTBs showed that five projects have also adopted a value chain perspective, including the research projects Blades2Build, EoLO-HUBs, REFRESH, CIRCUBLADE and SUSWIND, which clearly indicates that this will be a research focus going forward (Blades2build, 2023, European Commission, 2023b, European Commission, 2023f, Chalmers Industriteknik, 2023, National Composites Centre, 2021).

The collective results of the PhD dissertation present a novel contribution to research and practice by adopting the perspectives of value chain development and operations management to elaborate and expand on current knowledge. Previous studies such as Ratner et al. (2020) have remarked that great uncertainty surrounds the evaluation of EoL value chains for WTBs due to a “lack of primary data” and “because of the variety of logistic solutions for supply chains” (Ratner et al., 2020). Accordingly, the empirical data and results of this research of fully functioning value chains constitute a novel contribution to knowledge within this research field.

09.02.06 Value Chain Design and Execution Frameworks

Two of the objectives of this research was (1) to develop frameworks and decision support tools to evaluate impact and feasibility of the potential value chains of decommissioned WTBs, including assessment of sustainability and (2) to design and document full end-to-end value chains for EoL WTBs that have been validated by the actors in those value chains. To fulfil these objectives, several frameworks have been developed based on research findings. First, the roadmap for sustainable EoL value chains for WTBs was developed in Paper II and further elaborated on and validated by the actors in the value chain in Chapter 6. The framework presents how fully functioning end-to-end value chains can be designed for six potential EoL routes including material flow, operational processes, logistical processes, and applied technologies. Then, the framework for CE in decommissioning of LCPs developed in Paper III proposed how the entire decommissioning project for LCPs should be conducted. This includes all decommissioning activities of (1) planning, (2) preparation, (3) operational execution, and (4) post-decommissioning. These frameworks were empirically validated and elaborated on through the empirical findings of Paper IV. In addition to this work, the Three-Stage Framework for Sustainable Decision-Making (3-SuDeM) developed and validated in Paper V can be applied to assist stakeholders and organizations in value chains with sustainable decision-making. The results showed that applying the framework helped practitioners to qualify their decision-making process within the individual value chain activities. Finally, the scenario development and framework for assessment presented in Paper VI illustrated how to assess and evaluate entire future value chains considering different levels of circularity, TRL, cost, and timeframes.

09.02.07 Value Chain Processes – the Potential of Standardization

An important finding from both the modified roadmap of Chapter 6 (Figure 9) and cases A-D from Chapter 7 was that up to eight separate operational processes and four separate instances of transportation can occur in a full value chain for EoL WTBs, including (1) on site demolition, (2) on-site operations for sectioning, (3) first pre-processing, (4) landfilling (of non-recyclable parts), (5) second pre-processing, (6) material recycling, (7) post processing, and (8) material refining and application (Paper IV).

However, each process can include separate equipment, operations (and operators), location of workplace (indoor and outdoor), safety measures, organizations, management etc. Thus, these are complex systems that require planning, collaboration, and operational execution, which can be supported by the framework for CE in decommissioning of LCPs proposed in Paper III (Figure 6). That said, by applying a value chain perspective, the results from this PhD study have shown a clear commonality between the processes needed across potential EoL routes. In fact, it was found that processes 1-5 listed above are close to identical across the different recycling routes. This is an important finding as it signifies that efforts and investments in developing these processes will be needed no matter what recycling route is applied. Thus, it would be beneficial in all cases to identify potentials for optimization and standardization across value chains.

A surprising, yet critical finding to support this development is that results did not show any significant operational differences in the value chain processes due to the material or composition differences of the blades. This is important knowledge since the blade composition varies based on manufacturer and model (Mishnaevsky Jr et al., 2017). However, results from Papers IV and V showed that different technological solutions applied in value chain processes, such as equipment for sectioning, can vary based on organizational preferences and assessments. The 3-SuDeM framework developed and validated in Paper V for selection of sectioning equipment suggested that an excavator with a circular saw attachment was the preferred technology for WTB sectioning processes. While this technology was also recommended by Jensen and Skelton (2018), the result is dependent on the input from the test organization.

Another interesting finding resulting from the empirical cases (Paper IV), was that all the cases involved hundreds of kilometers of transportation by truck to move the materials between value chain processes. This was not found to be addressed in the literature so far but will have an environmental impact. This finding highlights the potential of either exploring alternative modes of transportation, or establishing value chain processes in close geographical proximity to each other in order to reduce energy consumption and lead-times as well as material handling, such as loading/un-loading etc.

Findings from the empirical case studies in Chapter 7 showed that to scale all the EoL routes, environmental and safety measures must also be implemented in all processes, especially when working on site. This includes collection of dust and debris and ensuring a safe workplace for operators, which emphasizes the fact that when designing new value chains, or eco-systems, you are also designing jobs. These aspects of EoL management have not been identified in current literature and are therefore a novel contribution.
These results are particularly interesting since they demonstrate how challenges can be mitigated and identified potential can be fulfilled. Thus, the operational execution of EoL management of WTBs can and should be optimized and standardized.

09.02.08 Model for Circular Value Chains for Wind Turbine Blades

A main objective of this research was to provide a complete roadmap of full end-of-life value chains in accordance with CE principles that can be implemented and operated an at industrial scale for future WTBs reaching their EoL. While Paper I shed further light on the expected waste volumes, the remaining research studies (Papers II-VI) and results from Chapters 6-8 all contribute to this objective. To fulfil the defined objective, a cohesive roadmap model consolidating and synthesizing results across Papers II-VI has been developed and is presented in Figure 11 - Circular value chains for EoL WTBs. The model also fulfils the set objective of how to identify and evaluate best practices across value chains and recycling technologies, including pre-processing and logistics. The model is considered to be a main contribution to both practice and academia and to present a new state-of-the-art for EoL WTB value chains.

The model starts with a blade being decommissioned and then presents all the potential circular strategies and interrelated value chain processes that the WTBs can follow for blade reuse, structural repurposing, or recycling through either cement-co-processing, mechanical recycling, solvolysis or pyrolysis.
The model both considers the TRL for all the routes, i.e. the future development and availability of technologies, while also considering the level of circularity. This is visualized through the use of different colors to show

if the value chain process can be implemented in the short, medium, or long term. Specific timeframes are not set, since this depends on investments and efforts in research and innovation, but the figure illustrates the expected sequence of value chain availability based on the research findings. Yet, an important result is that all the short-term value chain processes have been demonstrated at an industrial scale through cases A-D (Papers III and IV) and could therefore be implemented with the knowledge presented in this dissertation and with existing technologies. As depicted, the EoL WTB should aim to reach the highest level of material circularity possible at the time of decommissioning. Hence, if reuse is an option, this is what should happen before other alternatives and so forth. The value chains are continuously supported by assessments using pLCA or MCDM methods based on case specific variables for decision-making as listed in Figure 10, and as demonstrated in Papers V and VI.

The results of this dissertation do not point to one route or technology being preferred over all others. Based on the results, all the assessed EoL routes are expected to be feasible and to present an appropriate EoL solution for WTBs but with different timeframes for full development and implementation. Yet, most of the pre-processes and logistical processes are not dependent on this development and are crucial to all the routes. Thus, in unity all the EoL routes present a full solution to the waste challenge of WTBs.

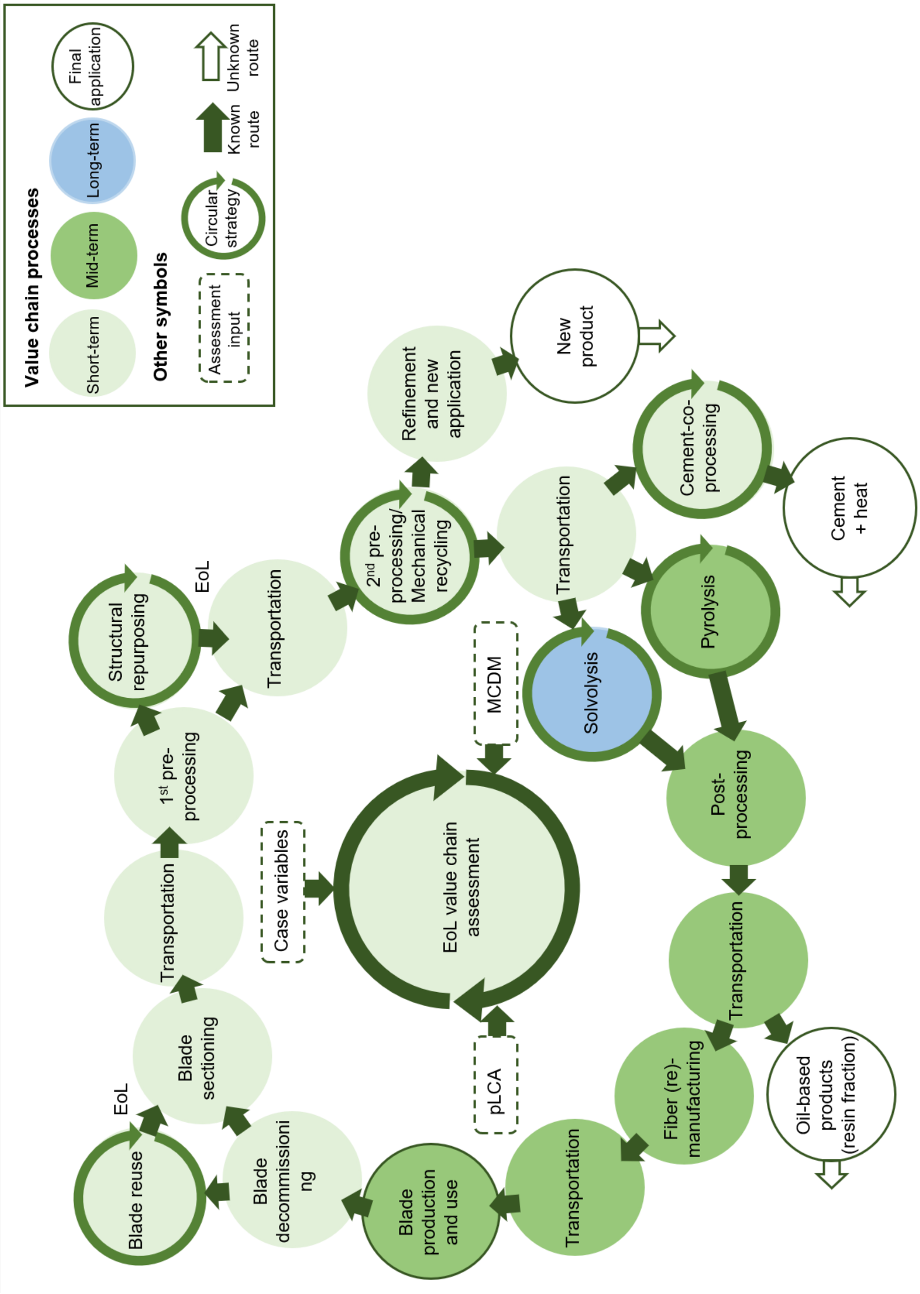


Figure 11 - Circular value chains for EoL WTBs

09.03 How to Overcome Barriers to End-of-life Value Chain Industrialization

In this study the establishment of circular value chains for EoL WTBs has been documented from a technological perspective that can be achieved in the short term. Figure 11 outlines all the identified circular value chains for EoL WTBs, including processes and technologies and how to assess these in terms of cost, environmental, and social impact based on case variables. Chapter 5 addressed the question of why these solutions are not yet available at an industrial scale, and in Chapter 5 eight main barriers to circular value chain implementation were presented in Figure 6. This section will discuss how to mitigate and overcome these barriers with the results described in Chapters 5-8.

The barrier of **low and unpredictable volumes of waste** was unfolded in Paper I and showed how a more accurate forecasting of future waste flow was achieved using empirical decommissioning data from Denmark. The analysis resulted in an important finding, which showed that the average lifetime before decommissioning was 29 years. This stood out as a significant result, since previous studies have determined a lifetime of 18-20 years without using empirical decommissioning data (Lichtenegger et al., 2020, Andersen et al., 2016, Cooperman et al., 2021). Yet the method and results of Paper I may also be applied in other geographical contexts. Thus, the method demonstrates how to mitigate this barrier and improve waste volume predictions to assist EoL value chain stakeholders in decision-making for timing and investments.

A topic not addressed in this dissertation is FRP waste from WTB production, which also represents a potential waste flow. Since blades are produced in a steady flow across OEMs, the composite waste from production facilities could be a waste stream that would also be suitable for inclusion in the proposed recycling value chains. While the research project TURBO (European Commission, 2023g) aims to reduce this waste mass, it is suspected that the waste that cannot be avoided could be recycled through the same processes as the EoL WTBs. If so, this would also mitigate the problem of low and unpredictable waste volumes.

The second barrier identified was **material complexity** caused by the nature of composite materials, in this case GFRP, which are thermosetting plastic based. While several projects such as Zebra (LM Wind Power, 2023) or the recyclable blade by Siemens Gamesa Renewable Energy

(2021) have tested new recyclable resin systems, the benefit of these systems will not be obtained until EoL, which will be up to three decades after production according to results from Paper **I**. Thus, this barrier must be addressed for existing WTBs. Results of this research demonstrate how existing WTBs can, in fact, be recycled despite of the material complexity, but that this requires a full value chain designed specifically for this purpose. Thus, this barrier can be overcome through the implementation of value chains developed and presented in this research.

The third and fourth barriers were the **lack of alternative technologies at an industrial scale** and **low cost and easily assessable landfilling**, which has also been addressed through this research, where four recycling value chains have been designed, validated, and demonstrated for industrial scaling. To mitigate these barriers, efforts should be made to implement value chains, and to support this development, the self-imposed landfill bans by Ørsted, Vattenfall and Wind Europe (Ørsted, 2021, Vattenfall, 2021, WindEurope, 2022b), could be introduced industry-wide. This could be effective from the point of view of equal competition and of improving development and investment conditions for circular EoL solutions.

The fifth barrier identified was the **limited waste legislation causing low incentive for new solutions**. Beauson et al. (2021) noted that legislation is a powerful tool when it comes to promoting sustainable EoL options, while Jensen (2019) argued that legislation does not guarantee competencies or efficient processes. The fully designed, validated, and tested value chain solutions presented in this research thus address this call, by providing knowledge for efficient EoL processes. In addition, it also provides a knowledge foundation for policymakers and can serve as input for future legislation for the waste management of composites, which then would mitigate this barrier.

A study of the **public perception** of the wind energy sector presented in Chapter 5, constituted in the sixth identified barrier. The findings illustrated in Chapter 5 proved that until 2019 there was an overweight of positive stories in the public media about wind energy and EoL blades. After 2019 this changed, and predominantly negative stories were published about the lack of sustainable EoL options for WTBs. Even though this shifted back by 2021 with a focus on solutions, the interest and pressure from the public and the public media remained high, with 27 articles published in the Danish media in 2021-2022 alone. The pressure is expected to remain, creating a continuous encouragement for WTB owners to seek circular and sustainable EoL options for WTBs.

An identified barrier pertained to the **lack of available material and geometry information**. This information is required for recyclers to design appropriate EoL value chains, as this will influence processes and equipment, as well as the final secondary applications. As described in Chapter 5, the product material passport was developed and launched by the DecomBlades project in 2023 (DecomBlades, 2023). The material passport standard may help to overcome this barrier since the required information can now be obtained from OEMs. This does, however, require a full adaptation and implementation of the material passport standard across OEMs and blade models.

That said, the empirical results of this research study did not show any significant variances in EoL value chain processes like sectioning, preprocessing, or logistics depending on blade material or geometry. This finding is therefore highly relevant to overcoming the last identified barrier of **WTBs being large complex structures** with high variations in length, geometry, and material composition. These variables have been explored through the empirical case studies of Chapter 7, where findings showed that even though these variations could impact the project lead-time and type of equipment applied, the main value chain processes and sequences were the same.

A striking result was that information sharing and collaboration across the value chains were found to be essential for mitigation of all barriers. The empirical findings from the case studies of Chapter 7 support this notion and demonstrate the types of actors/organizations involved, and how and when they are involved.

The cost impact of circular EoL solutions has not been addressed in this research but does influence decision-making, as found in Papers V and VI. Profit-driven organizations are naturally cost-oriented, but even so, based on the research findings, it is encouraged that the level of material circularity should weigh the most and be a main driver for decision-making on future EoL routes. In other words, to achieve circular EoL value chains, it should be accepted that until full industrialization has been reached, alternatives to landfill can come at a higher cost.

09.04 Implementation of Circular Economy

While the industrial domain studied in this research was the wind energy sector, and specifically EoL WTBs, the research findings also contribute to theory and knowledge on CE and its operational implementation. In literature, as much as 221 definitions of CE have been proposed while the important knowledge gap concerning the operational execution of CE implementation remains (Kirchherr et al., 2023). Yet, Kirchherr et al. (2023) concluded that CE potentially has more meaning to academia than to practice. This is a notion supported by Corvellec et al. (2022), who criticize CE for being too theoretical, while Barreiro-Gen and Lozano (2020) also pointed out the gap between CE theory and CE practice. If CE is not implemented and operationalized, it will remain at a strategic and conceptual level and not produce any real impact. Thus, an important contribution by this research is how operations management can aid the implementation of CE through tangible practices and frameworks for CE implementation. In particular, with a focus on the circular principles of reuse, repurpose and recycling (Kirchherr et al., 2017, Potting et al., 2017) at a micro level focusing on supply chains (Jackson et al., 2014).

09.04.09 Practices and Frameworks

This research set out to move forward both research and practice as regards the implementation of circular EoL value chains, to contribute to the sustainable development and implementation of CE as called for by Korhonen et al. (2018). This objective has been fulfilled through the results of this study where full EoL value chain systems have been developed, including frameworks and models for decision-making and implementation. For CE to make a positive contribution to sustainability (3BL), Velenturf and Purnell (2021) found that a systems perspective must be adopted that considers all three aspects of the 3BL through the value chain. The research approach of value chain design and assessment adopted in this PhD dissertation thus supports this notion. In addition, the results expand on the findings by Velenturf and Purnell (2021) by providing the methods and frameworks for CE value chains development and assessment based on the 3BL.

Among the results of this research, the framework for CE in decommissioning of LCPs (Paper III), the Three-Step Framework for Sustainable Decision-Making (Paper V), and the framework of emerging-scenarios assessment (Paper VI) have been developed. All three frameworks

present a direct contribution to literature by proposing how CE can be implemented at a value chain level based on collaboration (Zanjirani Farahani et al., 2022). This includes value chain development (Paper VI), large EoL projects for LCPs (Paper III), and decision-making at a process level (Paper V). The assessment methods developed and validated in Papers V and VI both contribute to the critical assessments needed of full value chain solutions to ensure that CE implementation is indeed sustainable (Korhonen et al., 2018).
The findings contribute to previous research that has explored the practices that can be adapted by organizations to implement CE (Kalmykova et al., 2018), the barriers to and opportunities for manufacturing and supply chains (Kumar et al., 2019, Govindan and Hasanagic, 2018) and CE implementation strategies (Lieder and Rashid, 2016). The methods and technologies needed for CE implementation at the micro level are provided which Barreiro-Gen and Lozano (2020) found to be scarcely addressed in literature.

09.04.10 Value Chain Collaboration

The findings of this study also highlighted the importance of collaboration throughout the (future) EoL value chains for operational execution of CE principles. The research results support the findings by Eisenreich et al. (2022) and Johansen et al. (2022) that involvement of stakeholders in the value chain is key for successful CE implementation. This has been demonstrated throughout the research results where EoL value chains have been co-created and validated by actors in the system (Chapters 6 and 7) and by the fact that impact assessments of full value chain solutions require data and knowledge from all value chain entities (Paper VI). The cross-sector collaboration demonstrated by the DecomBlades project has also shown how cooperation in the value chain paves the way for new technologies and solutions, such as case D, Paper IV. The collaboration to create new systems does not only present an interesting contribution to literature on CE implementation, but also sets a great example for other industries on how to approach similar challenges.

Another important contribution of this research is the fact EoL value chains have been developed and validated by the actors within the system. The methods and frameworks developed in this research can assist in evaluating the impact, feasibility, and effectiveness of new systems across organizations and value chains with multiple stakeholders. These findings support the results of Kirchherr et al. (2023), who found that CE implementation relies on collaboration between stakeholders. Barreiro-Gen and Lozano (2020) also called for collaboration to bridge the gap between CE theory and practice, and the research results of this dissertation demonstrate how this can be done through collaboration between competitors, suppliers, universities, and other stakeholders identifying and testing solutions.

09.04.11 Implications for Other Industrial Domains

In addition to the above-mentioned implications, an objective of this research was to demonstrate new business systems for recycling and set examples for other industries. While EoL WTBs were the main unit of analysis, the results, frameworks, and models developed can also benefit other industrial sectors working towards EoL value chain design and implementation. Applying a value chain perspective was found to be a comprehensive and detailed approach to developing new EoL systems, and one that could be applied to other industrial systems. In addition, the framework for CE in decommissioning of LCPs developed in Paper III could also be applied in other sectors where complex LCPs need to be handled at EoL such as constructions, vessels, submarines etc. However, further research for test and validation is proposed in these contexts. Finally, the specific EoL value chains for WTBs developed in this research could also be applicable in other industries where composites are used such as aerospace, leisure boats, or the construction sector. This may require modifications to some of the processes or technologies, but it is suspected that the solutions could be largely utilized. Thus, future research is suggested to test the EoL value chains in different industrial domains.

09.04.12 Trade-off Between Technological Readiness Level, Level of Circularity and Cost

A key contribution from this research to the field of CE is the uncovering of circularity levels versus TRL and cost. As demonstrated by Figure 11, some EoL value chains could be established in the short term while other systems aiming for higher levels of circularity are further developed. In addition, it points out the importance of ensuring that new systems make an overall positive environmental contribution which should be assessed using LCA as proposed in Paper VI.

While the research results and Figure 11 imply that the highest possible level of circularity should be aimed for, they also raise the question of whether lower levels of circularity should be adopted until solutions with higher levels of circularity have reached a high TRL. In other words, should you spend resources implementing a EoL value chain with a low level of circularity but a high TRL? Or should you wait and invest in improving TRL of technologies with higher levels of circularity?
While this research does not directly address how development and operating costs influence EoL value chain development, it is an important aspect from a business- and profit perspective as the implementation of circular systems could come with a higher cost than the current linear alternatives. Yet, if profit-driven organizations have benefited monetarily from using valuable earth resources, they should ensure that these resources are not lost and lose their value. If so, it also raises the questions which stakeholders should manage and cover this cost, and how should it be managed? These questions might be of a more political nature but need answering for CE to become a reality.

09.05 Paper VII – The Operations Management Researcher's Role: The Observer or the Facilitator of New Sustainable Business Eco-systems?

In addition to the discussion of research results and contributions, a separate research study has been completed to explore how researchers can and should collaborate with industrial stakeholders for CE implementation. The manuscript is appended as Paper VII and raises the question: What is the operations management researcher's role: the observer or the facilitator of new sustainable business eco-systems? This conference manuscript was developed and presented at the conference of the European Operations Management Association (EurOMA) 2023 in Leuven, Belgium. The content and results have also been presented and discussed at the Scandinavian Academy of Industrial Engineering and Management (ScAIEM) 2023 conference in Kongsberg, Norway. The manuscript was developed to reflect on my own role as a researcher within a large collaborative research project such as DecomBlades. Thus, the paper does not directly answer the research questions posed in this dissertation and has therefore not been included in the main research results. Yet, the manuscript provides an important contribution to my own learning, and meta-reflection of what it requires to be a researcher in this

research context. Hence, the study contributes to the discussion of the barriers, drivers, and abilities of operations management researchers to engage as facilitators of new sustainable business systems.

Purpose – To create sustainable impact, shared best solutions must be implemented across industries, value chains and eco-systems, rather than within single organizations. For this purpose, collaborative research projects with multiple stakeholders can be a way forward for creating new innovative solutions for sustainable practices. In this context, projects where coopetition is involved, i.e. where competing organizations collaborate towards shared goals, can lead to successful solutions, with the support of a neutral facilitator. Given the increasing numbers of collaborative research projects between research and academia, this study sets out to investigate how a researcher can or should engage in research projects for new sustainable business systems where coopetition is involved. It particularly sought to explore the barriers, drivers, and abilities of researchers to engage in such projects and what role they should play.

Methodology – In this research study, a literature review was first conducted on the relationships between the concepts of coopetition, business eco-systems and industrial sustainability. Based on the review, a conceptual framework was developed to explain the relationships between these concepts. Based on the conceptual framework, the role of the operations management researcher was explored and elaborated on based on empirical data. For data collection, four individual round-table discussions were held at the 10th conference of the Scandinavian Academy of Industrial Engineering and Management in Uppsala, Sweden, where 24 junior and senior scholars participated from the field of industrial engineering and operations management. The groups were given four questions to spark discussions and reflections. All group discussions were recorded, transcribed, and coded using descriptive text coding followed by a synthesizing of identified themes and topics. The findings were elaborated on using key statements from participants and consolidated in a new framework.

Findings – The findings from the literature review indicated that having a neutral third-party as a facilitator is a driver of successful coopetition between organizations. Furthermore, it found that coopetition can be a driver for successful industrial sustainability and new business eco-systems. Thus, the findings suggested a positive relationship between

neutral facilitation in projects involving the constructs of coopetition, industrial sustainability, and the formation of new business systems. The empirical findings suggested that the role of the researcher as a third-party facilitator can be a positive enabler in this context. The results were consolidated in a framework of drivers, barriers and required abilities for operations management researchers as third-party facilitators for new sustainable business ecosystems. The findings showed that at least ten barriers and nine drivers for collaboration and facilitation are present for researchers engaging in multi-stakeholder projects. Ten researcher abilities were also identified as important for a researcher to possess and apply to mitigate the identified barriers and support the identified drivers. The main themes detected included the blurred lines between research and consulting, concerns of facilitating – such as not being able to publish, stress, or ability of being unbiased, and the fact the researcher's role can change over time.

Novel contribution and research implications – The proposed framework is a novel contribution to literature that consolidate the viewpoints and experiences from the operations management research community and elaborates on how researchers can and should engage in research projects. The findings have implications for researchers in general but specifically scholars involved in collaborative projects with industrial partners aiming at the development of new sustainable systems. Thus, results also contribute to a higher awareness among researchers, which can lead to improved research outcomes in the field of operations management. Finally, it elaborates on the responsibilities of research(ers) as a part of society and as an enabler to ensure sustainable societal development.

10 Conclusion

This PhD dissertation set out to study “How value chains for end-of-life wind turbine blades can be designed, operated, and industrialized in accordance with a circular economy”. To answer this research question four sub-research questions were defined and answered, based on a mixed-method research design, resulting in seven appended papers (I-VII) combined with additional studies, analyses, and findings compiled in Chapters 5-8. The combined results of this dissertation were discussed and elaborated on in Chapter 9.

This chapter will conclude on the collective research findings of the dissertation and provide a full and cohesive answer to the main research question. To do this, the conclusions of the four sub-research questions are first summarized and linked to the main research question. This is followed by a conclusion across this PhD dissertation as a collective piece of research. Finally, the research limitations and recommendations of future research will be elaborated on.

10.01 Overall Conclusion

First, sub-RQ1 set out to understand “why circular EoL value chains for wind turbine blades do not exist today?” The question was answered in Chapter 5. Based on the results from Paper I combined with additional research findings of barriers to circular EoL value chains, it can be concluded that circular EoL value chains for WTBs are required to responsibly handle the composite waste of the increasing numbers of WTBs being decommissioned. Grounded in historical decommissioning data from Denmark, it was found in Paper I, that the average time for WTB decommissioning is 29 years. This is 9-11 years longer than forecasted by previous studies, which implies that waste volumes may be delayed. Based on the findings in Chapter 5 it can also be concluded that there are at least eight key barriers to creating sustainable value chains for EoL WTBs. These findings are presented in Figure 6 and collectively answer the question why circular EoL value chains are not a reality.
The eight barriers include: (1) low and unpredictable volumes of waste, (2) material complexity, (3) lack of alternative technologies, (4) low cost and accessibility of landfilling, (5) limited waste legislation, (6) low pressure from the public until 2019, 7) large complex products, and (8) lack

of material and geometry information. These barriers must be overcome to facilitate the design, operation, and industrialization of circular value chains for WTBs.

Second, sub-RQ2 addressed the **design** aspect of the main research question, by answering the questions: “Which EoL value chain routes are potential end-to-end solutions for wind turbine blades and what technologies and processes are included in the design of these solutions”. Findings were consolidated in Chapter 6 and in Paper II.

Based on the findings from a systematic literature review presented in Paper II, it can be concluded that from a theoretical perspective there are six potential end-to-end value chain routes that can be applied as solutions for EoL WTBs. The six routes are collected in a cohesive roadmap (Figure 8) and include: (1) Structural repurposing, (2) thermal recycling, (3) chemical recycling, (4) cement co-processing, (5) mechanical recycling, and (6) incineration with energy recovery. However, it is concluded that incineration with energy recovery is not a circular strategy and that this route should not be used for EoL WTBs.

Based on a study and analysis of technological developments for EoL WTBs from 2020-2023 presented in Chapter 6, it can be concluded that there is an increased research focus on solvolysis and pyrolysis and that new promising research results have been achieved. These findings were compiled with the findings from Paper II in a modified version of the roadmap for sustainable value chains for end-of-life wind turbine blades (Figure 9). A consolidation of research results from Chapter 6 identified eight value chain steps, which were: (1) Dismantling and preparation, (2) Sectioning for transportation, (3) 1st pre-processing, (4) 2nd preprocessing (5) material processing, (6) output material, (7) product refinement, and (8) new product.

In conclusion, the modified roadmap with the eight value chain steps consolidates the academic state-of-the-art with the newest technological developments and thus specifies in detail how future EoL value chains for WTBs can be designed, including which technologies and processes are potential solutions for EoL value chains for WTBs.

Third, sub-RQ3 addressed the **operation** aspect of the main research question, by answering the question: “How can fully functioning value chains for end-of-life wind turbine blades be operated at an industrial scale to support a circular economy?” In Chapter 7, four case studies of EoL value chains for WTBs were completed, analyzed, and documented in Papers III and IV, which provided comprehensive empirical data on how fully functioning circular value chains for EoL WTBs can be designed and operated at an industrial scale.

Based on the findings presented in Chapter 7, it can be concluded that designing and operating fully functioning value chains for EoL WTBs in accordance with CE principles requires that: (a) all phases of decommissioning/EoL must be designed based on a value chain approach and CE principles; (b) a full decommissioning project should consist of four phases, i.e. overall planning, preparation for decommissioning, operational execution, and post-decommissioning; (c) all phases must be designed and operationally executed according to the highest circularity level possible; (d) within the third phase of operational execution up to eight steps and four separate points of transportation may be required.

All steps in the EoL value chains must be designed as one complete system where all processes are developed and aligned in accordance with the specifications of the desired secondary product made from the WTB waste. In addition, partner collaboration upstream and downstream in the value chain is found to be essential to assess, design and operate successful EoL value chains.

Finally, all four cases demonstrated functioning value chains for EoL WTBs in accordance with CE principles for recycling. Based on these results, it can be concluded that the recycling routes of cement co-processing, mechanical recycling, and pyrolysis are technically and practically feasible to operate for over ten metric tons of WTB material. In addition, it was concluded that the operational execution of each empirical case required up to eight process steps and four separate points of transportation. These findings were in alignment with the proposed value chain roadmap for EoL WTBs (Figure 9) and thus validated its application.

Fourth, sub-RQ4 studied the aspects of circular value chain **industrialization** by answering the questions: "How can it be evaluated which circular value chains for EoL WTBs should be industrialized and what variables influence this decision?"

Findings from Paper V concluded that the most frequently applied method for sustainable decision-making was the method of Multi-Criteria Decision-Making (MCDM). A complete Three-Stage Framework for Sustainable Decision-Making (3-SuDeM) was developed and successfully tested in collaboration with a Danish waste management organization to assist in the evaluation of and selection between four different technologies for WTB sectioning. It was concluded that applying the proposed framework positively aids the decision-making process by making sustainable decision-making approachable and manageable.

Findings from Paper VI resulted in a proposed five-step framework of emerging-scenarios assessment that integrates a prospective LCA approach and MCDM methodology to consider: (1) the challenges associated with the acuteness of increasing waste volumes, (2) differences in TRL, (3) difference in circularity levels, (4) the lack of weighted environmental, economic and social sustainability variables, and (5) SSP scenarios and different timeframes until 2050.

In conclusion, to evaluate which circular value chains for WTBs should be industrialized, the assessment methods of MCDM and prospective LCA can be applied. Findings across Papers V and VI highlight the need to evaluate a complex set of variables in the assessments, including circularity level, local availability of technologies, TRL, expected waste volumes, SSP scenarios, data availability, future technical developments, cost, environmental, and social aspects. These were collected and illustrated in Figure 10.

Based on the combined results of this PhD study, it is concluded that the circular principles of reuse, repurposing and recycling can be applied for EoL WTBs. The routes of the three circular principles applied in the context of EoL WTBs are consolidated and summarized in Figure 11, which illustrates how to design, operate, and industrialize circular value chains for EoL WTBs. The study concludes that when a WTB is decommissioned, it should first be assessed if it can be reused as spare parts, either as it is or following repair or refurbishing. If this is found not to be an option, it should be assessed if the circular strategy of structural repurposing can be applied. Following this, an assessment of case variables through the methods of MCDM and LCA should be conducted to determine which of the four recycling routes of mechanical recycling, cement co-processing, pyrolysis or solvolysis should be applied in the given circumstances.

Findings throughout this study showed that the recycling technologies are not at the same TRL. Thus, based on research and development, the routes can be implemented within different timeframes. However, from an operational, and logistical point of view, there are no obstacles to industrialization. In the short term, the routes of cement co-processing and mechanical recycling are feasible and acceptable routes for EoL WTBs. All value chain steps and technologies required to implement and scale these routes exist today. Yet, cement co-processing is found to be at the lowest circularity level and should therefore only be used until other solutions become available. In the medium term, the thermal recycling route of pyrolysis was also found to be an appropriate route as results show that through pyrolysis, glass fibers can be separated from the resin fractions to allow the materials to be recycled separately. The pyrolysis case reported and analyzed in this research study concerning two full WTBs showed that the value chain for pyrolysis is also feasible, but that further development is needed to reach a higher TRL. However, the case results found that recovered fibers can replace virgin materials in the production of new glass fibers, which can then be used for new WTBs. In the long-term, results led to the conclusion of solvolysis also being a promising and applicable EoL route allowing for fiber and resin separation. However, it is the EoL route that is currently at the lowest TRL compared to the other technologies, and it needs further development and testing to reach industrial maturity.

The collective findings of this research show that the design and development of full value chains in collaboration between the involved actors is key for successful circular waste solutions. By applying a value chain perspective, this PhD study has shown how the first five value chain processes, i.e. (1) site demolition, (2) on-site operations for sectioning, (3) first pre-processing, (4) landfilling (of non-recyclable parts), and (5) second pre-processing, are close to identical across the four assessed recycling routes. In addition, it can also be concluded that there are no significant operational differences in the value chain processes due to material or composition differences of the WTB. It was, however, found that the technologies used for the processes, such as sectioning equipment, depended on organizational preferences, knowledge, and availability. Thus, based on these results it can be concluded that there are several potentials for process optimization and standardization of value chain processes 1-5, including geographical dispersion of facilities, transportation modes, process automatization and working environment measures.

The applied value chain perspective and the use of empirical data from industrial cases are found to be novel contributions to both academia and practice on how a WTB reaches a state of a new product through up to eight individual processes and four points of transportation. The findings are significant as they demonstrate how circular systems can be designed, operated, and industrialized based on a value chain approach to process design, logistics, stakeholder collaboration and co-creation. Thus, the results have implications for theory on operational execution and implementation for CE in practice.

In summary, the model in Figure 11 - Circular value chains for EoL WTBs, merges the value chain processes that should be included to design, operate, and industrialize circular value chains for EoL WTBs. It is concluded that circular value chains for EoL WTBs are technically and operationally feasible and can be achieved by (1) applying a value chain approach to system development, (2) applying the model of circular value chains for EoL WTBs to design and implement industrial facilities, (3) assessing value chain routes using LCA and MCDM methods based on specific case variables, (4) working on standardization, optimization and automatization of value chain processes common to the various EoL routes to reduce complexity and cost, (5) investing in research and development to improve TRL of pyrolysis and solvolysis, and (6) establishing collaboration between value chain actors, including sharing of knowledge and material data. By doing so, circular value chains for EoL WTBs can and should soon be a reality.

10.02 Research Limitations

This dissertation has combined seven research papers to answer the main research question and four sub-research questions posed. While important results and contributions to literature, knowledge and theory have emerged, there are some limitations to this study that should be considered, and which open for new research agendas.

This research study has adopted a case study methodology for empirical collection and analysis, and while this method has clear advantages as outlined in Chapter 4, it also has some limitations. Four cases have been studied in detail, yet, including more cases could capture more variance between cases. Also, the included cases were based in Denmark or Finland, which could have implications for how the EoL operations were designed and executed. Thus, future research should include more empirical industrial case studies in other geographical contexts to further validate and test the findings of this research. In addition, case studies from other industries utilizing similar composite materials are suggested for future research to test if the EoL value chain systems developed in this study could, in fact, also be applied for other products. Other methods of empirical data collection and analysis are also suggested such as surveys with a broader range of actors.

The waste volumes that were included in the four presented empirical studies are also relatively low, compared to the forecasted waste volumes. Yet, due to low TRL and early stage of implementation of circular EoL value chains, relevant cases with higher volumes were not identified. This limitation could have an impact on how EoL value chains are designed in terms of capacity and applied equipment or technology. Especially the less mature routes such as pyrolysis and solvolysis are yet to be studied based on larger volumes of waste. Thus, future research should include higher volumes of waste, especially for the routes of solvolysis and pyrolysis.

While several opportunities for standardization were identified and discussed in Chapter 9, these results point towards the need for optimization of EoL value chains across processes as regards transportation modes and distances, social impacts, and process automation. Each of these areas are potential paths for future research.

The fact that I as a researcher have been working in close collaboration with industrial partners through the DecomBlades projects has, as discussed in Chapter 4, both provided unique opportunities and access to data. Yet, having engaged with other organizations could potentially have an impact on results, which is a limitation to this study. Thus, future research is suggested to test and validate the results with other actors in the wind energy sector.

The study pertains to a European context and in some instances to a Danish context such as in Paper I. Even though the geographical boundaries of this study were scoped as part of the research delimitations, geographical differences in other countries or regions, such as legislation, industrial context, or political context, are not captured. Future research should therefore seek to validate and expand on the presented findings of this research in other geographical contexts.

10.03 Recommendations of Future Research Paths

Despite promising results from this study, several questions and research topics still remain. Future studies on the topic of EoL WTBs and composite materials are therefore recommended and are listed below to set the direction of further research:

1. **Focus on full value chain solutions.**
   Future research should continue to explore full value chain perspectives for CE operationalization and implementation. This should both consider EoL WTBs, but also other industries working with LCPs or composite-based products.

2. **Continued validation and testing of developed frameworks.**
   The frameworks and methods developed in this research should be further tested and developed through more cases looking at other geographical contexts, higher waste volumes and different EoL routes.

3. **Optimization and standardization of operations.**
   The value chain processes identified across the various EoL routes should be standardized for optimization while focusing on reducing transportation, social and environmental impacts and increasing the TRL.

4. **Explore collaboration/partnerships across the value chain.**
   Future research should seek to understand the effect and role of collaboration and coopetition in sustainable and circular system developments and implementation.

5. **Industrialize the process of mechanical recycling.**
   Future research should further investigate how to develop and industrialize the process of mechanical recycling for both EoL WTBs and other composite products.

6. **Innovate and develop the solvolysis route.**
   Findings suggest that solvolysis will have an increased role in the value chains for EoL WTBs and should be explored further as a method for material separation and for material recycling. This includes an investigation of the quality and cleanliness of glass fibers from the solvolysis process.

7. **Continue development and scaling of pyrolysis.**
   The learnings and successful outcome of the PoC for the pyrolysis process (presented in case D, Paper IV) should be further developed into a full industrial-scale facility. This will require further research in operations management and standardization of the process.

8. **Investigate composite production waste.**
   As noted in the discussion, a way of securing a steadier inflow of waste materials is by including WTB composite production waste in the proposed value chains. However, the feasibility and scaling of this must be further researched and developed.

9. **Investigate processing/refinement of output materials.**
   For both the technologies of solvolysis and pyrolysis, the output materials must be further processed and refined to represent a value for off takers. These processes must be further researched and innovated for optimal product outputs, especially pertaining to the retrieved resin fractions.

10. **Commercialization**
    The commercial value of secondary products made from EoL composite materials must be further explored to commercialize the identified EoL value chains. Thus, future efforts must be targeting the identification of applications, customers, and product value for secondary products.

References

AHRENS, A., BONDE, A., SUN, H., WITTIG, N. K., HAMMERSHØJ, H. C. D., BATISTA, G. M. F., SOMMERFELDT, A., FRØLICH, S., BIRKEDAL, H. & SKRYDSTRUP, T. 2023. Catalytic disconnection of C–O bonds in epoxy resins and composites. *Nature,* 617**,** 730-737.

AITKEN, J. 1998. Supply chain integration within the context of a supplier association: case studies of four supplier associations.

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.

ANDERSON, C. G. 2020. *Wind Turbines: Theory and Practice,* United Kingdom, Cambridge University Press.

BARREIRO-GEN, M. & LOZANO, R. 2020. How circular is the circular economy? Analysing the implementation of circular economy in organisations. *Business Strategy and the Environment,* 29**,** 3484-3494.

BEAUSON, J., LAURENT, A., RUDOLPH, D. & JENSEN, J. P. 2021. The complex end-of-life of wind turbine blades: A review of the European context. *Renewable and Sustainable Energy Reviews***,** 111847.

BLADES2BUILD. 2023. *Blades2build* [Online]. Available: https://blades2build.com/ [Accessed 2023].

BORTOLOTTI, P., BOTTASSO, C. L. & CROCE, A. 2016. Combined preliminary–detailed design of wind turbines. *Wind Energy Science,* 1**,** 71-88.

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**,** 7395-7422.

CENTRE FOR ENERGY RESOURCES. 2018. *Section 32a: Guidelines on decommissioning plans for offshore oil and gas facilities or installations* [Online]. [Accessed 2023].

CETEC. 2023. *CETEC, Circular Economy for Thermosets Epoxy Composites* [Online]. Available: https://www.project-cetec.dk/uk/ [Accessed 16.10.2023].

CHALMERS INDUSTRITEKNIK. 2023. *CIRCUBLADE – Holistic solutions to upcycle End-of-Life wind turbine blades* [Online]. Available: https://chalmersindustriteknik.se/en/news/circublade-holistic-solutions-to-upcycle-end-of-life-wind-turbine-blades/ [Accessed 2023].

CHATZIPARASKEVA, G., PAPAMICHAEL, I., VOUKKALI, I., LOIZIA, P., SOURKOUNI, G., ARGIRUSIS, C. & ZORPAS, A. A. 2022. End-of-life of composite materials in the framework of the circular economy. *Microplastics,* 1**,** 377-392.

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.

CHERRINGTON, R., GOODSHIP, V., MEREDITH, J., WOOD, B. M., COLES, S. R., VUILLAUME, A., FEITO-BOIRAC, A., SPEE, F. & KIRWAN, K. 2012. Producer responsibility: Defining the incentive for recycling composite wind turbine blades in Europe. *Energy Policy,* 47**,** 13-21.

CHRISTOPHER, M. 2016. *Logistics and supply chain managment* FT Publishing.

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**,** 105439.

CORVELLEC, H., STOWELL, A. F. & JOHANSSON, N. 2022. Critiques of the circular economy. *Journal of industrial ecology,* 26**,** 421-432.

DE FREITAS NETTO, S. V., SOBRAL, M. F. F., RIBEIRO, A. R. B. & SOARES, G. R. D. L. 2020. Concepts and forms of greenwashing: A systematic review. *Environmental Sciences Europe,* 32**,** 1-12.

DECOMBLADES. 2023. *DecomBlades* [Online]. Available: www.decomblades.dk [Accessed 10.02.2023 2023].

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.

DEKKERS, R., CAREY, L. & LANGHORNE, P. 2022. *Making Literature Reviews Work: A Multidisciplinary Guide to Systematic Approaches*, Springer.

DELVERE, I., ILTINA, M., SHANBAYEV, M., ABILDAYEVA, A., KUZHAMBERDIEVA, S. & BLUMBERGA, D. 2019. Evaluation of polymer matrix composite waste recycling methods. *Environmental and Climate Technologies,* 23**,** 168-187.

DEUTSCHE INSTITUT FÜR NORMUNG E.V. (DIN) 2020. DIN SPEC 4866:2020-08. Sustainable dismantling, disassembly, recycling and recovery of wind turbines; Text in German and English.

DUL, J. & HAK, T. 2007. *Case study methodology in business research*, Routledge.

DURAKOVIC, A. 2023. 22 MW Offshore Wind Turbine in the Works for 2024/25. *OffshoreWind.biz.*

EISENREICH, A., FÜLLER, J., STUCHTEY, M. & GIMENEZ-JIMENEZ, D. 2022. Toward a circular value chain: Impact of the circular economy on a company's value chain processes. *Journal of Cleaner Production,* 378**,** 134375.

ELKINGTON, J. 1998. Accounting for the triple bottom line. *Measuring Business Excellence*.

ELLEN MACARTHUR FOUNDATION. 2024. *Circular economy introduction* [Online]. Available: https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview [Accessed 08-01-2024 2024].

ENERGINET 2022. 2022 sætter dansk rekord i vind og sol. *Ritzau.*

EUROPEAN COMMISSION 2018. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. European Comission,.

EUROPEAN COMMISSION. 2020a. *Carbo4Power, New generation of offshore turbine blades with intelligent architectures of hybrid, nano-enabled multi-materials via advanced manufacturing* [Online]. Cordis EU research results Available: https://cordis.europa.eu/project/id/953192 [Accessed 16.10.2023].

EUROPEAN COMMISSION 2020b. *Circular economy action plan : for a cleaner and more competitive Europe*, Publications Office.

EUROPEAN COMMISSION. 2023a. *Blades2Build, RECYCLE, REPURPOSE AND REUSE END-OF-LIFE WIND BLADE COMPOSITES – A COUPLED PRE- AND CO-PROCESSING DEMONSTRATION PLANT* [Online]. Cordis EU research results Available: https://cordis.europa.eu/project/id/101096437 [Accessed 16.10.2023].

EUROPEAN COMMISSION. 2023b. *EoLO-HUBs, Wind turbine blades End of Life through Open HUBs for circular materials in sustainable business models* [Online]. Cordis EU research results Available: https://cordis.europa.eu/project/id/101096425 [Accessed 16.10.2023].

EUROPEAN COMMISSION. 2023c. *ESTELLA, DESign of bio-based Thermoset polymer with rEcycLing capabiLity by dynAmic bonds for bio-composite manufacturing* [Online]. Cordis EU research results Available: https://cordis.europa.eu/project/id/101058371 [Accessed 16.10.2023].

EUROPEAN COMMISSION. 2023d. *EuReComp, European recycling and circularity in large composite component* [Online]. Cordis EU research results Available: https://cordis.europa.eu/project/id/101058089 [Accessed 16.10.2023].

EUROPEAN COMMISSION. 2023e. *RECREATE, REcycling technologies for Circular REuse and remanufacturing of fiber-reinforced composite mATErials* [Online]. Cordis EU research results Available: https://cordis.europa.eu/project/id/101058756 [Accessed 16.10.2023].

EUROPEAN COMMISSION. 2023f. *REFRESH, Smart dismantling, sorting and REcycling of glass Fibre REinforced composite from wind power Sector through Holistic approach* [Online]. Cordis EU research results Available: https://cordis.europa.eu/project/id/101096858 [Accessed 16.10.2023].

EUROPEAN COMMISSION. 2023g. *TURBO, Towards tURbine Blade production with zero waste* [Online]. Cordis EU research results Available: https://cordis.europa.eu/project/id/101058054 [Accessed 16.10.2023].

EUROPEAN COMMISSION. 2023h. *VIBES, IMPROVING RECYCLABILITY OF THERMOSET COMPOSITE MATERIALS THROUGH A GREENER RECYCLING TECHNOLOGY BASED ON REVERSIBLE BIOBASED BONDING MATERIALS* [Online]. Cordis EU research results Available: https://cordis.europa.eu/project/id/101023190 [Accessed 16.10.2023].

EUROPEAN PARLIAMENT & COUNCIL OF THE EUROPEAN UNION 1999. Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste.

EUROPEAN PARLIAMENT & COUNCIL OF THE EUROPEAN UNION 2010. Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control).

FLYNN, B. B., SAKAKIBARA, S., SCHROEDER, R. G., BATES, K. A. & FLYNN, E. J. 1990. Empirical research methods in operations management. *Journal of operations management,* 9**,** 250-284.

FONTE, R. & XYDIS, G. 2021. Wind turbine blade recycling: An evaluation of the European market potential for recycled composite materials. *Journal of Environmental Management,* 287.

GEISSDOERFER, M., SAVAGET, P., BOCKEN, N. M. & HULTINK, E. J. 2017. The Circular Economy–A new sustainability paradigm? *Journal of cleaner production,* 143**,** 757-768.

GHAFFAR, S. H., BURMAN, M. & BRAIMAH, N. 2020. Pathways to circular construction: An integrated management of construction and demolition waste for resource recovery. *Journal of cleaner production,* 244**,** 118710.

GOVINDAN, K. & HASANAGIC, M. 2018. A systematic review on drivers, barriers, and practices towards circular economy: a supply chain perspective. *International Journal of Production Research,* 56**,** 278-311.

HALLIWELL, S. 2010. FRPs—the environmental agenda. *Advances in structural engineering,* 13**,** 783-791.

HART, C. 2018. *Doing a literature review,* London, Sage Publications Ltd.

HENG, H., MENG, F. & MCKECHNIE, J. 2021. Wind turbine blade wastes and the environmental impacts in Canada. *Waste Management,* 133**,** 59-70.

HILL, J. S. 2023. *Vestas claims major breakthough in wind turbine blade recycling* [Online]. RenewEconomy. Available: https://reneweconomy.com.au/vestas-claims-major-breakthough-in-wind-turbine-blade-recycling/ [Accessed 16.10.2023].

INFOMEDIA 2022. Dansk Mediearkiv.

INTERNATIONAL ELECTROTECNICAL COMMISSION 2019a. EC 61400-1:2019 RLV, Wind energy generation systems - Part 1: Design requirements. IEC.

INTERNATIONAL ELECTROTECNICAL COMMISSION 2019b. IEC 61400-3-1:2019 Wind energy generation systems - Part 3-1: Design requirements for fixed offshore wind turbines. IEC.

INTERNATIONAL ENERGY AGENCY. 2024a. *EA Wind Task 45: Recycling wind turbine blades* [Online]. Available: https://iea-wind.org/task45/ [Accessed].

INTERNATIONAL ENERGY AGENCY. 2024b. *Record prices, fuel shortages, rising poverty, slowing economies: the first energy crisis that's truly global* [Online]. Available: https://www.iea.org/topics/global-energy-crisis [Accessed 06. May 2024].

JACKSON, M., LEDERWASCH, A. & GIURCO, D. 2014. Transitions in theory and practice: Managing metals in the circular economy. *Resources,* 3**,** 516-543.

JEC COMPOSITES. 2022. *ZEBRA project achieves key milestone with production of the first prototype of its recyclable wind turbine blade* [Online]. Online. Available: https://www.jeccomposites.com/news/zebra-project-achieves-key-milestone-with-production-of-the-first-prototype-of-its-recyclable-wind-turbine-blade/ [Accessed 16.10.2023].

JEGEN, M. 2023. Life cycle assessment: from industry to policy to politics. *The International Journal of Life Cycle Assessment***,** 1-10.

JENSEN, J. P. 2019. Evaluating the environmental impacts of recycling wind turbines. *Wind Energy,* 22**,** 316-326.

JENSEN, J. P. & SKELTON, K. 2018. Wind turbine blade recycling: Experiences, challenges and possibilities in a circular economy. *Renewable and Sustainable Energy Reviews,* 97**,** 165-176.

JOHANSEN, M. R., CHRISTENSEN, T. B., RAMOS, T. M. & SYBERG, K. 2022. A review of the plastic value chain from a circular economy perspective. *Journal of Environmental Management,* 302**,** 113975.

KALMYKOVA, Y., SADAGOPAN, M. & ROSADO, L. 2018. Circular economy – From review of theories and practices to development of implementation tools. *Resources, Conservation and Recycling,* 135**,** 190-201.

KAZEMI, M., KABIR, S. F. & FINI, E. H. 2021. State of the art in recycling waste thermoplastics and thermosets and their applications in construction. *Resources, Conservation and Recycling,* 174**,** 105776.

KEIVANPOUR, S., KADI, D. A. & MASCLE, C. 2015. End of life aircrafts recovery and green supply chain (a conceptual framework for addressing opportunities and challenges). *Management Research Review,* 38**,** 1098-1124.

KIRCHHERR, J., REIKE, D. & HEKKERT, M. 2017. Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, conservation and recycling,* 127**,** 221-232.

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.

KLEINDORFER, P. R., SINGHAL, K. & VAN WASSENHOVE, L. N. 2005. Sustainable operations management. *Production and operations management,* 14**,** 482-492.

KNOTH, K., FUFA, S. M. & SEILSKJÆR, E. 2022. Barriers, success factors, and perspectives for the reuse of construction products in Norway. *Journal of Cleaner Production,* 337**,** 130494.

KORHONEN, J., HONKASALO, A. & SEPPÄLÄ, J. 2018. Circular economy: the concept and its limitations. *Ecological economics,* 143**,** 37-46.

KRAUKLIS, A. E., KARL, C. W., GAGANI, A. I. & JØRGENSEN, J. K. 2021. Composite material recycling technology—state-of-the-art and sustainable development for the 2020s. *Journal of Composites Science,* 5.

KUMAR, V., SEZERSAN, I., GARZA-REYES, J. A., GONZALEZ, E. D. & AL-SHBOUL, M. D. A. 2019. Circular economy in the manufacturing sector: benefits, opportunities and barriers. *Management Decision,* 57**,** 1067-1086.

KUMARI, S., AGARWAL, S. & KHAN, S. 2022. Micro/nano glass pollution as an emerging pollutant in near future. *Journal of Hazardous Materials Advances,* 6**,** 100063.

KUUSAKOSKI RECYCLING. 2022. *THE KIMURA PROJECT OFFERS RECYCLING SOLUTIONS FOR INDUSTRIAL COMPOSITE WASTE* [Online]. Available: https://www.kuusakoski.com/en/global/news/2022/the-kimura-project-offers-recycling-solutions-for-industrial-composite-waste2/ [Accessed].

LARSEN, K. 2009. Recycling wind. *Reinforced Plastics,* 53**,** 20-23,25.

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**,** 30-39.

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,* 106**,** 120-131.

LIEDER, M. & RASHID, A. 2016. Towards circular economy implementation: a comprehensive review in context of manufacturing industry. *Journal of cleaner production,* 115**,** 36-51.

LIU, P. & BARLOW, C. Y. 2017. Wind turbine blade waste in 2050. *Waste Management,* 62**,** 229-240.

LIU, P., MENG, F. & BARLOW, C. Y. 2019. Wind turbine blade end-of-life options: An eco-audit comparison. *Journal of Cleaner Production,* 212**,** 1268-1281.

LM WIND POWER. 2023. *'ZEBRA project' launched to develop first 100% recyclable wind turbine blades* [Online]. Available: https://www.lmwindpower.com/en/stories-and-press/stories/news-from-lm-places/zebra-project-launched [Accessed].

LUND, K. W. & MADSEN, E. S. 2024. State-of-the-art value chain roadmap for sustainable end-of-life wind turbine blades. *Renewable and Sustainable Energy Reviews,* 192**,** 114234.

MACARTHUR, E. 2013. Towards the circular economy. *Journal of Industrial Ecology,* 2**,** 23-44.

MAREI. 2021. *WindLEDeRR, A comprehensive decision support tool for end-of-life wind turbines of Ireland; Lifetime Extension, Decommissioning, Repowering, Repurposing* [Online]. MaREI. Available: https://www.marei.ie/project/windlederr/ [Accessed 16.10.2023].

MATTSSON, C., ANDRÉ, A., JUNTIKKA, M., TR NKLE, T. & SOTT, R. Chemical recycling of End-of-Life wind turbine blades by solvolysis/HTL. 2020. IOP Publishing Ltd.

MEMIJA, A. 2022. Vestas 15 MW Prototype Turbine Produces First Power. *OffshoreWIND.*

MILES, M. B., HUBERMAN, A. M. & SALDAÑA, J. 2018. *Qualitative data analysis: A methods sourcebook*, Sage publications.

MISHNAEVSKY JR, L., BRANNER, K., PETERSEN, H. N., BEAUSON, J., MCGUGAN, M. & SØRENSEN, B. F. 2017. Materials for wind turbine blades: An overview. *Materials,* 10**,** 1285.

MISHNAEVSKY, L., JR. 2021. Sustainable end-of-life management of wind turbine blades: Overview of current and coming solutions. *Materials,* 14**,** 1-26.

MOLINA, M. G. & MERCADO, P. E. 2011. Modelling and control design of pitch-controlled variable speed wind turbines. *Wind turbines.* IntechOpen.

MORINI, A. A., RIBEIRO, M. J. & HOTZA, D. 2021. Carbon footprint and embodied energy of a wind turbine blade—a case study. *International Journal of Life Cycle Assessment*.

MORTENSEN, S. W. 2024. Bliver kaldt pioner i dansk vindkraft: »Det gik op for mig, at det her går da ad helvede til, hvis ikke vi lykkes«. *Finans.*

NANDA, S. & BERRUTI, F. 2021. Municipal solid waste management and landfilling technologies: a review. *Environmental Chemistry Letters,* 19**,** 1433-1456.

NAQVI, S. R., PRABHAKARA, H. M., BRAMER, E. A., DIERKES, W., AKKERMAN, R. & BREM, G. 2018. A critical review on recycling of end-of-life carbon fibre/glass fibre reinforced composites waste using pyrolysis towards a circular economy. *Resources, Conservation and Recycling,* 136**,** 118-129.

NATIONAL COMPOSITES CENTRE. 2021. *SusWIND, Accelerating sustainable composite materials and technology for wind turbine blades* [Online]. Available: https://www.nccuk.com/what-we-do/sustainability/suswind/ [Accessed 16.10 2023].

OLIVER, R. K. & WEBBER, M. D. 1982. Supply-chain management: logistics catches up with strategy. *Outlook,* 5**,** 42-47.

PAIK, J. K. 2022. *Ship-shaped offshore installations: design, construction, operation, healthcare and decommissioning*, Cambridge University Press.

PAULSEN, E. B. & ENEVOLDSEN, P. 2021. A Multidisciplinary Review of Recycling Methods for End-of-Life Wind Turbine Blades. *Energies,* 14**,** 4247.

PORTER, M. E. 1985. *Competitive advantage: creating and sustaining superior performance*, The Free Press.

POTTING, J., HEKKERT, M. P., WORRELL, E. & HANEMAAIJER, A. 2017. Circular economy: measuring innovation in the product chain. *Planbureau voor de Leefomgeving*.

RAHIMIZADEH, A., KALMAN, J., HENRI, R., FAYAZBAKHSH, K. & LESSARD, L. 2019. Recycled glass fiber composites fromwind turbine waste for 3D printing feedstock: effects of fiber content and interface on mechanical performance. *Materials,* 12.

RAMIREZ-TEJEDA, K., TURCOTTE, D. A. & PIKE, S. 2017. Unsustainable wind turbine blade disposal practices in the united states: A case for policy intervention and technological innovation. *New Solutions,* 26**,** 581-598.

RANI, M., CHOUDHARY, P., KRISHNAN, V. & ZAFAR, S. 2021. A review on recycling and reuse methods for carbon fiber/glass fiber composites waste from wind turbine blades. *Composites Part B: Engineering,* 215.

RATNER, S., GOMONOV, K., REVINOVA, S. & LAZANYUK, I. 2020. Eco-Design of Energy Production Systems: The Problem of Renewable Energy Capacity Recycling. *Applied Sciences-Basel,* 10.

RENTIZELAS, A., TRIVYZA, N., OSWALD, S. & SIEGL, S. 2021. Reverse supply network design for circular economy pathways of wind turbine blades in Europe. *International Journal of Production Research*.

RIBEIRO, M. C. S., FIÚZA, A., FERREIRA, A., DINIS, M. L., CASTRO, A. C. M., MEIXEDO, J. P. & ALVIM, M. R. 2016. Recycling approach towards sustainability advance of composite materials' industry. *Recycling,* 1.

RISE. 2023. *Rekovind2 - Digitization of wind blade streams* [Online]. RISE. Available: https://www.ri.se/en/what-we-do/projects/rekovind2-digitization-of-wind-blade-streams [Accessed 16.10.2023 2023].

ROCKMANN, K. W. & VOUGH, H. C. 2023. Using Quotes to Present Claims: Practices for the Writing Stages of Qualitative Research. *Organizational Research Methods***,** 10944281231210558.

SAKELLARIOU, N. 2018. Current and potential decommissioning scenarios for end-of-life composite wind blades. *Energy Systems,* 9**,** 981-1023.

SALDAÑA, J. 2021. The coding manual for qualitative researchers. *The coding manual for qualitative researchers***,** 1-440.

SENIOR SPECIALIST – SUSTAINABILITY AND ADVANCED MATERIALS 2023. Cetec project. *In:* KRISTINE WILHELM LUND (ed.).

SIEMENS GAMESA RENEWABLE ENERGY. 2021. *Siemens Gamesa pioneers wind circularity: launch of world's first recyclable wind turbine blade for commercial use offshore* [Online]. Online: Siemens Gamesa Renewable Energy. Available: https://www.siemensgamesa.com/newsroom/2021/09/launch-world-first-recyclable-wind-turbine-blade [Accessed 2023].

SIHVONEN, S. & RITOLA, T. 2015. Conceptualizing ReX for aggregating end-of-life strategies in product development. *Procedia Cirp,* 29**,** 639-644.

SLACK, N., CHAMBERS, S. & JOHNSTON, R. 2010. *Operations Management,* England, Pearson Education Limited.

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,* 115**,** 83-94.

SULTAN, A. M., MATIVENGA, P. T. & LOU, E. 2018. Managing Supply Chain Complexity: Foresight For Wind Turbine Composite Waste. *In:* LAURENT, A., LECLERC, A., NIERO, M., DONG, Y., OLSEN, S. I., OWSIANIAK, M., BEY, N., RYBERG, M. & HAUSCHILD, M. Z. (eds.) *25th Cirp Life Cycle Engineering.*

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**,** 199-207.

THE BUNDESTAG 2012. Circular Economy Act – (Kreislaufwirtschaftsgesetz – KrWG).

TOPHAM, E. & MCMILLAN, D. 2017. Sustainable decommissioning of an offshore wind farm. *Renewable Energy,* 102**,** 470-480.

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.

TYGESEN, P. 2022. Da Tvind byggede verdens største vindmølle med hjælp fra atomkrafttilhængere, en fremskridtsmand og en eksnazist. *Information.*

UNITED NATIONS 2015a. Paris Agreement

UNITED NATIONS. 2015b. *SDG12: Responsible consumption and production* [Online]. Available: https://www.globalgoals.org/goals/12-responsible-consumption-and-production/ [Accessed 20-02-2024 2024].

UNITED NATIONS (ed.) 2024. *UN Climate Change Conference - United Arab Emirates*.

VANSON, G., MARANGÉ, P. & LEVRAT, E. 2022. End-of-Life Decision making in circular economy using generalized colored stochastic Petri nets. *Autonomous Intelligent Systems,* 2**,** 3.

VATTENFALL. 2021. *Vattenfall commits to landfill ban and to recycle all wind turbine blades by 2030* [Online]. Available: https://group.vattenfall.com/press-and-media/pressreleases/2021/vattenfall-commits-to-landfill-ban-and-to-recycle-all-wind-turbine-blades-by-2030 [Accessed 2024].

VEERS, P. S., ASHWILL, T. D., SUTHERLAND, H. J., LAIRD, D. L., LOBITZ, D. W., GRIFFIN, D. A., MANDELL, J. F., MUSIAL, W. D., JACKSON, K. & ZUTECK, M. 2003. Trends in the design, manufacture and evaluation of wind turbine blades. *Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology,* 6**,** 245-259.

VELENTURF, A. P. & PURNELL, P. 2021. Principles for a sustainable circular economy. *Sustainable Production and Consumption,* 27**,** 1437-1457.

VIDAL, P. D. C. J., GONZÁLEZ, M. O. A., DE MELO, D. C., DE OLIVEIRA FERREIRA, P., SAMPAIO, P. G. V. & LIMA, L. O. 2022. Conceptual framework for the decommissioning process of offshore oil and gas platforms. *Marine Structures,* 85**,** 103262.

VOSS, C., JOHNSON, M. & GODSELL, J. 2016. Case Research. *In:* KARLSSON, C. (ed.) *Research Methods for Operations Management.* Taylor & Francis Ltd.

VOSS, C., TSIKRIKTSIS, N. & FROHLICH, M. 2002. Case research in operations management. *International journal of operations & production management*.

WILLIAMSON, R. 2023. *Australian scientists design cheaper carbon fibre recycling to cut wind turbine waste* [Online]. Australia: RenewEconomy. Available: https://reneweconomy.com.au/australian-scientists-design-cheaper-carbon-fibre-recycling-to-cut-wind-turbine-waste/ [Accessed 16.10.2023].

WIND VALUE. 2023. *Wind Value, End of Life Decisions for Wind Farms: An Opportunity for Climate Action and for Energy Communitie* [Online]. Wind Value. Available: https://windvalue.ie/ [Accessed 16.10.2023].

WINDEUROPE 2020. How to build a circular economy for wind turbine blades through policy and partnership.

WINDEUROPE. 2022a. *The Netherlands run another successful auction based on non-price criteria* [Online]. WindEurope Available: https://windeurope.org/newsroom/news/the-netherlands-run-another-successful-auction-based-on-non-price-criteria/ [Accessed 2023].

WINDEUROPE. 2022b. *WindEurope* [Online]. Available: https://windeurope.org/newsroom/press-releases/wind-industry-calls-for-europe-wide-ban-on-landfilling-turbine-blades/ [Accessed 24.02.22 2022].

WINDEUROPE, CETFIC & EUCIA 2020. Accelerating Wind Turbine Blade Circularity.

YIN, R. K. 2018. *Case Study Reearch and Applications, Design and Methods*, Sage Publications

YU, Y., YAZAN, D. M., BHOCHHIBHOYA, S. & VOLKER, L. 2021. Towards Circular Economy through Industrial Symbiosis in the Dutch construction industry: A case of recycled concrete aggregates. *Journal of cleaner production,* 293**,** 126083.

ZANJIRANI FARAHANI, R., ASGARI, N. & VAN WASSENHOVE, L. N. 2022. Fast fashion, charities, and the circular economy: challenges for operations management. *Production and Operations Management,* 31**,** 1089-1114.

ØRSTED. 2021. *Ørsted commits to sustainable recycling of wind turbine blades* [Online]. Available: https://orsted.com/en/media/news/2021/06/702084352457649 [Accessed 2024].