Design and evaluation of recycling and recovery infrastructures for glass and carbon fiber reinforced plastics

An application in the wind energy industry

Von der Fakultät für Wirtschaftswissenschaften der
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Fakultät für Wirtschaftswissenschaften der
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von
Valentin Sommer

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In that sense ...

"Et hät noch immer jod jejange."
(§3 Kölsche Grundgesetz)

Part I.

Preface

1. Outline of the Thesis

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Introduction

The increasing trend of anthropogenic resource consumption is not compatible with a sustainable global development. To counteract the increasing global consumption of natural resources, the transformation of the current linear economy towards a circular economy is regarded indispensable. To achieve this transition, waste management is highlighted as a key measure by political decision makers (European Commission, 2010, 2011, 2015). In this regard, "*'waste management' (refers to) the collection, transport, recovery and disposal of waste* [...]" (cf. European Parliament and Council of the European Union, 2008, Article 3 Nr. 9).

In the European Union (EU), the EU waste management law (European Parliament and Council of the European Union, 2008) builds the legal foundation to steer treatment of waste. Herein, the "[..] *following waste hierarchy shall apply as a priority order in waste prevention and management legislation and policy: (a) prevention; (b) preparing for re-use; (c) recycling; (d) other recovery, e.g. energy recovery; and (e) disposal*" (cf. European Parliament and Council of the European Union, 2008, Art.4 1.). Recent amendments to the directive on waste require that current "*waste management in the Union should be improved and transformed into sustainable material management, with a view to protecting, preserving and improving the quality of the environment,* [...], *ensuring prudent, efficient and rational utilisation of natural resources, promoting the principles of the circular economy,* [...], *reducing the dependence of the Union on imported resources, providing new economic opportunities and contributing to long-term competitiveness.* [...] *(To) make the economy truly circular, it is necessary to take additional measures on sustainable production and consumption, by focusing on the whole life cycle of products in a way that preserves resources and closes the loop.*" (cf. European Parliament and Council of the European Union, 2018, (1))

However, many challenges arise when implementing such waste treatment systems like uncertain waste masses or unknown legal and technological developments. This is particularly true for innovative products and the resulting waste streams, since they are in the development stage and still in the phase of market introduction. Herein, information is missing concerning: i) the quantity and quality of the future waste streams, ii) legal and technological developments in recycling, iii) the development of markets for secondary materials. For these waste streams, information on the upcoming waste quantities as well as on the materials' properties regarding the respective End-of-Life waste management processes are missing. Besides, by the time waste masses first occur and increase, the treatment processes are rarely fully technologically mature. Moreover, many of the uncertainties are interdependent. For example, the demand for secondary materials highly depends on their availability at high quality secondary markets, which in return depends on the one hand on the technological development of recycling processes and on the other hand on steady material supply, which depends on the uncertain quantity and quality of End-of-Life waste (Sommer et al., 2020; Job et al.; Liu et al., 2019).

Against this background, thorough ex-ante analyses are critical to provide both political decision makers and investors with decision support on the design of recycling systems for innovative products and materials before large quantities of material occur. For political decision makers, information regarding the economic and environmental impact of potential policy measures on the waste treatment system provides a valuable indication of how to steer waste management such that the transformation from a linear to a circular economy will be successful with respect to a sustainable development. For investors, information regarding the total system costs considering potential legal, technological and market developments supports their investment decisions. In particular for innovative products and materials, which are in an evolving state but not yet established on the market, such ex-ante analyses are required to provide the stakeholders with relevant information at an early stage, i.e. before the generated waste masses reach a critical level and become an immediate challenge for a sustainable waste management due to the above mentioned factors.

Aims and Scope of the Thesis

Against this background, this thesis presents an analysis approach that provides relevant information to support the aforementioned stakeholders in their respective decisions. Applying the approach in order to ex-ante analyze the management of future waste streams highlights important information to achieve a sustainable material management as well as a circular economy. In brief, the thesis shows that sophisticated ex-ante analysis provide relevant information for decision makers.

A specific application case is analyzed throughout the course of this thesis: the waste management of glass and carbon fiber reinforced plastics (GFRP/CFRP) from rotor blades of wind power plants. The focus on GFRP/CFRP waste from rotor blades of wind power plants is motivated by the increasing upcoming waste masses as well as by discussions between scientists and political decision makers on the treatment of these waste streams (Lefeuvre et al., 2019; Lichtenegger et al., 2020; Liu and Barlow, 2017; Liu et al., 2019; Zotz et al., 2019).

Structure and Contribution of the Thesis

The remainder of the Preface (Part I) contains two additional Chapters. These Chapters provide a detailed description of the underlying planning problem (Chapter 2) and a literature review (Chaopter 3). The second part of this thesis (Part II) contains three Chapters (4, 5 and 6), each representing one publication with specific analyses related to the waste management of GFRP/CFRP. The third part of this thesis (Part III) contains one Chapter (7), which represents the conclusion of this thesis.

Chapter 2 provides a detailed description of the underlying planning problem regarding the waste management of GFRP/CFRP. Based on this description, the key research questions are derived. The case study from the wind energy industry is first introduced and waste stream specific research questions that are answered in the course of the thesis are derived.

Chapter 3 places the thesis in the broader research field of Reverse Logistics. Within Reverse Logistics, researchers focus on the planning of strategic logistics networks, in particular recycling and recovery infrastructures. The established methodological approaches in the field that are generally applied to answer research questions similar to the ones derived in Chapter 2 are introduced.

Chapter 4 presents an estimation of GFRP/CFRP waste streams from rotor blades of wind power plants based on simulation and regression functions. It is highlighted that existing estimations lack in detail. The estimation results show that GFRP/CFRP waste from rotor blades of wind power plants will tremendously increase in the future. More than 500.000 [t] of GFRP/CFRP waste only from wind energy industry will occur between 2020 and 2030 in the EU. This results in big challenges as the optimal treatment paths for these waste streams are still unknown and the required recycling infrastructures are yet missing.

Chapter 5 presents a deterministic mixed integer linear mathematical optimization model for the design and evaluation of recycling and recovery infrastructures to deal with the upcoming GFRP/CFRP waste streams in the EU. The developed decision support system analyzes the economic impact of potential political regulations as well as the economic impact of developing secondary markets on the overall choice of treatment paths, respectively on the design of the required infrastructures. The results show that potential political regulations impact the choice of treatment for GFRP strongly, whereas the choice of treatment for CFRP is not impacted by political regulations but depends mainly on the existence of markets for secondary materials.

Chapter 6 presents a decision support system that integrates the results of a regionalized Life Cycle Assessment into a deterministic mixed integer linear mathematical optimization model for the design of recycling and recovery infrastructures for GFRP/CFRP waste streams. Herein, the waste management of GFRP/CFRP is not simply evaluated from an economic, but also from an environmental perspective. The impact of potential political regulations is analyzed. The results show that regardless of any political regulations, the optimal treatment for CFRP is chemical recycling through solvolysis due to large economic and environmental benefits. In contrast, the optimal treatment for GFRP varies between incineration (economically favored), mechanical recycling (environmentally favored at low additional costs) and chemical recycling through solvolysis (neither favored from an economic nor environmental perspective, but required in the case of certain political regulations).

Chapter 7 concludes this thesis by briefly summarizing the previous chapters and their contributions. Recommendations for researchers and practitioners are derived and the applicability of the presented approach in practice is discussed. Finally, an outlook on further research with regard to the generalisation of the presented approach is given.

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2. Recycling and Recovery of GFRP/CFRP

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The following two Sections describe applications and End-of-Life waste treatment options of glass and carbon fiber reinforced plastics (GFRP/CFRP). The case study is shortly introduced. Six research questions are derived, which will be answered throughout this thesis.

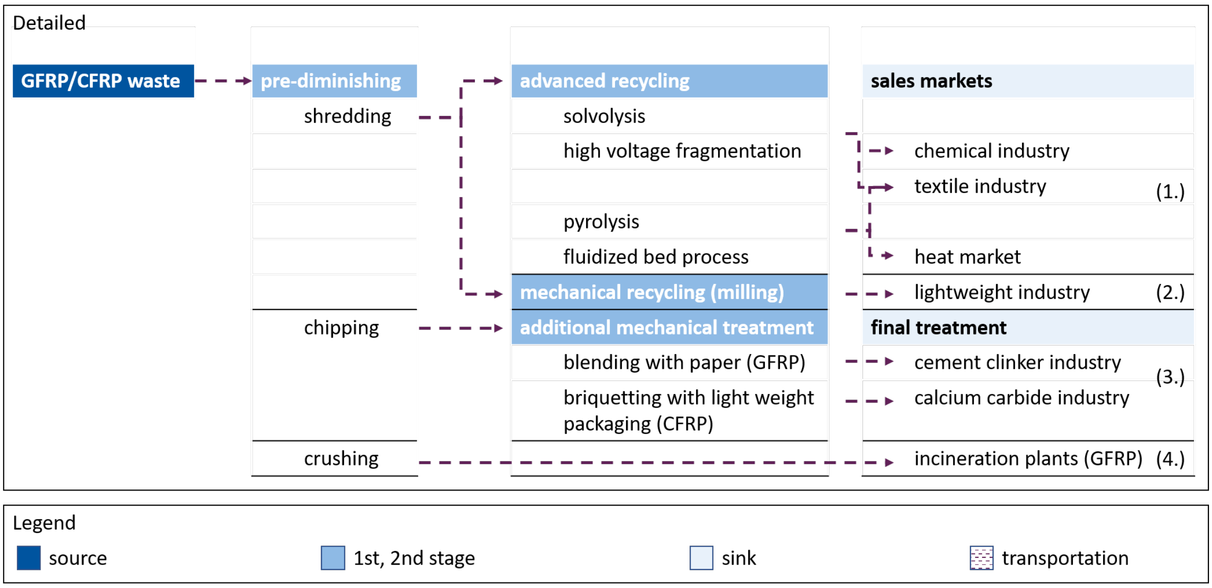
GFRP/CFRP from Rotor Blades of Wind Power Plants

As energy generation by wind power has been increasing in recent years by the means of the Energy Transition in the European Union, the occuring End-of-Life waste of rotor blades is projected to increase considerably (Liu and Barlow, 2015; TheWindPower, 2016; WindEurope, 2018). GFRP and CFRP are applied as construction materials within rotor blades (Fichaux et al., 2011; Liu and Barlow, 2017; Lichtenegger et al., 2020), since the lightweight properties of these fibre reinforced plastics match the high requirements of the application field in terms of mechanical performance at low weight. According to the German Federal Environmental Agency, GFRP and CFRP of rotor blades depict the most challenging structural part of a wind power plant with regard to the End-of-Life waste treatment: Ex-ante analyses of future waste management for theses waste streams are necessary due to limited knowledge on future quantities as well as technological challenges in the recycling processes and missing secondary markets (Zotz et al., 2019).

Waste Management of Glass and Carbon Fiber Reinforced Plastics

GFRP/CFRP are composites made of a glass or carbon fiber based reinforcement (GF/CF) embedded in a plastic matrix, mostly thermosetting epoxy resin (Martins et al., 2017; Ehrenstein, 2006). Due to the composition of fibers and epoxy resin, GFRP/CFRP have extraordinary lightweight properties, which are beneficial within the usage phase of the product. For example, the reduction in total weight leads to a reduction of fuel consumption in vehicles or enables leaner and larger components in the construction industry or in wind power plants (Sauer, 2019; Liu et al., 2019; Ehrenstein, 2006). However, the primary production of the constituent materials GF, CF and the plastic matrix is energy-, resource- and cost-intensive (Deng, 2014; Gutiérrez and Bono, 2013; Kaur et al., 2016; Sommer and Walther, 2020). In this regard, recycling and subsequent reuse of the individual components might lead to economic and environmental benefits through substitution of the materials' primary production.

Figure 1: Waste treatment options for GFRP/CFRP in accordance with Sommer et al. (2021)



Sommer et al. (2021) describe the current state-of-the-art waste treatment options for GFRP/CFRP End-of-Life waste and highlight the (dis)advantages of the waste treatment options from an economic as well as environmental perspective. Figure 1 visualizes the waste treatment options. The waste treatment options are divided into (1.) chemical and thermal recycling, (2.) mechanical recycling, (3.) co-processing and (4.) energy recovery. Tables 1 and 2 describe each process as well as each combination of material and final sink from an environmental, economic and technological perspective.

With respect to Tables 1 and 2 as well as Figure 1, it can be seen that choosing the best treatment option for GFRP and CFRP is challenging for several reasons: From a technological perspective, the yield rate and quality of the output materials differ depending on the input materials. Although the most efficient technologies in terms of yield rate and quality promise high revenues and recycling rates, these technologies require large investments and are very energy-intensive. In contrast, other treatment options require only small investments and promise high environmental benefits, but allow to achieve only small recycling rates. In addition, the economic and environmental benefits depend specifically on the material treated. While the recycling of the valuable CFRP seems to be beneficial from an economic perspective, the recycling of the GFRP, which is lower in value, might not. Concerning the environmental perspective, it is also challenging to decide which waste treatment option is most beneficial. Also, challenges exist regarding the quality of secondary materials. When the fiber reinforcement is separated from the plastic matrix, e.g. through chemical or thermal recycling, the quality of the recycled GF (rGF) and CF (rCF) is degraded in terms of mechanical performance. As a result of the loss in quality, future applications and demand for these secondary materials are still unknown (Job et al., 2016; Liu et al., 2019). Because of these obstacles, there is little incentive for economically driven stakeholders, e.g. investors, to invest in the required treatment infrastructures. As a consequence, the potential economic and environmental benefits remain untapped.

Table 1: Environmental, economic and technical parameterization of treatment technologies in accordance with Sommer et al. (2021)

	Environmental parameters [1]		Economic parameters				Efficiency				Data
Technology	GWP burden $\left[\frac{\text{kg CO2eq}}{\text{kg}}\right]$	GWP benefit[2] $\left[\frac{\text{kg CO2eq}}{\text{kg}}\right]$	Invest $\left[\frac{\text{mil.€}}{\#}\right]$	Variable $\left[\frac{\text{1,000€}}{\text{t}}\right]$	Fix $\left[\frac{\text{mil.€}}{\#\text{a}}\right]$	Capacity $\left[\frac{\text{1,000t}}{\#}\right]$	Yield [%] GF	Yield [%] CF	Quality [%] GF	Quality [%] CF	
Diminishing[3]	17.64	-	0.25	0.1	15	15	95	95	-	-	[1,2]
Briquetting[4]	443.35	-	-	-	-	-	-	-	-	-	[1,3]
Blending[4]	62.3	-	-	-	-	-	-	-	-	-	[1,4]
Milling	47.7	-	0.25	0.1	15	4	58	58	78	50	[1,5]
HVF[5]	10,592	-	2.45	6.12	294	0.1	60	60	88	83	[1,6]
Pyrolysis	3,902	648	0.9	1.1	108	1	70	70	52	78	[1,7]
Fluidized bed	1,862	648	1	10	120	1	44	90	50	75	[1,8]
Solvolysis	4,370	-	6.4	1.5	768	1	100	100	58	95	[1,7]

[1]: Liu et al. (2019), Vo Dong et al. (2018), Sommer and Walther (2020); [2]: Andritz AB (2019), Vecoplan AG (2019); [3]: AGEB (2019); [4]: Potgieter (2014); [5]: Howarth et al. (2014); [6]: Mativenga et al. (2016); [7]: Pillain et al. (2019); [8]: Meng et al. (2018);
[1] Based on the German Energy mix.
[2] Due to the heat recovery by the thermal recycling processes.
[3] Diminishing means crushing, shredding, chipping in dependence of the recycling/recovery path.
[4] For the economic and efficiency parameter part of pre-diminishing.
[5] High voltage fragmentation.

Table 2: Environmental and economic parameters of each material-sink combination in accordance with Sommer et al. (2021)

		Environmental		Economic		Data
Material	Sink	Burden $\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$	Benefit $\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$	Revenue $\left[\frac{€}{\text{t}}\right]$	Costs $\left[\frac{€}{\text{t}}\right]$	
Blended GFRP	cement clinker	686	1,150	-	100	[1,2]
Briquetted CFRP	calcium carbide	1,884	2,226	-	100	[1,3]
Crushed GFRP	incineration	610	742	-	100	[1,4]
Milled GFRP	lightweight	0	3,910	250	-	[1,5]
Milled CFRP	lightweight	0	3,910	2,500	-	[1,5]
rP	chemical	0	3,910	1,500	-	[1,5]
rGF	textile	0	2,225	250	-	[1,5]
rCF	textile	0	23,430	8,000	-	[1,6]

[1]: in accordance with Sommer and Walther (2020) and Vo Dong et al. (2018); [2]: Bundesverband WindEnergie e.V., Hahn (2017); [3]: AGEB (2019); [4]: Job (2013); Hedlund-Åström (2005); [5]: Ecoinvent v.3.5; [6]: Pillain et al. (2019), ELCD (2015);

Against this background, six Research Questions (RQ1-RQ6) will be answered within the scope of three individual publications. The first Research Question (RQ1) aims at estimating future GFRP/CFRP waste streams from rotor blades of wind power plants as demanded by Zotz et al. (2019). As highlighted, the choice of economically and environmentally optimal End-of-Life waste treatment for GFRP/CFRP is challenging. Also, policy regulations might be required to exploit environmental benefits. Thus, the remaining five Research Questions (RQ2-RQ6) aim at analyzing the impact of potential political regulations as well as the optimal choice of End-of-Life waste treatment for GFRP/CFRP from an economic and environmental perspective:

1. How much GFRP/CFRP waste from rotor blades of wind power plants will occur in the future? [RQ1]
2. What is the optimal End-of-Life treatment for GFRP/CFRP from an economic perspective? [RQ2]
3. What is the impact of uncertain secondary market development on the End-of-Life waste treatment for GFRP/CFRP and on the total system costs? [RQ3]
4. What is the impact of commonly applied political regulations on the End-of-Life waste treatment for GFRP/CFRP from an economic perspective, i.e. what is the trade-off between achievable recycling quotas and total system costs? [RQ4]
5. What is the optimal End-of-Life waste treatment for GFRP/CFRP from an economic and environmental perspective? [RQ5]
6. What is the impact of recycling quotas on the End-of-Life waste treatment for GFRP/CFRP from an economic and environmental perspective, i.e. are commonly applied political regulations target oriented in terms of steering an economically and ecologically beneficial system? [RQ6]

In the course of the **1st publication** (Chapter 4), RQ1 concerning the quantities of future waste masses is answered. Herein, the challenge is to predict future End-of-Life GFRP/CFRP waste masses from rotor blades of wind power plants in the EU. The estimation approach bases on simulation and regression analysis. The estimated GFRP/CFRP End-of-Life waste masses were used as a basis in the subsequent material flow based analyses.

In the course of the **2nd publication** (Chapter 5), RQ2-4 are answered. At first, the overall planning problem on designing recycling and recovery infrastructures for End-of-Life GFRP/CFRP waste is introduced by providing a detailed summary of the established and future waste treatment options for End-of-Life GFRP/CFRP waste. The primary focus of this publication lies on the impact analysis of political regulations, i.e. recycling and recovery quotas, as well as the impact of secondary material markets on the optimized treatment of End-of-Life GFRP/CFRP waste and the overall economic cost. A decision support system is developed based on a mathematical optimization model. The material flow based mathematical optimization model designs the optimal logistical infrastructure for the treatment of GFRP/CFRP waste streams against an economic objective. The impact of political regulations and secondary market development is systematically analyzed through sensitivity analyses.

In the course of the **3rd publication** (Chapter 6), RQ5 and RQ6 are answered. Herein, environmental indicators complement economic criteria in the analysis. Hence, the economically as well as the environmentally optimized treatment of GFRP/CFRP waste streams is analyzed. Again, a decision support system is developed based on a mathematical optimization model. The material flow based mathematical optimization model designs the optimal logistical infrastructure for the treatment of GFRP/CFRP waste streams from an economic and environmental perspective. To do so, a multi-objective-decision-making approach is developed. To fully account for the environmental impact, a detailed Life Cycle Assessment of the primary production, the waste processing as well as the final treatment processes at potential sinks is conducted. The impact of political regulations on the overall economic and environmental objectives are systematically analyzed through sensitivity analyses.

In summary, the analysis approach consists of three parts: *i*) a waste mass estimation as basis for any subsequent analysis, *ii*) a mathematical optimization model that designs and evaluates the required waste treatment infrastructure for the estimated waste streams from an economic perspective under varying scenarios, e.g. legal recycling targets or secondary material demand, *iii*) a mathematical optimization model based on a multi-objective decision making approach and an integrated Life Cycle Assessment to design and evaluate the required waste treatment infrastructure for the estimated waste streams from an economic as well as environmental perspective under varying scenarios.

In the following Chapter 3, the derived planning problem is placed in the broad context of Reverse Logistics.

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3. Literature review

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The following Chapter introduces the research area of Reverse Logistics. Herein, researchers focus on the design of strategic networks that augment the classical forward supply chain in the reverse (backward) direction, with the aim to recover product or material value. Based on this, the planning problem of the thesis, presented in Chapter 2, is discussed from the perspective of Reverse Logistics.

Reverse Logistics

For the last three decades, researchers tackled the challenge of reusing products and materials (cf. Thierry et al., 1995) for various reasons, e.g. political regulations, social motivations, economical or environmental effects (Dekker et al., 2004). To do so, the classical forward supply chain is complemented by a backward supply chain. In line with this, Fleischmann (2000) defines Reverse Logistics as "[...] *the process of planning, implementing, and controlling the efficient, effective inbound flow and storage of secondary goods and related information opposite to the traditional supply chain direction for the purpose of recovering value or proper disposal.*" Figure 1 shows the forward supply chain as well as the waste management options at the End-of-Life of products in accordance with Thierry et al. (1995) and European Parliament and Council of the European Union (2008). In this thesis, infrastructures for specific waste management options, the recycling and (other) recovery of GFRP/CFRP waste streams from rotor blades of wind power plants are analyzed (cf. Figure 1). Figure 2 depicts a generic network structure of a backward supply chain. Comparable networks were further developed and investigated for complex products (e.g. Walther et al., 2012, for WEEE).

Within the research area of Reverse Logistics, quantitative methods, in particular mathematical optimization models, have been used to cope with the strategic, tactical and operational planning tasks regarding the backward supply chains. In particular the area of strategic network planning is prominent (Govindan et al., 2015). For different material flows and use cases, infrastructure systems have been designed and analyzed with the aim to re-distribute, process, re-use or recycle waste streams under different target criteria. Herein, the real-world planning problem, e.g. where to locate technology capacities for waste treatment, is commonly formulated as a mathematical optimization model. This model endogenously determines the specified decisions considering all real-world restrictions, e.g. technical or market capacity restrictions, and seeks for the optimal solution with respect to the desired objective, e.g. minimizing the total costs of recycling End-of-Life waste or minimizing the usage of primary materials.

The first publications on such decision-support models for the design of backward supply chains are by Thierry et al. (1995); Kroon and Vrijens (1995) and Bloemhof-Ruwaard et al. (1996). Thierry et al. (1995) list possible recycling measures and raise awareness for

Figure 1: Waste management options in accordance with Thierry et al. (1995)

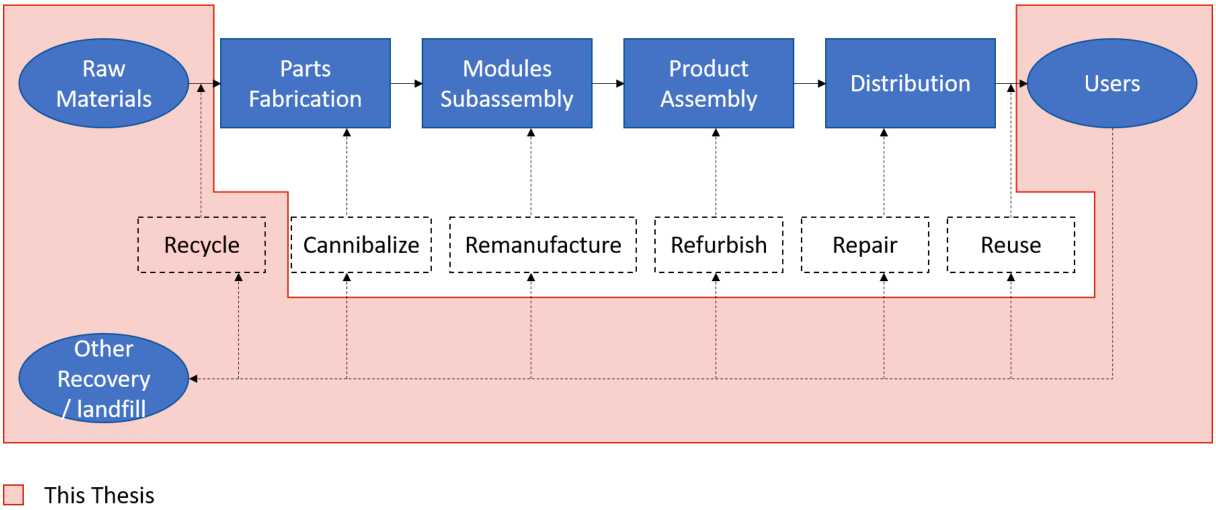
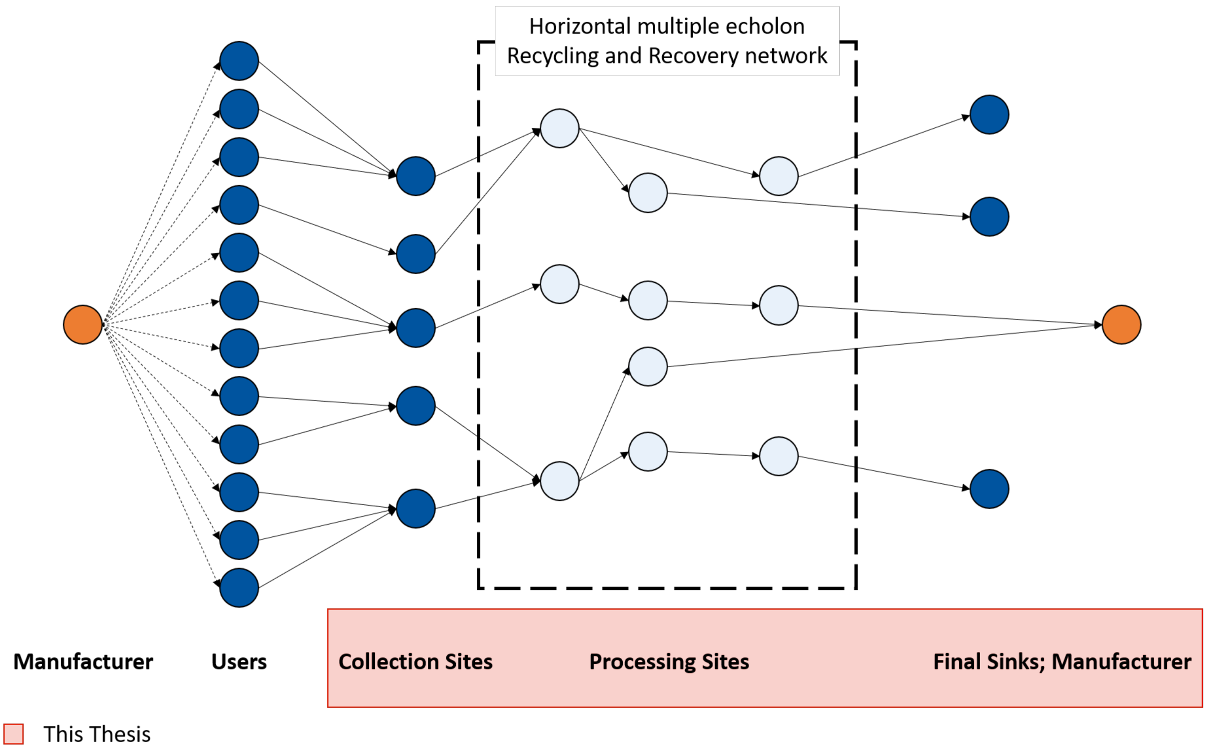


Figure 2: Backward supply chain for the waste management of products in accordance with Walther (2010)



recycling products. Kroon and Vrijens (1995) deal with the return of containers in the context of Reverse Logistics, by developing a mathematical optimization model to analyze the total costs of the required infrastructure. Bloemhof-Ruwaard et al. (1996) develop a mathematical model that simultaneously considers the forward and reverse material flows within a network. Herein, they solve a Capacitated Facility Location Problem and determine the strategic locations of treatment capacities. Barros et al. (1998) address the recycling of sand in the Netherlands. Similar to Bloemhof-Ruwaard et al. (1996) a two-stage Capacitated Facility Location Problem is solved. Fleischmann et al. (1997) divide the main research flows within Reverse Logistics into distribution, production and storage planning. They provide a detailed review of existing publications. Realff et al. (1999) develop a mathematical model for the design of a multi-stage backward production process in the carpet industry. Jayaraman et al. (1999) formulate a mathematical optimization model that simultaneously supports the location decision of the recovery and distribution network, the material flow quantities between the elements of the network and the production and inventory quantities of the recycled products. Krikke et al. (2003) focus on establishing a closed-loop supply chain, i.e. the integration of the forward and reverse supply chain for refrigerators. Fleischmann (2001) formulates a generic model, the reverse network model. The reverse network model is an extension of the classical warehouse-location problem and combines the two warehouse-location problems of the forward and the reverse material flows. The integration of the two warehouse-location problems is formulated by balancing constraints.

The foundation of the research field Reverse Logistics was laid by the aforementioned publications. Herein, depending on the real-world planning problem that is studied, the mathematical optimization models differ, i.e. the planning of a collection and counting system for deposit bottles differs from the planning of recycling infrastructure for lithium-ion batteries. However, although the publications differ in the specific real-world problems or the implemented mathematical optimization models, they have certain components in common. Such components are used to classify the publications in the research field: Single/Multi Period(s), Single/Multi Product(s), (Un-)Capacitated Locations, Dynamic Decisions, Uncertainty and/or Single/Multi Objective(s) (cf. the most recent literature reviews by Govindan et al., 2015; Govindan and Soleimani, 2017). Table 1 lists various publications that focus on the design of logistics infrastructure. Each publication is characterized in terms of the above classification, reflecting the characteristics of the developed mathematical optimization models. Hence, generic and application-oriented mathematical models were developed that consider multiple material or waste streams, dynamic development over time such as dynamic installation of capacities as well as uncertain parameters and multiple evaluation criteria. One of "*the most important extension in current objective functions is regarding green, sustainable, environmental and resilience objectives*" (Govindan et al., 2015). Researchers are increasingly implementing multi-objective-decision making approaches to account for this requirement.

Concerning the planning problem described in Chapter 2, the design and evaluation of the recycling and recovery infrastructure for GFRP/CFRP can be classified as a multi-product, multi-period, capacitated and multi-objective planning problem within the re-

Table 1: Overview Literature Reverse Logistics.

Author(s)	Period		Product		Capacity			(I)	Uncertainty				Objective	
	S	M	S	M	(II)	(III)	(IV)		(V) (V(a))	(V(b))	(VI)	(VII)	S	M
Kroon and Vrijens (1995)	✓		✓		✓								✓	
Bloemhof-Ruwaard et al. (1996)	✓		✓			✓							✓	
Barros et al. (1998)	✓			✓		✓							✓	
Jayaraman et al. (1999)	✓			✓		✓							✓	
Realff et al. (1999)		✓		✓		✓							✓	
Krikke et al. (2003)	✓			✓	✓								✓	
Jayaraman et al. (2003)	✓			✓		✓							✓	
Schultmann et al. (2003)	✓		✓			✓	✓						✓	
Realff et al. (2004)		✓		✓		✓			$\checkmark_s$				✓	
Salema et al. (2007)	✓			✓		✓					✓		✓	
Srivastava (2008)		✓		✓		✓	✓						✓	
Frota Neto et al. (2008)	✓			✓		✓								✓
Min and Ko (2008)		✓		✓		✓	✓	✓					✓	
Pati et al. (2008)	✓			✓		✓								✓
Lee and Dong (2009)		✓		✓		✓		✓			✓		✓	
Francas and Minner (2009)	✓			✓		✓	✓				✓		✓	
Pishvaee et al. (2009)	✓		✓			✓					✓		✓	
S. et al. (2010)	✓		✓			✓	✓							✓
Pishvaee and Torabi (2010)	✓			✓		✓						✓		✓
Salema et al. (2010)		✓		✓		✓							✓	
Kara and Onut (2010)	✓			✓		✓			$\checkmark_s$	$\checkmark_s$			✓	
El-Sayed et al. (2010)		✓	✓			✓					✓		✓	
Pishvaee et al. (2011)	✓		✓			✓			✓	✓			✓	
A. et al. (2012)		✓		✓		✓	✓	✓					✓	
Amin and Zhang (2012)	✓			✓		✓								✓
Hasani et al. (2012)		✓		✓		✓			✓	✓			✓	
Vahdani et al. (2012)	✓			✓		✓			✓	✓				✓
Amin and Zhang (2013a)	✓			✓		✓					✓			✓
Amin and Zhang (2013b)	✓			✓		✓					✓			✓
Ramezani et al. (2013)	✓			✓		✓	✓		$\checkmark_s$				✓	
Ramezani et al. (2014)		✓	✓		✓							✓	✓	
Amin and Zhang (2014)	✓			✓		✓								✓
Hatefi and Jolai (2014)	✓		✓			✓			$\checkmark_s$	✓			✓	
Gao and Ryan (2014)	✓			✓		✓			✓	✓	✓		✓	
Altmann and Bogaschewsky (2014)		✓	✓			✓		✓	$\checkmark_s$	$\checkmark_s$				✓
Zeballos et al. (2014)		✓		✓		✓					✓		✓	
Soleimani et al. (2014)	✓			✓		✓					✓		✓	
Soleimani and Govindan (2014)	✓			✓		✓					✓		✓	
Fallah et al. (2015)	✓		✓			✓						✓	✓	
Hasani et al. (2015)		✓		✓		✓		✓		✓			✓	
Garg et al. (2015)	✓			✓		✓								✓
Soleimani and Kannan (2015)		✓		✓		✓							✓	
Soleimani et al. (2016)		✓		✓		✓					✓		✓	
Talaei et al. (2016)	✓			✓	✓				$\checkmark_s$	$\checkmark_s$		✓		✓

In column headings: S: Single; M: Multi.
(I-IX): (I) = Dynamic Decisions Integrated; (II) = Uncapacitated; (III) = Capacitated; (IV) = Decision on Capacity; (V) = Robust; (VI) = Stochastically; (VII) = Fuzzy; (V(a)) = Solution (Robust); (V(b)) = Model (Robust). $\checkmark_s$ means that the definition of Robust was not met, but rather a stochastic/different approach was taken.

search field of Reverse Logistics. First, the strategic planning task to design recycling and recovery infrastructures falls within the area of Reverse Logistics following the definition of Fleischmann (2000). Second, as rotor blades contain GFRP and/or CFRP depending on the specific wind turbine type, both waste streams must be considered simultaneously (cf. Sommer et al., 2020). Also, the existing and potential recycling and recovery paths contain multiple stages with several intermediate products. Hence, a multi-product formulation is required. Third, as future waste masses will increase over time and political as well as technological developments must be considered, a multi-period formulation is required. Fourth, decisions regarding investments in different capacity modules must be considered when choosing the site-specific capacities of treatment technologies. Fifth, in order to consider both economic and environmental criteria, prior Life Cycle Assessments and a multi-objective decision-making approach are needed.

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Part II.

Publications

4. Estimation of Glass and Carbon Fiber Reinforced Plastic Waste from End of Life Rotor Blades of Wind Power Plants within the European Union

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Abstract

The European Union is aiming at a circular economy and increased resource efficiency, which requires a waste management at the end-of-life of products. This is especially challenging for new and innovative products for which no recycling infrastructure exists so far. Wind power plants are such a product, for which large amounts of waste are expected within the next years as more and more plants reach their end-of-life. Especially the end-of-life rotor blades of wind power plants pose challenges with regard to waste management, since treatment options for the installed glass and carbon fiber reinforced plastics are still in a development stage. Moreover, material specific characteristics and technical aspects require separate treatment of these materials. To plan efficient treatment infrastructure, detailed knowledge on future waste streams is required. Against this background, this paper aims at estimating the mass of glass and carbon fiber reinforced plastic waste from rotor blades. To do so, we derive material specific weight functions and material specific shares to calculate the amount of installed glass and carbon fiber reinforced plastics in rotor blades. We apply normally distributed lifetimes to project the calculated installed masses into the future and account for uncertainties within a simulation study. The estimation model is applied to a dataset of wind power plants within the European Union. Based on the considered dataset, we estimate that 570 [Mt] of fiber reinforced plastic waste will occur between 2020 and 2030 in the European Union of which 18 [Mt] are carbon fiber reinforced plastic waste.

Keywords: Waste management, Rotor blades, Wind energy industry, Glass fiber reinforced plastics, Carbon fiber reinforced plastics, Waste estimation

1 Introduction

The horizon 2020 strategy of the European Union (EU) aims at increasing resource efficiency and establishing a circular economy to cope with limited natural resources and to decouple economic growth from resource consumption (European Commission, 2015, 2011, 2010). In line with this, regulations have been developed that define the European waste management, i.e. the treatment of products before and after they become waste. Herein, the preferential order of and responsibilities for waste treatment as well as demanding recycling and recovery targets are set for priority waste streams like construction and demolition waste, end-of-life vehicles, electrical and electronic equipment, batteries and accumulators or plastic (European Commission, 2018; European Parliament and the European Council, 2008, 2006, 2003, 2000). In the 2008 established EU directive on waste, the most preferred measure is the prevention of waste, i.e. the re-use of products to avoid waste. Once the products became waste, the preferential order of waste management from best to least preferred is preparing for re-use, recycling, other recovery (especially energy recovery) and disposal of waste (European Parliament and the European Council, 2008). In 2018, an amendment to the EU directive on waste was published, in which the EU calls for a transformation of waste management towards sustainable material management, *"[...] with a view to [...] ensuring prudent, efficient and rational utilization of natural resources [and] promoting the principles of the circular economy [...]"* (European Parliament and the European Council, 2018, (1)). It is stressed that *"the targets laid down in the directive on waste [. . .] for preparing for re-use and recycling of waste should be increased to make them better reflect the Union's ambition to move to a circular economy"* (European Parliament and the European Council, 2018, (3)). Herein, political regulations for waste management often require that certain recycling or recovery targets have to be fulfilled. Especially innovative products and technologies, such as batteries of electrical vehicles, photovoltaic systems and composition materials, pose challenges for a waste management with target fulfillment, as detailed information on the mass and quality of future waste streams and on further treatment options is often missing. For instance, unknown market developments, e.g. regarding the number of installed photovoltaic systems or of wind power plants or regarding the development of e-mobility, lead to an uncertainty in future waste streams. Moreover, product designers rarely consider(ed) the separation of the construction materials at the end-of-life within the design phase, especially for products with a long lifetime.

Wind power plants are such an innovative technology, for which knowledge on potential waste streams and treatment technologies is still limited. The current knowledge gaps result as markets are still developing. In addition, research on the treatment of some of the materials, like fiber reinforced plastics (FRP) and rare earths, as well as research on recycling technologies is still ongoing. In line with this, planning of infrastructures for targetoriented and efficient treatment of certain parts of wind power plants, in particular rotor blades, is currently challenging due to these knowledge gaps.

In the course of the Energy Transition, wind power generation has expanded widely within the EU (Eurostat, 2019). Installed power production capacities have increased from 12 [GW] in 2000 to 170 [GW] in 2017 (WindEurope, 2018). With an average power production capacity per wind power plant of 2 [GW] Lefeuvre et al. (2019), an estimated amount of 85.000 wind power plants were operated in the EU in 2017. Taking into account an average service life of $16-25$ years (Albers et al., 2018; Lefeuvre et al., 2019; Lichtenegger et al., 2020), the annual amount of waste masses from wind power plants is expected to increase considerably. Accordingly, the EU as well as national governments address the problem of increasing waste streams from wind power plants (Liu and Barlow, 2017; Zotz et al., 2019). A recent study of the German Environmental Protection Agency (UBA), for instance, emphasizes the importance of an ex-ante analysis and allocation of future costs for the treatment of upcoming wind power waste (Zotz et al., 2019). Herein, in particular the treatment of end-of-life rotor blades with regard to the installed FRP is highlighted.

The potential of re-use, as preferred waste prevention, is limited for wind power plants. Re-use of wind turbines is limited as the steady improvement of the efficiency of new wind turbines limits the demand for older wind turbines (Fichaux et al., 2011; Vestas, 2019a). Contractors specializing in wind turbine refurbishment for the second-life market concentrate on small wind turbines with a rated power production capacity of less than 1 [GW] (Albers et al., 2018). Other general lifetime extension measures are usually already considered in the calculation of the lifetimes of wind turbines, i.e. expected waste masses are postponed (cf. Lichtenegger et al., 2020). As re-use options are limited, recycling, recovery or disposal of wind power plants becomes essential. While efficient recycling infrastructures for the tower and the foundation of wind power plants exist, the treatment of wind turbines and in particular of rotor blades remains challenging due to the applied main construction materials: glass fiber reinforced plastics (GFRP) and carbon fiber reinforced plastics (CFRP) (Albers et al., 2018; Kaiser and Seitz, 2016), for which treatment options are still being researched (e.g. Gopalraj and Kärki, 2020; Limburg et al., 2019; Oliveux et al., 2015). Only one large-scale treatment option for GFRP exists, which is the co-processing in cement kiln. However, the processing amount is restricted with regard to regional capacities (Lange, 2017; Schmidl, 2010).

Against this background, this publication aims to close knowledge gaps with regard to a target oriented waste management of rotor blades focusing on the estimation of future GFRP and CFRP waste streams. Future GFRP and CFRP waste streams are estimated based on data of operating wind power plants in the EU. Thus, this publication serves as a basis for the detailed planning of feasible recycling and recovery infrastructures for the main construction materials of rotor blades of wind turbines. Ex-ante evaluation of future treatment costs can be obtained merging these estimations with additional data on available treatment options.

The remaining publication is structured as follows: Section 2 provides information on rotor blades of wind power plants that is relevant for the understanding of the developed estimation approach. Section 3 presents an estimation approach that enables detailed spatial and material specific calculation of installed GFRP and CFRP masses and involves realistic mapping of the installed masses into the future. Section 4 concludes the findings and presents an outlook on further research.

2 Rotor blades of wind turbines

Rotor blades consist of a variety of construction materials: FRP, structural adhesives, wood, paint and metals (Liu and Barlow, 2017). As motivated, we concentrate the publication on the estimation of future FRP waste and therefore denominate the noncritical materials as other materials. In particular, we do not consider aggregated FRP, but differ between GFRP and CFRP to account for their respective constituents. Both FRPs are complex composites consisting of a glass (GFRP) respectively carbon (CFRP) fiber based reinforcement and an epoxy-resin based polymer matrix (Liu and Barlow, 2017). We reason the separate consideration of GFRP and CFRP in the planning of recycling and recovery infrastructures in the following.

Wind turbines are characterized by their power production capacity [MW] and the diameter of its rotor [m] (cf. wind turbine denominations e.g. Vestas (2019b)). However, the variety of wind turbine types is high, i.e. there exist wind turbines for low, medium and high wind speed zones as well as for onshore and for offshore conditions from several manufacturers (Liu et al., 2019). Especially, wind turbine types differ depending on the manufacturer's preference with regard to the applied main construction materials GFRP and CFRP in the rotor blades (Liu et al., 2019). Some manufacturers use only GFRP, others a mixture of GFRP and CFRP (cf. data sheets of wind turbines e.g. SiemensGamesa (2019); Vestas (2019b)) as main construction materials. The effects of the choice of the main construction materials on an efficient waste/end-of-life treatment of the rotor blades is threefold:

First, the total weight of the rotor and hence, the total amount of occurring waste is affected. For instance, SiemensGamesa and Vestas manufacture wind turbines for the same wind zone, but applying different material compositions. While SiemensGamesa uses GFRP as the main construction material, Vestas more often combines GFRP and CFRP as the main construction materials. Comparing two rotor blades of these two manufacturers with almost equal power production capacity of 3.45 [MW] for similar wind zones (IA, IIA), the Vestas rotor blades are $8-12$ [m] shorter than the Siemens rotor blades due to the choice of construction materials. As this also results in a significant reduction in weight (SiemensGamesa, 2019; Vestas, 2019b), an estimation based solely on the power production capacity (that is similar for both wind turbines) is not appropriate. Moreover, the total weight of equally long rotor blades of different main construction materials (GFRP vs. GFRP/CFRP) differs due to lower density of CFRP in comparison to GFRP (Jamieson and Hassan, 2011). Hence, the choice of the wind turbine type, i.e. length, total weight and utilized construction materials of the rotor blades, differs depending on the manufacturer and on the geographical location of a wind park site. As a result, the regional amount of upcoming GFRP and CFRP waste highly depends on the installed wind turbine type. This has to be considered in an estimation of the waste streams.

Second, due to different technical characteristics of the specific fibers, e.g. the electric conductivity and high resistance against thermochemical processes of the carbon fibers as well as the low melting point and possible vitrification of the glass fibers, these materials require a distinguished treatment (Ehrenstein, 2006; The Society of Fiber Science and Technology, 2016, e.g.[)]. Extensive literature exists concerning the treatment of GFRP as well as CFRP waste (e.g. Gopalraj and Kärki, 2020; Liu et al., 2019; Oliveux et al., 2015). Herein, it is stated that thermal, chemical or mechanical recycling of FRP is generally possible, but technologically difficult. Differences regarding the recycling technologies exist. Ginder and Ozcan (2019) state that thermal recycling of GFRP results in low quality glass fibers. In contrary, thermal recycling of CFRP results only in slight loss of performance of the carbon fibers. Similar outcomes result for chemical recycling. For a comparison between the treatment of GFRP and CFRP in the context of mechanical, thermal and chemical recycling see Liu et al. (2019).

Third, recovery paths and secondary markets are also material specific. So far, secondary markets for recycled fibers do not yet exist. However, while economic feasibility of a recycling of the valuable carbon fibers and monomers seems reasonable Liu et al. (2019), secondary markets for the low value glass fibers are unlikely (Ginder and Ozcan, 2019; Lichtenegger et al., 2020; Heida, 2016). Other potential recovery paths are also material specific due to the chemical composition of the fibers: While co-processing options for GFRP only exist in the cement clinker industry, co-processing for CFRP may be only possible in the steel or calcium carbide industry (Schmidl, 2010; Walter, 2017, e.g.[)]. While the incineration of GFRP in hazardous waste incineration plants is technologically possible but undesired, the incineration of CFRP is challenging as process temperatures are too low and dwelling times are too short for complete destruction of the carbon fibers

(Stockschläder et al., 2018, 2019). Concluding, it is necessary to consider both main construction materials independently within the planning of necessary recycling infrastructure for technical and economic reasons.

Hence, the planning of such infrastructures requires knowledge on material specific waste streams on a very detailed basis to project regional treatment capacities for potential future treatment options. Depending on the wind turbine type, either GFRP or GFRP and CFRP are applied in addition to other materials like metals, core, adhesives and paintings. Estimation approaches should regard the availability of data and information. So far, most approaches in literature base on the overall power production capacity and calculate total mass of FRP, i.e., they do not account for material specific estimations. However, material specific shares of the total blade weight can be derived to calculate material specific masses based on the power production capacity. An even more accurate estimation becomes possible if information on individual wind turbines is available based on knowledge about material specific masses of rotor blades of different wind turbine types. Additionally, realistic projections of the calculated masses are required, which demands for adequate information on the lifetime of rotor blades.

In the following section, we develop an estimation approach that allows for an accurate material specific calculation of the installed GFRP and CFRP masses if information on individual wind turbines is available. In addition, we also extent existing approaches based on the power production capacity by applying material specific shares to the total rotor blade weight. Furthermore, we develop a simulation study to vary uncertain parameters such as the material specific masses and material specific shares as well as stochastic lifetimes.

3 Estimation of GFRP and CFRP waste

In the following, estimations on the future amount of end-of-life GFRP and CFRP waste masses from rotor blades of wind power plants are presented. Other than in the existing literature, material specific estimations and detailed geographical information is provided, the weight differences due to the choice of the main construction materials are regarded and a realistic stochastic lifetime is applied.

First, we review existing approaches for the forecasting of FRP and total blade waste from rotor blades of wind turbines in Section 3.1. In Section 3.2, we develop an estimation approach that contributes to the existing literature by providing the required level of detail. In Section 3.3, we outline the results of the applied approach on a dataset representing 75 [%] of the installed power production capacity in 2015 for the EU-28. In Section 3.4, we conclude the findings and present the contributions of the estimation approach. The Appendices A–C provide supporting information for Section 3.2.

Table 1: Literature on waste mass estimations from wind energy industry.

Publication	Determining masses (step 1)					Projecting masses (step 2)	
	method	FRP[1]	GFRP[2]	CFRP[3]	WD[4]	method	lifetime [a]
Albers et al. (2009)	average	✓	-	-	-	det.	20
Larsen (2009)	average	✓	-	-	-	det.	20
Papadakis et al. (2010)	average	✓	-	-	-	det.	20
Liu and Barlow (2015)	average	✓	-	-	✓	det.	20
Bank and Arias (2016)	average	✓	-	-	-	det.	20
Andersen et al. (2016)	regression	✓	-	-	✓	det.	20
Liu and Barlow (2017)	average	✓	-	-	✓	det.	20
Pehlken et al. (2017)	average	✓	-	-	-	det.	20
Sultan et al. (2018)	average	✓	-	-	-	det.	25
Lefeuvre et al. (2019)	average	-	-	✓	-	det.	25
This paper	regression const. law[5] average	✓	✓	✓	✓	**stoch.**	$\mathcal{N}(17.08, 12.67)$[6]

1 Fiber reinforced plastics.
2 Glass fiber reinforced plastics.
3 Carbon fiber reinforced plastics.
4 Weight differences in dependence on the construction method and dimensions.
5 Constitutive law.
6 $\mathcal{N}\left(\mu, \sigma^2\right)$.

3.1 Existing waste mass estimations

The estimation of end-of-life waste from installed rotor blades requires two mayor steps: the installed material masses of rotor blades are calculated and the calculated installed material masses are projected as resulting waste masses. As discussed, it is necessary to distinguish between GFRP and CFRP. In addition, differences in the total weight of rotor blades due to their dimensions as well as due to the choice of the main construction materials are essential for an appropriate mass estimation. Moreover, a realistic lifetime must be considered to forecast waste streams. In line with this, we differentiate existing publications with regard to these characteristics.

As it can be seen in Table 1, almost all publications focus on estimating aggregated FRP or total blade waste, instead of distinguishing between GFRP and CFRP waste. In addition, most authors neglect differences in the total blade weight that depend on the dimensions of rotor blades and on the construction materials. Andersen et al. (2016), Liu and Barlow (2015) and Lichtenegger et al. (2020) consider the resulting weight differences. Only Lefeuvre et al. (2019) estimate CFRP specific waste instead of aggregated FRP or total blade waste. Yet, the authors neglect differences in the total weight of rotor blades. Nearly all approaches base on newly installed power production capacity per year ([MW]) multiplied by several factors (uniform or [tons/MW]) to calculate the annually installed FRP or total masses. Only Andersen et al. (2016) and a recently published study of Lichtenegger et al. (2020) calculate the installed masses based on regression functions similar to this study. Concerning the projection of waste masses, all existing publications consider an expected lifetime in their estimation. Lichtenegger et al. (2020) state that they generated a stochastic distribution function, but rather use knowledge gains to better estimate an average lifetime of a wind turbine instead of the rough estimation of the average lifetime of other existing approaches.

Summarized, no approach estimates GFRP and CFRP specific waste streams. Moreover, no approach considers realistic mapping of the installed masses into the future exploiting the potential of stochastic lifetime distributions. Within the following, we develop an estimation approach that fills this literature gap.

3.2 Methodological approach

The developed estimation approach is a two-step procedure. In contrast to the other publications, we estimate material specific waste streams and vary uncertain parameters within a simulation study. In line with this, we forecast a range of possible material specific waste stream scenarios over the time horizon.

In the first step, we calculate the GFRP and CFRP masses that are currently installed in operating wind parks throughout the EU. Since the available information on wind parks is diverse, the calculation of the installed GFRP and CFRP masses depends on the information given. We develop four different data availability cases that dictate the necessary calculation steps [a) straight forward, b) main construction materials, c) Liu's case, d) Albers' case] with decreasing necessary data availability (see Section 3.2.2). Depending on the case, uncertainties in the distribution of GFRP and CFRP masses exist. Therefore, we vary parameters that influence the installed GFRP and CFRP masses to account for these uncertainties in a simulation study.

In the second step, we project the calculated installed GFRP and CFRP masses into the future (Section 3.2.3). To do so, we do not consider a deterministic lifetime as done in most publications so far, but generate an operating time of each wind park individually based on a stochastic distribution function. To account for the uncertainty, we further vary the individual lifetimes in a simulation study. The data that is used to derive the stochastic distribution function represents several influencing factors, such as lifetime extension measures, full-load hours and regional subsidies to improve economic efficiency and others.

The design of the simulation study is explained in Section 3.2.4. The available datasets that were used to develop the methodology are described in the following.

3.2.1 Databases

The methodological approach for spatial and material specific waste mass estimation is based on three datasets.

The first dataset (dataset1) contains general data on operating wind parks p ($p \in \mathcal{P}$) in the EU (TheWindPower, 2016): the installed wind turbine type (w_p), the number of installed wind power plants (n_p), the year of commissioning (t_p), the total power production capacity (c_p), the wind parks' specific location. The simulation study is applied on dataset1.

The second dataset (dataset2) contains general data on wind turbine types ($w/w_p \in \mathcal{W}$), respectively (w_p) with regard to wind park p of dataset1 (WindTurbineModels (2017); manufacturer data): the wind turbine specific power production capacity $\left(c_w/c_{w_p}\right)$, its rotor blades' material specific masses $\left(m_{aw}/m_{aw_p}, \forall a \in \mathcal{A} = \{GFRP, CFRP\}\right)$, length $\left(r_w/r_{w_p}\right)$, the main construction materials $\left(cm_w/cm_{w_p}\right)$. The four-calculation cases are developed based on dataset1 and dataset2. From dataset1, we gained knowledge on usable wind park data, and from dataset2, we developed material specific weight functions (Appendix A).

The third dataset (dataset3) contains data on German wind parks (Bundesnetzagentur, 2019): their date of commissioning and date of operation end. The generated stochastic distribution function bases on dataset3.

3.2.2 Step 1: Calculation of installed GFRP and CFRP masses

The aim of the first step is to calculate the installed GFRP and CFRP masses for each wind park p: e_{pa}. Herein, we differentiate four cases.

In case *a) straight forward*, e_{pa} is calculated straight forward by equations 1 matching dataset1 and dataset2. Herein, the known number of wind turbines n_p is multiplied by the known material specific masses m_{aw_p} of the known installed type of wind turbines w_p at wind park p.

$$e_{pa} = m_{aw_p} n_p \qquad \forall p \in \mathcal{P}, a \in \mathcal{A} \quad (1)$$

The incompleteness of dataset1 and dataset2 in terms of specific wind turbine type w_p, material specific waste masses m_{aw_p} and/or number of installed wind turbines n_p requires a distinction of three additional calculation cases as discussed in the following.

Case *b) main construction materials*, is similar to case a), but the installed material specific masses $\left(m_{aw_p}\right)$ are determined beforehand. This is necessary for wind parks for which the type of installed wind turbine is known, but the weight of the installed wind turbine is not due to missing manufacturer data. Dataset2 contains information on the specific wind turbine type (w_p), its main construction materials $\left(cm_{w_p}\right)$ and rotor blades' length $\left(r_{w_p}\right)$, but lacks information on the corresponding GFRP and CFRP masses $\left(m_{aw_p}\right)$. In this case, m_{aw_p} is determined by material specific weight functions of the installed rotor blades' length $\left(r_{w_p}\right)$ within previous calculation steps. As a result, m_{aw_p}

can be determined, and equations 1 can be applied. The development of the material specific weight functions is presented in Appendix A. Within this calculation case, we face uncertainties in the amount of CFRP, represented by α (cf. Appendix A).

Cases *c) Liu's* and *d) Albers'* have to be applied, if the wind turbine type that is installed at wind park p is unknown, i.e. if only information on the installed power production capacity is provided. Most existing estimations base on these two approaches. As a result, e_{pa} cannot be obtained based on wind turbine type specific material masses, hence equations 1 cannot be applied. For these wind parks, calculations are based on the total power production capacity (c_p) and the expected tonnage of waste per installed power (μ_p). At first, the total blade waste is determined following either the approaches of Liu and Barlow (2017) in case *c)* or of Albers et al. (2009) in case *d)*. Herein, case *c) Liu's* is applied if additional information on the number of wind turbines is given, since an average power production capacity can be determined. As both approaches are not able to determine material specific installed masses, we need a material specific allocation parameter γ_{pa} for each of the power production classes introduced by Liu and Barlow (2017) and Albers et al. (2009). In Appendix B, we use the derived material specific weight functions and the extensive dataset1 to develop material specific shares in dependence of the power production classes introduced by Liu and Barlow (2017) and Albers et al. (2009). The installed GFRP and CFRP masses at each wind park p (e_{pa}) are subsequently calculated by applying equations 2. With these calculation cases, we also face uncertainties in the amount of CFRP, represented by a range of potential material specific shares for each material (GFRP, CFRP) and power production class. In line with this, within the simulation we generate γ_{pa} values in dependence of specified ranges (cf. Appendix B).

$$e_{pa} = \mu_p c_p \gamma_{pa} \qquad \forall p \in \mathcal{P}, a \in \mathcal{A} \quad (2)$$

The required and used information concerning the cases *a)*, *b)*, *c)* and *d)* are summarized in Table 2. Combining these four calculation cases, the installed GFRP and CFRP masses (e_{pa}) can be calculated for each wind park p depending on the available data. Herein, uncertainties exist that are tackled within a simulation study. Afterwards, the calculated installed GFRP and CFRP masses must be further mapped into future years depending on the date of commissioning (t_p) and lifetime (lt_p) of a wind park p. Herein, all existing publications assume a deterministic lifetime of $16 - 25$ years (cf. Table 1).

3.2.3 Step 2: Projecting & aggregating installed GFRP and CFRP masses

By knowing the year of commissioning of each wind park p (t_p), the estimated material masses at p (e_{pa}) can be projected into the future. In contrast to all existing publications, we determine a probability function based on empirical data as presented in Appendix C and further use the distribution function within the estimation, respectively vary lifetimes in accordance to the distribution function within the conducted simulation study. The calculated installed GFRP and CFRP masses that are projected into the future represent the end-of-life GFRP and CFRP waste masses for each wind park p in any t of the time horizon (e_{pat}). Equations 3 depicts the estimation considering the wind park specific period of commissioning (t_p) and applying a wind park specific lifetime (lt_p). Subsequently, knowing the annual waste masses of each wind park p, equations 4 are applied to calculate annual waste masses per region (e_{sat}), where $\mathcal{P}_s$ states the set of wind parks p within a certain region s $s \in \mathcal{S}$, e.g. within Europe, within regions of the EU-28, or within selected countries.

$$e_{pat} = \begin{cases} e_{pa} & \text{, if } t = t_p + lt_p \\ 0 & \text{, else} \end{cases} \qquad \forall p \in \mathcal{P}, a \in \mathcal{A}, t \in \mathcal{T} \quad (3)$$

$$e_{sat} = \sum_{p \in \mathcal{P}_s} e_{pat} \qquad \forall s \in \mathcal{S}, a \in \mathcal{A}, t \in \mathcal{T} \quad (4)$$

In the following, we describe the simulation study that allows us to cope with relevant uncertainties within step 1 and step 2.

3.2.4 Simulation study

In step 1 and step 2, we face uncertainties with regard to the impact on the reduction of the total blade weight if applying CFRP as well as with regard to the lifetime of rotor blades. To account for these uncertain parameters, we developed a simulation study that repeatedly execute step 1 and step 2 for individual scenarios ($NumberScenarios$). In line with this, within each scenario ($CurrentScenario$), we generate scenario specific waste streams.

In step 1, we vary parameters a and cpa (cf. eqs. (GFRP/CFRP 3 and 4) in Appendix A, Table 3 in Appendix B), which affects the calculated installed GFRP and CFRP masses.

In step 2, we vary parameter lt_p (cf. eq. 3), which affects the temporal projection of the installed GFRP and CFRP masses. The simulation procedure is summarized in the following pseudo code: *CurrentScenario* is the running index of the number of scenarios to be generated. *NumberScenarios* represents the total number of scenarios. Each run results in a scenario of future waste streams that differ due to variation of individual Lifetime, Alpha and Gamma values. The function *Case* gets the specific case depending on the

Table 2: Differences between the four calculation cases in terms of used information.

cases	w_p	n_p	c_p	cm_{w_p}	r_{w_p}	e_{pa}	additional information
a) straight forward	✓	✓				eqs. 1	m_{aw_p} given in dataset$_2$
b) construction method	✓	✓		✓	✓	eqs. 1	m_{aw_p} calculated (Appendix A)
c) Liu's		✓	✓			eqs. 2	μ_p, γ_{pa} (Appendix B)
d) Albers			✓			eqs. 2	μ_p, γ_{pa} (Appendix B)

Table 3: Material specific allocation parameter

$\mathcal{C}_{Liu} \cup \mathcal{C}_{Albers}$	c_c [MW]	μ_c [t/MW]	$\mathcal{L}_c$ [m]	$\gamma_{ca\mid\ t_p<2001}$ [-]		$\gamma_{ca\mid\ t_p>2001}$ [-]	
				GFRP	CFRP	GFRP	CFRP
1	(0.0,1.0)	8.43	[10,22]	.89	0	.89	0
2	[1.0,1.5)	12.37	[26,37]	.87	0	.87	0
3	[1.5,2.0)	13.34	[34,45]	.86	0	[.79, .83]	[.015, .04]
4	[2.0,5.0)	13.41	[41,58]	.84	0	[.76, .81]	[.016, .044]
5	[5.0,∞)	12.37	[62,80]	.82	0	[.72, .77]	[.018, .05]
$\varnothing$	-	10.00	-	.83	0	.81	.025

available data (cf. Table 2). The function *ConstructionMethod* gets the construction method of the wind turbines at the wind park that becomes necessary for cases *a)* and *b)*. The function *Lifetime* generates a normally distributed life time for the wind park (cf. Appendix C). The function *Alpha* generates a uniformly distributed value between 3.0 and 8.5 to account for the uncertainty of the impact of CFRP on the total blade weight (cf. Appendix A). The function *Gamma* generates a uniformly distributed value between the given ranges in dependence of the power production classes defined by Liu and Barlow (2017) and Albers et al. (2009) (cf. Appendix B, in particular Table 3). The function *Mue* gets the mass per installed power depending on the power production capacity class of Liu and Barlow (2017) or Albers et al. (2009). Equations (GFRP 1) as well as (GFRP/CFRP 3 and 4) can be found in Appendix A.

Conclusive, it should be highlighted that the overall estimation approach can be applied to detailed datasets of wind parks as well as to datasets showing aggregated data like regional information on the newly installed power production capacity. Line 3 in the pseudo code indicates that for each data point the installed GFRP and CFRP masses are calculated and further projected. It is not relevant whether the data point is a single wind park or the cumulated wind park installations of a country. However, on an aggregated level, most likely only cases c) and d) will be applicable, since detailed information is missing. However, even for such cases, the overall estimation approach enables material specific estimation.

3.3 Application and results

We apply the simulation study on dataset1 that consists of 14.009 operating wind parks (61.000 wind power plants) installed between 1995 and 2015 in the EU-28. Herein, for 26, 40, 32 and 2 of the wind parks information is available such that cases *a)*, *b)*, *c)* and *d)* can be applied in step 1, respectively. In line with this, for nearly two third of the installed power production capacity, the installed masses can be estimated by cases *a)* and *b)*, and thus are based on either specific information on the material masses of the installed wind turbine or on the material and substitution functions.

The wind parks included in the dataset account for 106.5 [GW] power production capacity at the end of 2015. According to WindEurope (2018), the total power production capacity of wind power is estimated to be 141 [GW] (2015). Fig. 1 shows a comparison between the considered dataset and WindEurope (2018) in terms of installed power production capacity per year and total power production capacity within the EU over time. As can be seen, the wind plants considered for the estimation of end-of-life waste account for approximately 75 [%] of the total power production capacity installed estimated by WindEurope (2018):

We estimate possible future waste streams by a simulation study. To do so, 1.000 simulation runs are conducted following the pseudo code from Section 3.2.4. The resulting annual waste masses within the EU and within four European sub regions are determined for each simulation run. In total, 1.000 possible future waste streams are determined. Fig. 2 a) and b) show the average of the annual GFRP and CFRP waste streams for the 1.000 simulation runs. The regional waste streams are depicted in stapled bars for the average case. It can be seen that GFRP masses increase parallel to the total power production capacity. The amount of end-of-life GFRP and CFRP waste from installed rotor blades increases on average from 35 to 58 [Mt] and from 0.7 to 2.0 [Mt] between 2020 and 2028, respectively. In comparison, the amount of CFRP waste streams show a stronger increase. The slight drop at the end of the time horizon can be explained by the underlying data set (see Fig. 1). Fig. 2 c) and d) show two boxplot diagrams that describe the variation of the occurring GFRP and CFRP waste masses over the time horizon and over the 1.000 simulation runs for each geographical region, i.e. the annual variation of waste masses within the 1.000 possible future scenarios. Exemplary, in Fig. 2 c) the first box-plot represents the set of estimated annual occurring GFRP in the EU. Herein, on average 50 [Mt] are expected, which is in line with the results depicted in Fig. 2 a). However, the maximum annual GFRP in the EU is 87 [Mt] in one specific year within one of the 1.000 scenarios. As can be seen, the annual amount of GFRP and CFRP can vary strongly over the time horizon due to the uncertain material specific ratios and operating times. The highest degree of variation can be observed in Western Europe.

Figure 1: Dataset vs. WindEurope (2018).

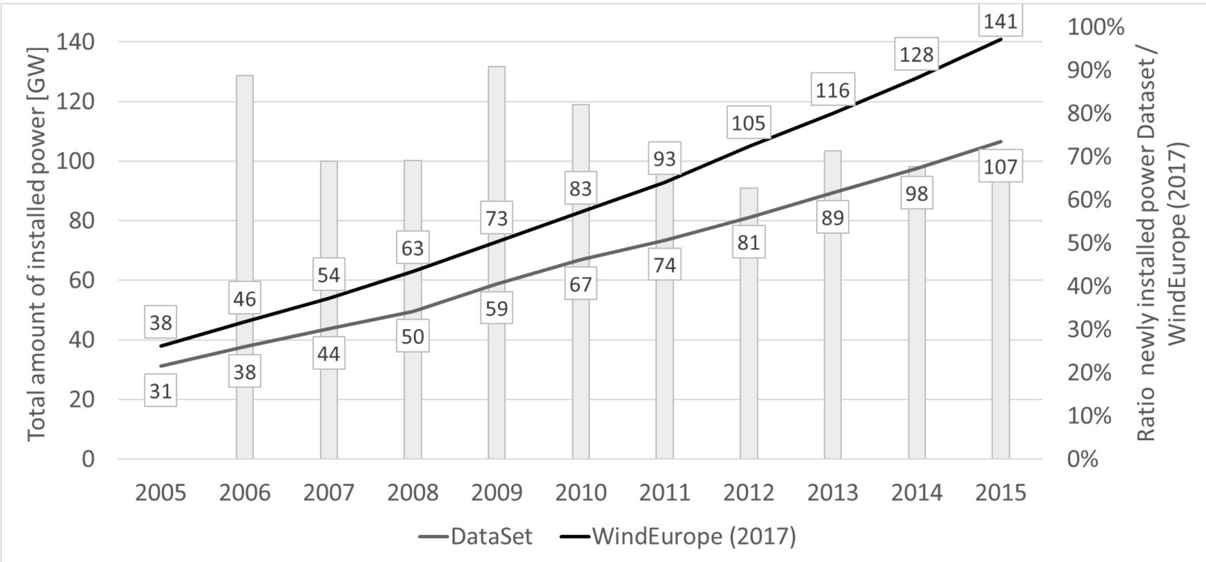
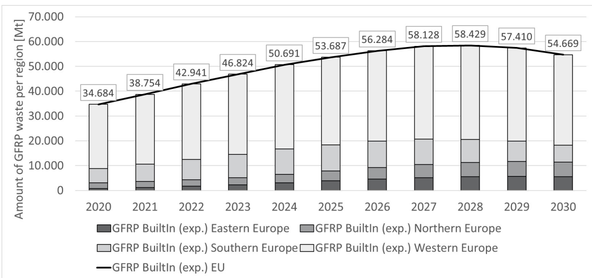
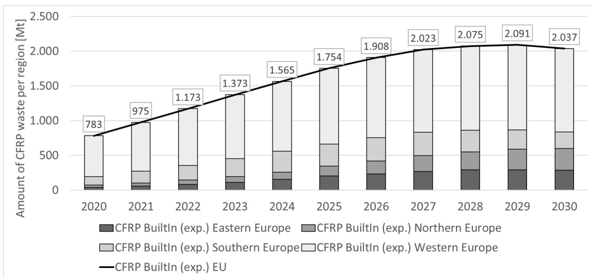


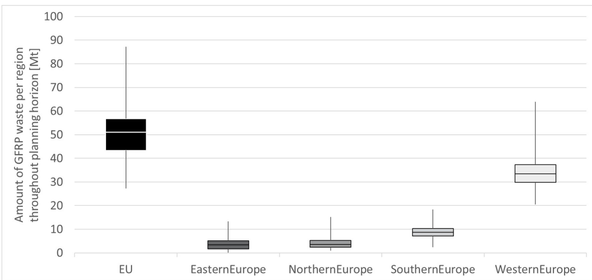
Figure 2: Results of the simulation study. Diagrams a) and b) show the development for the expected GFRP and CFRP waste within Europe over time. Diagrams c) and d) show ranges of annual GFRP and CFRP waste masses within European regions.



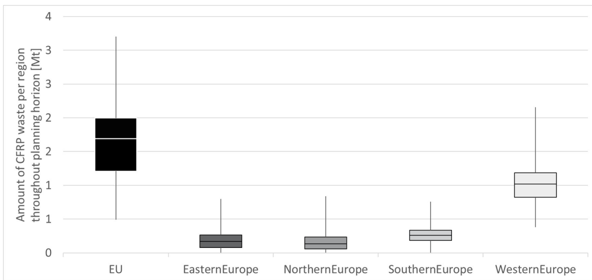
(a) Occurring GFRP waste within the EU.



(b) Occurring CFRP waste within the EU.



(c) Distribution of GFRP waste within the EU over the planning horizon.



(d) Distribution of CFRP waste within the EU over the planning horizon.

3.4 Evaluation of results and approach

Comparing the estimated end-of-life GFRP and CFRP waste streams to other approaches is difficult due to differences in the methodology and in the underlying database. A direct comparison between the estimated annual waste masses is impossible due to the stochastic instead of deterministic lifetime projection. Moreover, the data of most publications bases on the annually installed power production capacity. However, dataset1 is not exhaustive 75 [%] of WindEurope (2018), i.e. it must be taken into that most likely not every single wind power plant within the EU is listed in the underlying dataset1. Especially installations during the years 2010–2015 seem to be missing (cf. Fig. 1). Hence, a comparison between the annually installed material masses is not possible. However, the average tonnage per installed power [tons/MW] of our approach can be compared to the tonnage per installed power estimated by other approaches. Hence, we use the average tonnage per power as key performance indicator (KPI) to show that the estimation approach leads to robust results. Moreover, we list the ranges of CFRP ratios for GFRP/CFRP rotor blades and compare the result with the average ratio of CFRP used Lefeuvre et al. (2019):

Applying the developed estimation approach on dataset1, the average tonnage of waste per power production capacity between 2005 and 2015 results in 9.7 [tons/MW], which is almost equal to the value of 10 [tons/MW] assumed by other publications (Albers et al., 2009; Lefeuvre et al., 2019). Concerning the ratio of CFRP, the ratio of the annual waste masses estimated is increasing towards 2 [%], which seems realistic, as most rotor blades still consist of GFRP. Approximately 29 [%] of the considered wind parks in dataset1 consist of GFRP/CFRP rotor blades. The ratio of installed CFRP in GFRP/CFRP rotor blades ranges between 2.3 and 5.1 [%]. The results of the calculation approach are slightly lower than the CFRP application ratio assumed by Lefeuvre et al. (2019) (6 [%]). Summarizing, the results are plausible with regard to the overall waste mass and with regard to the CFRP specific mass and ratio. Also, the results seem reliable as calculations mostly base on cases *a) straight forward* and *b) main construction materials* using regression functions with a high coefficient of determination (see Appendix A for coefficients of determination R^2). Regarding our results, the estimated impact of the share of CFRP on the total amount of waste is rather small (cf. 9.7 vs. 10 [tons/MW]). However, this is because the corresponding KPI (9.7 [tons/MW]) is calculated for the whole EU-28, where most installed wind parks have rotor blades consisting only of GFRP. Thus, the impact of CFRP on the total weight reduction is small. However, these results could change, if the approach would be applied to other regions (e.g. China) or to smaller regions with more CFRP/GFRP wind power plants (see example in Section 2 and Fig. 3 in Appendix A).

In contrast to the existing publications, the effort to obtain the necessary data is high. However, the effort of a material specific estimation of GFRP and CFRP seems necessary, regarding the technical and waste management aspects discussed in Section 2. Herein, not only a material specific but also a detailed geographical estimation was regarded as essential for feasible planning of recycling and recovery infrastructures. As no other publication deals with the distinct estimation of GFRP and CFRP and a projection of the installed waste masses considering unknown operating times, we developed an estimation approach that considers the local conditions and year of construction as well as differences in the choice of construction materials and resulting differences on the total weight. Moreover, we consider uncertainties of the distribution of the installed GFRP and CFRP in quantity and time within the simulation study.

4 Contribution

The aim of the publication is a detailed spatial and material specific estimation of GFRP and CFRP waste from rotor blades of wind power plants, motivated by material specific treatment options and wind turbine dependent waste masses caused by the choice of the main construction materials. Currently, other estimation approaches still lack such a material specific estimation, as well as a realistic projection of waste masses. An estimation approach was developed that allows determining the influence of the different construction materials and the geographic localization of future waste streams. Moreover, a lifetime probability function and material specific weight ratios were determined for realistic waste mass projection and future estimations. In addition, we developed a simulation study to account for uncertainties within the estimation approach. Using this approach, we improved the level of detail in estimating GFRP and CFRP waste from rotor blades of wind power plants significantly. In addition, we extended the approaches by Albers et al. (2009) and Liu and Barlow (2017) such that GFRP and CFRP specific waste masses can now be estimated. To the best of our knowledge, this is the first approach that allows for a material specific estimation. Nevertheless, there are some aspects for future research:

Within the estimation approach, we assume that after a certain operating time, the GFRP and CFRP masses of decommissioned rotor blades must be treated. We do not consider a prevention of waste or re-use, i.e. a certain number of wind turbines that might be re-used, e.g. by repositioning of wind turbines or as playground materials or cupboards. Such re-use measures might result in a geographical and temporal shift of future waste masses. However, re-use measures might be integrated in our approach by adjusting equations 3 such that a number of wind power plants (depending on the capacity class, age or other influencing parameters) within a wind park p that is re-used is omitted from the calculation of the GFRP and CFRP waste.

Concerning the lifetime or operating time distribution function, it should be noted that dataset3 bases on wind power plants installed, commissioned, operated and decommissioned in Germany. Thus, the determined distribution function includes national behaviour influenced by parameters such as decreasing economic efficiency due to phasing out of subsidies, national electricity markets and lifetime extension measures. To improve the accuracy of the estimations, regional and, at best, wind turbine type specific operating time distribution functions should be considered. Thus, geographical differences with regard to governmental subsidies, but also with regard to divergent utilization of wind power plants due to different wind zones could be represented. Moreover, it should also be noted that future policy regulations might have a huge influence on the results. If subsidies lead to lifetime extensions or reductions (e.g. through repowering), the distribution function must be adjusted (Albers et al., 2018).

The developed estimation approach can be enhanced further by including additional uncertainties within the determination of the GFRP and CFRP masses, especially with regard to the material functions presented in Appendix A. Herein, the coefficients of determination (see Appendix A for R^2) could be used to derive a set of possible curve shapes. Moreover, as stated by Jamieson and Hassan (2011) the amount of installed CFRP differs depending on the manufacturers' preference. Currently, this aspect is implemented by a variation of different values of α and γ_{pa} within the simulation study (see Appendices 1 and 2). In line with this, the estimation could be improved by determining similar weight functions depending on the amount of CFRP, i.e. total weight functions for rotor blades being constructed with little, medium and high amount of CFRP.

Regardless of these potential extensions, the detailed compilation of information on GFRP and CFRP waste from rotor blades of wind turbines serves as a basis for future research, e.g. designing waste stream specific Europe-wide recycling and recovery infrastructures and forecast achievable recycling, recovery and circularity targets based on material flows.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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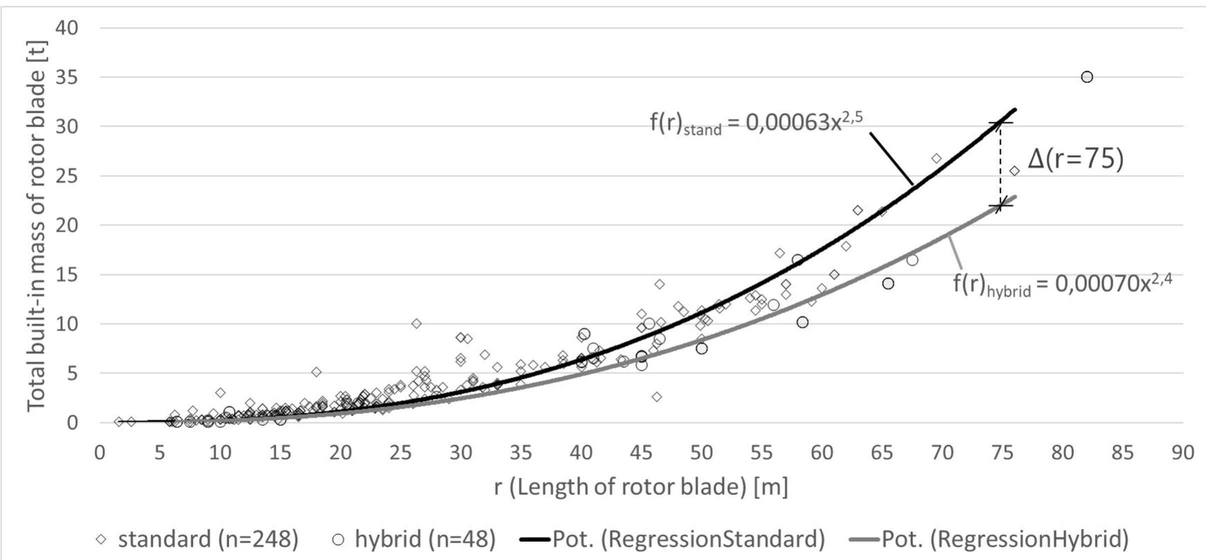
Appendix A. Mass compositions for case b)

Concerning the weight differences due to the application of both main construction materials, it must be noted that GFRP and CFRP are used within the skin and spar caps as well as tensile beams of rotor blades, subsequently denoted as exterior and interior parts of rotor blades. Mostly, GFRP is used in the exterior and interior parts of rotor blades (Mishnaevsky et al., 2017). Since 2001, some manufacturers substitute GFRP from the interior parts of the rotor blades by CFRP, i.e. rotor blades of the respective wind turbine type consist of GFRP in the exterior and CFRP in the interior parts (Jamieson and Hassan, 2011; TheWindPower, 2016; WindTurbineModels, 2017). For the sake of simplicity, we denote GFRP rotor blade if only GFRP is utilized as main construction materials (besides metals, core, adhesive and painting) and GFRP/CFRP if otherwise. As CFRP has even better mechanical characteristics compared to those of GFRP (Ehrenstein, 2006), the substitution allows for a further reduction in the rotor blades' total weight while retaining the same dimensions and guaranteeing the same mechanical resistance. Fig. 3 shows two scatter plots describing the total weights of 248 GFRP and 48 GFRP/CFRP rotor blades from 296 different wind turbine types in dependence of their respective lengths r (WindTurbineModels, 2017). The reduction in the rotor blades' total weight by applying CFRP in the interior parts results as $\Delta(r) = f(r)_{GFRP} - f(r)_{GFRP/CFRP}$, with $f(r)_{GFRP}$ and $f(r)_{GFRP/CFRP}$ representing the total blade waste in dependence of the length and the construction method. Assuming that the design of the rotor blades do not differ regardless of the construction method, the weight of the remaining materials (*others*) are equal regardless the construction method, $\Delta(r)$ can be expressed as stated (cf. Jamieson and Hassan, 2011).

Figure 3: Total blade weight in dependence of the main construction materials.



For case b), the specific GFRP and CFRP masses of a wind turbine type are not known. However, as the wind turbine type is known, the length of the wind turbines' rotor blades r and their main construction materials (GFRP, GFRP/CFRP) are known. This information can be used to determine the material masses for the specific wind turbine type. Data from WindTurbineModels (2017) and technical wind turbine data sheets were analyzed to derive the two scatter plots depicted in Fig. 3 that represent the total blade weight of GFRP and GFRP/CFRP rotor blades in dependence of their length. Equations GFRP and GFRP/CFRP describe the corresponding total blade weight functions that match the corresponding 248 and 48 data points with $R^2_{GFRP} = .92$ and $R^2_{GFRP/CFRP} = .91$, respectively (cf. Fig. 3). The mass of the rotor blades is divided into GFRP and CFRP and other materials.

$$f(r)_{GFRP} = .00063r^{2.5} = f(r)_{GFRP|GFRP} + \underbrace{f(r)_{GFRP|CFRP}}_{=0} + others(r) \tag{GFRP}$$

$$f(r)_{GFRP/CFRP} = .00070r^{2.4} = \underbrace{f(r)_{GFRP/CFRP|GFRP} + f(r)_{GFRP/CFRP|CFRP} + others(r)}_{f(r)_{GFRP}-\Delta(r)} \tag{GFRP/CFRP}$$

The following sections describe the calculation of the amount of GFRP and CFRP mass in dependence of the construction method.

A.1 GFRP rotor blade

The amount of GFRP within a GFRP rotor blade is calculated as its total weight excluding other materials (equation GFRP 1). The CFRP mass is zero (equation GFRP 2).

$$f(r)_{GFRP|GFRP} = f(r)_{GFRP} - \underbrace{others(r)}_{=metal(r)+core(r)+adhesive(r)+painting(r)} \tag{GFRP 1}$$

$$f(r)_{GFRP|CFRP} = 0 \tag{GFRP 2}$$

For the remaining materials $others(r)$, we derived regression functions based on datasets:

$$metal(r) = .0007r^{3.38} \tag{metal}$$

$$metal\left(r\right) = .0023r^{3.25} \tag{core}$$

$$metal\left(r\right) = .0713r^{2.12} \tag{adhesive}$$

$$metal\left(r\right) = .0168r^{2.51} \tag{painting}$$

A.2 GFRP/CFRP rotor blade

For GFRP/CFRP rotor blades, the weight reduction $\Delta\left(r\right)$ compared to a GFRP rotor blade due to replacing the GFRP based interior parts with CFRP based interior parts resembles the amount of GFRP removed $m^{out}_{GFRP}\left(r\right)$ less the amount of CFRP inserted $m^{in}_{CFRP}\left(r\right)$ (equation GFRP/CFRP 1).

$$\Delta\left(r\right) = m^{out}_{GFRP}\left(r\right) - m^{in}_{CFRP}\left(r\right) \tag{GFRP/CFRP 1}$$

In addition, Jamieson and Hassan (2011) state that an equally shaped interior part constructed from CFRP instead of GFRP is 3 to 8.5 times less heavy, depending on the amount and type of carbon fibers used (equations GFRP/CFRP 2). Parameter α states the weight factor, which varies between manufacturers, depending on the amount of CFRP and the installed wind turbine type.

$$m^{out}_{GFRP}\left(r\right) = \alpha m^{in}_{CFRP}\left(r\right) \qquad \forall \alpha \in [3.0, 8.5] \tag{GFRP/CFRP 2}$$

The material specific masses of a *GFRP/CFRP* rotor blade can be calculated based on $\Delta(r) = f(r)_{GFRP} - f(r)_{GFRP/CFRP}$, equations GFRP/CFRP 1 and GFRP/CFRP 2 resulting in equations (GFRP/CFRP 3 and 4).

$$f\left(r\right)_{GFRP/CFRP|GFRP} = f\left(r\right)_{GFRP} - m^{out}_{GFRP}\left(r\right) - others\left(r\right) \tag{GFRP/CFRP 3}$$

$$f\left(r\right)_{GFRP/CFRP|CFRP} = m^{in}_{CFRP}\left(r\right) \tag{GFRP/CFRP 4}$$

Appendix B. Mass ratios for case *c) Liu's* and case *d) Albers'*

Considering Liu‘s and Albers’ case, the material specific mass calculation for each wind park p (e_{pa}) bases on the total installed power production capacity at a wind park p (c_p) (cf. equations MaterialSpecific). As mentioned in Section 3.2.2, at first the total blade waste (tw_p) is calculated following the approaches developed by Liu and Barlow (2017) and Albers et al. (2009). The authors calculate the total blade waste by multiplying the total power production capacity at wind park p (c_p) with a factor, that states the expected tonnage of waste per installed power (μ_p in [tons/MW]). Herein, the publications differ: Liu and Barlow (2017) consider five different power production capacity classes of wind turbines: $(0, 1.0)$, $[1.0, 1.5)$, $[1.5, 2.0)$, $[2.0, 5.0)$ and $[5.0, \infty)$ [MW]. For each power production class c ($c \in \mathcal{C}_{Liu}$) the authors determine a power production class specific tonnage per power (μ_c). In contrast, Albers et al. (2009) only consider one average power production class $\varnothing$ ($\varnothing \in \mathcal{C}_{Albers}$) with a specific tonnage per power ($\mu_\varnothing$) (cf. Table 3). Applying these two approaches on wind parks p in dataset1, the approach of Liu and Barlow (2017) can be used if in addition to the total power production capacity (c_p) also the number of wind turbines (n_p) at a specific wind park p is known. Hence, an average power production capacity per wind turbine can be calculated by c_p/n_p and the wind park p specific waste tonnage per power μ_p can be chosen accordingly. If the number of wind parks is not known, μ_p is equal to $\mu_\varnothing$ following the approach of Albers et al. (2009).

$$e_{pa} = \underbrace{\mu_p c_p}_{tw_p} \gamma_{pa} \qquad \forall p \in \mathcal{P}, a \in \mathcal{A} \quad \text{(MaterialSpecific)}$$

However, regardless of the approach used to determine the total blade waste (tw_p), the authors do not define material specific mass ratios that allow to determine material specific tonnages per installed power. Within the following, material specific weight ratios per power production capacity class c $c \in \mathcal{C}_{Liu} \cup \mathcal{C}_{Albers}$ of Liu and Barlow (2017) and Albers et al. (2009) are determined (γ_{ca}) using the material specific functions in equations GFRP/CFRP 1 and GFRP/CFRP 2 as well as GFRP/CFRP 3 and GFRP/CFRP 4 from Appendix A. Subsequently, the determined material specific weight ratios (γ_{ca}) can be used for each wind park p depending on the information available, hence (γ_{pa}) is chosen in accordance to case *c) Liu's* or case *d) Albers'*.

B.1 Case *c) Liu's*

At first, a set of representative number of rotor blades' length ($\mathcal{L}_c$) is assigned using the extensive dataset2 of wind turbine types with known power production capacity and rotor blades length for each power production capacity class c ($c \in \mathcal{C}_{Liu}$) (cf. Table 3).

Second, the material specific weight ratio is determined for a *GFRP* and *GFRP/CFRP* rotor blade for each of the rotor blades lengths r that are assigned to the power production class c ($r \in \mathcal{L}_c$). Equations Liu 1 show the calculation for $\gamma_{cr}^{GFRP/CFRP|GFRP}$, i.e. the GFRP specific weight ratio for a *GFRP/CFRP* rotor blade, exemplarily. The GFRP and CFRP specific weight ratios for a *GFRP* and *GFRP/CFRP* rotor blade are calculated accordingly.

$$\gamma_{cr}^{GFRP/CFRP|GFRP} = \frac{f\left(r\right)_{GFRP/CFRP|GFRP}}{f\left(r\right)_{GFRP/CFRP}} \qquad \forall c \in \mathcal{C}_{Liu}, r \in \mathcal{L}_c \quad \text{(Liu 1)}$$

Subsequently, the share of *GFRP* and *GFRP/CFRP* rotor blades within a power production capacity class must be included. For example wind turbines with a power production capacity of merely 1 [MW] were mostly installed before 2001 and are configured with short *GFRP* rotor blades, while wind turbines with a power production capacity of more than 5 [MW] were mostly installed after 2010 and are configured with long *GFRP* or *GFRP/CFRP* rotor blades depending on the wind turbine. Parameter β_c describes the power production class specific ratio of total power of *GFRP/CFRP* rotor blades, determined from the extensive dataset1 and dataset2. Herein, for wind turbines with a power production capacity of less than 1.5 [MW] the ratio of *GFRP/CFRP* rotor blades is almost zero. This is congruent with Lefeuvre et al. (2019), i.e. $\beta_1 = \beta_2 = 0$. For wind turbines with a power production capacity of more than 1.5 [MW], the ratio is .36 in average, which is less than the .66 of Lefeuvre et al. (2019). However, their estimation bases on market shares of manufacturers on a global level, while our calculation is performed for EU-28. As most Chinese manufacturers use *GFRP/CFRP* rotor blades (Lefeuvre et al., 2019), the estimated ratio by Lefeuvre et al. (2019) is somehow biased and cannot be applied to the EU-28. Moreover, SiemensGamesa and Nordex that do not use *GFRP/CFRP* rotor blades are widely represented in Europe (Lefeuvre et al., 2019). Equations Liu 2 show the calculation.

$$\gamma_{cra} = \left(1 - \beta_c\right) \gamma_{cr}^{GFRP|a} + \beta_c \gamma_{cr}^{GFRP/CFRP|a} \qquad \forall a \in \mathcal{A}, c \in \mathcal{C}_{Liu}, r \in \mathcal{L}_c \quad \text{(Liu 2)}$$

By averaging ccra over the power production class specific integer rotor blade lengths ($\mathcal{L}_c$]), material specific weight ratios are determined for the five power production classes of Liu and Barlow (2017) (equations Liu 3). Results are shown in Table 3. The depicted ranges result due to maximum and minimum α-values (cf. equations GFRP/CFRP 2). Values were calculated for wind turbines installed before and after 2001, since the extensive dataset1 and dataset2 showed that the first *GFRP/CFRP* rotor blades were installed in

2001 (e.g. Vestas 2000–90, Vestas Nearshore 2000–80, Enercon 2000–66).

$$\gamma_{ca} = \frac{1}{|\mathcal{L}_c|} \sum_{r \in \mathcal{L}_c} \gamma_{cra} \qquad \forall a \in \mathcal{A}, c \in \mathcal{C}_{Liu} \quad \text{(Liu 3)}$$

B.2 Case *d) Albers'*

Material specific weight ratios for Albers' case are determined by calculating the average of the material specific weight ratios of the five power production classes of Liu and Barlow (2017) equations Albers 1). If a range was determined for any power production class of Liu and Barlow (2017), concerning γ_{ca} (cf. Table 3), the mean value is chosen. Results are shown in Table 3.

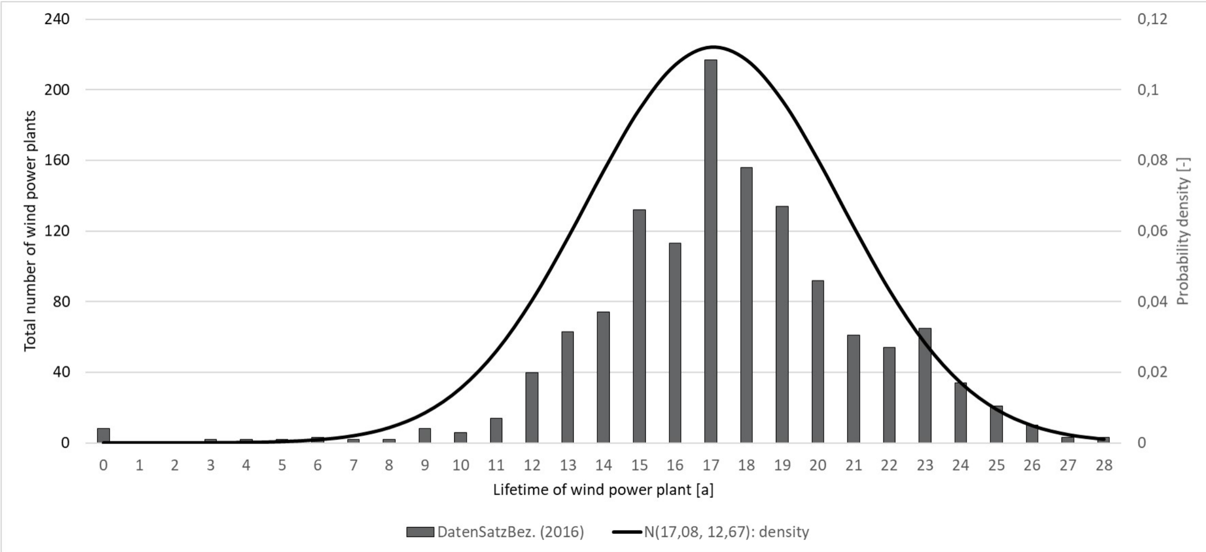
$$\gamma_{\varnothing a} = \frac{1}{|\mathcal{C}_{Liu}|} \sum_{c \in \mathcal{C}_{Liu}} \gamma_{ca} \qquad \forall a \in \mathcal{A} \quad \text{(Albers 1)}$$

Applying the values within the estimation approach concerning *Liu's* and *Albers'* case, a respective capacity class is chosen for each wind park p. If no information on the number of wind power plants within wind park p is given, $mu_{\varnothing}$ and $\gamma_{\varnothing a}$ are applied (*Albers'* case). Otherwise, one capacity class of Liu and Barlow (2017) and the respective μ_c and γ_{ca}-values or ranges are chosen in dependence of the quotient c_p/n_p (*Liu's* case).

Appendix C. Lifetime of rotor blades

Instead of assuming a deterministic lifetime of 20 [a] as most publications (cf. Table 1), Zimmermann et al. (2013) construct a Weibull function to represent the lifetime of rotor blades. Herein, they base their choice on the reason that Weibull functions are often used as a mathematical representation of lifetimes or machine failures (e.g. Abernethy et al., 1983; Dodson, 2006). Assuming an average lifetime of 20 [a], the authors derive the corresponding Weibull function. In contrast to Zimmermann et al. (2013), Lichtenegger et al. (2020) derive a logistic distribution function based on a large dataset of German and Danish demolished wind power plants. According to statistical tests on this large data set, the logistic distribution fits best. Compared to Zimmermann et al. (2013), the approach of Lichtenegger et al. (2020) seems to be more sophisticated, since the authors use actual data of rotor blade lifetimes to determine a function that represents the rotor blades' lifetime. However, the parameters of the logistic distribution function are not specified and can only be derived from the graphical representation of the e-component of the publication. Herein, the median α and standard deviation of the function seem to be 16˘18 and 3˘4 [a] respectively.

Figure 4: Density function of wind power plants and dataset3 visualization.



Dataset3 on German wind power plants with known dates of commissioning and demolition allows us to derive a stochastic distribution function (Bundesnetzagentur, 2019). Herein, 1.314 wind turbines with power production capacities of up to 5.0 [MW] show an average lifetime of 17.08 [a] with a standard deviation of 3.56 [a]. Fig. 4 shows the density function of $\mathcal{N}\,(17.08, 12.67)$ and the discrete distribution of the wind turbine lifetimes based on the dataset3. A Kolmogorov-Smirnov statistical test was executed to determine whether the lifetime distribution is normally distributed. According to the dataset3, the lifetime of a wind turbine is $\mathcal{N}\,(17.08, 12.67)$ distributed for a confidence interval of 98 [%]. These parameters seem to be in line with the estimations of Lichtenegger et al. (2020) as derived from their graphical presentation. It should also be noted that future policy regulations might have a huge influence on the results. If subsidies lead to lifetime extensions or reductions (e.g. through repowering), the distribution function must be adjusted.

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5. Recycling and Recovery Infrastructures for Glass and Carbon Fiber Reinforced Plastic Waste from Wind Energy Industry: A European Case Study.

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Abstract

Establishing recycling and recovery infrastructures for innovative materials like high-performance composites is very challenging. For such materials, recycling and recovery infrastructures are not yet established, research on end-of-life treatment technologies is still in the development state, and secondary markets for recycled materials are still missing. Against this background, we provide an ex-ante analysis on the design of future cost-minimal recycling and recovery for glass (GFRP) and carbon (CFRP) fiber reinforced plastic waste from rotor blades of wind power plants based on a mathematical optimization model. We present insights into future capacities and technologies for the recycling and recovery infrastructures within the EU-28. We systematically analyze the impacts of political regulations and of secondary markets on the design of these infrastructures. While future recycling of CFRP mainly depends on the development of secondary markets independent of political regulations, GFRP is mainly combusted in incineration plants or co-processed in cement clinker plants. Hence, political decision makers should focus on providing measures that support the development of secondary markets for recycled carbon fibers and provide incentives for co-processing of GFRP to overcome capacity limitations.

Keywords: Recycling and recovery infrastructures, Decision support, Rotor blades from wind turbines, Glass fiber reinforced plastics, Carbon fiber reinforced plastics

1. Introduction

The transformation of the current linear economy towards a circular economy is an essential requirement to counter the increasing global consumption of natural resources (European Parliament, 2020). In a circular economy, materials and constituents are recycled or recovered in order to substitute primary materials in production processes, thus preventing the exploitation of nonrenewable resources.

In the European Union (EU), waste management, i.e. the "*[...] collection, transport, recovery and disposal of waste, [...]*", is highlighted as a key measure to achieve a circular economy (European Commission, 2011b, 2010, 2015). In this context, recovery is defined as "*[..] any operation the principal result of which is waste serving a useful purpose by replacing other materials [...]*", while recycling is defined as "*[..] any recovery operation by which waste materials are reprocessed into products, materials or substances not includ(ing) energy recovery [...]*" (cf. European Parliament and Council of the European Union, 2008, art. 3 (15,17)). The EU defines a hierarchical order of waste management, i.e. preparation for re-use, recycling, other recovery (e.g. energy recovery) and disposal. Recycling and recovery of waste is promoted over disposal by setting recycling and recovery quotas for specified waste streams, e.g. end-of-life vehicles, batteries, plastics, construction and demolition waste (European Commission, 2018; European Parliament and Council of the European Union, 2006, 2000, 2003). As a future option, circularity quotas are currently discussed, i.e. quotas that require that material cycles are closed and prohibit downcycling or energy recovery. Consequently, circularity enforces closed production loops, increases resource efficiency and maximizes retention of the economic value (Morseletto, 2020).

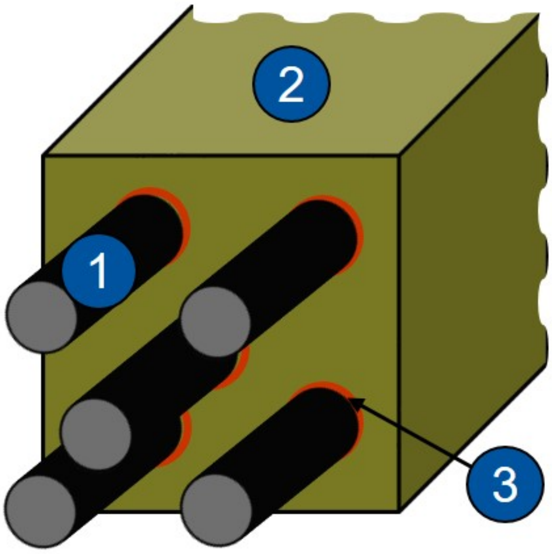
Fulfilling recycling and recovery or even circularity quotas is especially challenging for innovative products and technologies, like lithium-ion batteries or high performance composite materials. For these products, recycling and recovery infrastructures are not yet implemented. Moreover, research on end-of-life treatment technologies for these innovative products and their contained materials and substances is still limited. Also, secondary markets for recycled materials are often not yet established (Job et al.; Liu et al., 2019). These challenges are not easy to overcome as they also interact: with lack of markets for recycled materials there is no incentive to develop and install recycling infrastructures and vice versa. In such a challenging environment, political incentives such as subsidies on recycled materials, the funding of technology development or the stipulation of recycling quotas can steer the implementation of recycling infrastructures and avoid less preferred recovery or disposal pathways of the waste masses.

End-of-life rotor blades of wind turbines depict such a challenging waste stream for which the implementation of recycling and recovery infrastructures is still lacking for several reasons. First, recycling and recovery technologies for glass fiber reinforced plastics (GFRP) and carbon fiber reinforced plastics (CFRP), as the major construction materials of end-of-life rotor blades, are still at the research state. Also, secondary markets for the potential recycled materials do not yet exist, and future demand for these recycled materials is uncertain. However, recent publications that estimate future waste masses in the EU highlight the necessity to establish a recycling and recovery infrastructure as the waste masses will steadily increase in the upcoming years (Lefeuvre et al., 2019; Liu et al., 2019; Sommer et al., 2020). In line with this, the German Federal Environment Agency explicitly points to the need for an analysis of the total system costs of potential future recycling and recovery infrastructures for end-of-life rotor blades, particularly focusing on the challenging materials GFRP and CFRP (Zotz et al., 2019). This study highlights that the uncertain amount of future waste masses, the fragmented research in recycling and recovery technologies and the uncertain development of secondary markets may require legal policies to foster the development of recycling and recovery infrastructures.

Against this background, this paper aims at an ex-ante analysis of the design of optimal recycling and recovery infrastructures for GFRP and CFRP from rotor blades of wind power plants and resulting total system costs. We determine an optimal system design for aggregated waste streams, herein exploiting economies of scale and learning curves. To do so, we develop a material flow based mathematical optimization model to economically optimize the selection of recycling and recovery technologies and the regional distribution of treatment capacities. We apply this model on expected GFRP and CFRP waste masses in the EU-28, analyze cost-minimal recycling and recovery infrastructures, and carry out scenario analyses to test the impact of political regulations and the development of secondary markets on the selection of technologies and on the total system costs. Our results allow to derive insights for political decision makers to decide on further actions, e.g. implementation of circularity and recycling quotas, subsidies on recycled materials or focus research areas.

The remainder of this paper is structured as follows: in Section 2, we introduce the materials characteristics and the recycling and recovery options for GFRP and CFRP. We further derive research questions. In Section 3, we discuss our choice of methodology and present a generic mathematical optimization model to design cost-minimal recycling and recovery infrastructures for GFRP and CFRP. In Section 4, we then present the data, experimental study and results to answer the research questions. We further derive recommendations for political decision makers and discuss our results with the relevant literature on GFRP and CFRP recycling and recovery. In Section 5, we conclude our work.

Figure 1: Schematic fiber reinforced plastic composite (own representation).



2. Materials

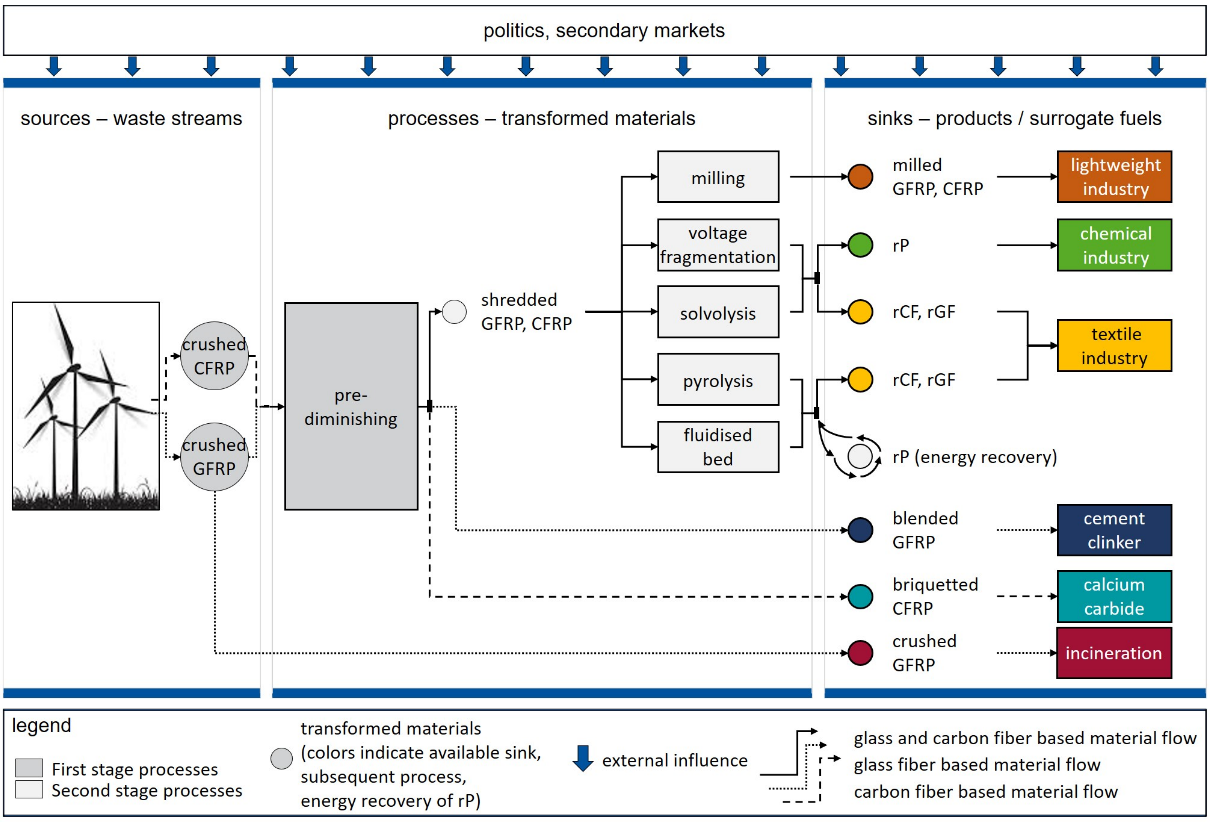
In Section 2.1, we introduce GFRP and CFRP as applied in the rotor blades of wind power plants, and provide insights into the challenges of the recycling and recovery of these waste streams. Afterwards, we introduce potential options for recycling (Section 2.2) and recovery (Section 2.3) of GFRP and CFRP based on recent literature. We then assess these recycling and recovery options in Section 2.4, and deduce research questions to be answered in this paper in Section 2.5.

2.1. GFRP and CFRP from rotor blades of wind power plants

Fig. 1 shows a schematic representation of a fiber reinforced plastic (FRP) composite, which consists of the fiber reinforcement (1), the polymer matrix (2) and the transition area between fiber reinforcement and polymer matrix (3).

Herein, the fiber reinforcement (1) that is applied in rotor blades of wind power plants can either be based on glass fibers GF) or carbon fibers (CF) depending on the component and the manufacturer's preference. The polymer matrix (2) is made of thermosetting epoxy-resin. The physical properties of the GF or CF reinforcement and the thermosetting epoxy-resin provide challenges for the recycling and recovery of end-of-life rotor blades of wind power plants (Ehrenstein, 2006; Liu and Barlow, 2017; Liu et al., 2019; Sommer et al., 2020). Even if the separation of the fiber reinforcement (1) and polymer matrix (2) is possible through thermo-chemical processes, the surface of the exposed fiber reinforcement (3) is often affected, hence the tensile strength of the recycled GF (rGF) and recycled CF (rCF) is lower than the tensile strength of virgin fibers (cf. Liu et al., 2019). As a result

Figure 2: Recycling and recovery options for GFRP and CFRP for rotor blades of wind power plants.



of these quality issues, secondary markets for recycled fibers are not yet developed. In line with this, research projects analyze other recovery options such as the combustion of GFRP and CFRP in industrial processes and incineration plants in case that recycling is not feasible or not economically viable. Herein, the material properties impact the choice of the final sink as high temperature and long dwelling times are required (cf. Holcim, 2019; Stockschläder et al., 2018, 2019; Walter, 2017).

Fig. 2 summarizes the recycling and recovery options for GFRP and CFRP of end-of-life rotor blades from wind power plants. As can be seen, the recycling and recovery starts with the disassembly of rotor blades where GFRP and CFRP based parts are separated by simple cutting processes. Afterwards, homogeneous GFRP and CFRP waste masses are separately crushed at nearby scrap yards (cf. Lange, 2018; Sommer et al., 2020). The two waste streams are pre-diminished and either recycled by additional technologies or combusted in incineration plants and co-processed in cement clinker and calcium carbide plants.

2.2. Recycling of GFRP and CFRP

Liu et al. (2019) present the state of the art end-of-life recycling options for rotor blades of wind power plants focusing on GFRP and CFRP. Herein, the authors introduce different technological approaches. For the sake of simplicity, we only highlight the main characteristics to distinguish the recycling technologies with regard to our analyses. For an extensive technological description the interested reader is referred to Liu et al. (2019) and the publications cited there.

Through **milling**, the polymer matrix and fiber reinforcement is not separated, but the macro molecular structure is changed such that the milled GFRP and milled CFRP can substitute the polymer matrix in the production of virgin FRP in industrial applications (cf. Li et al., 2016), which represents a downcycling.

High voltage fragmentation and **solvolysis** enable the recycling of the polymer matrix as well as of the fiber reinforcement separately. The recycled polymer matrix (rP) and the recycled fiber reinforcements (rGF, rCF) can potentially be utilized in the chemical and the textile industry. However, these technologies are still in a laboratory state (Selfrag AG, 2015; Vo Dong et al., 2018).

Pyrolysis and the **fluidized bed process** enable only the recycling of the fiber reinforcement (rGF, rCF), which could be potentially utilized in the chemical and the textile industry provided that secondary markets develop. The polymer matrix is not recycled, but is pyrolyzed with recovery of its energetic value.

All presented recycling technology are characterized by specific investments, cost structures, yield rates and output qualities. Herein, the yield rates describe the relation of the input material that is transformed into a certain output material quality. The output quality is measured based on the remaining tensile strength [in %] after the transformation process. As an example, we compare solvolysis and pyrolysis for a fiber reinforcement to polymer matrix ratio of .65 : .35. The technology specific yield rates and remaining tensile strengths are based on Liu et al. (2019) (see Table 1). Solvolysis allows for high quality recycling of 100 [%] of both components (fiber reinforcement and polymer matrix) without significant loss of tensile strength. Pyrolysis only allows for medium quality recycling of 70 [%] and low quality recycling of 30 [%] of the fiber reinforcement and energy recovery of the polymer matrix. Hence, solvolysis transforms 1 [ton] of GFRP into .65 [tons] high quality rGF and .35 [tons] rP. Thus, the yield rate is 100 [%]. The reduction in tensile strength is negligible. In comparison, pyrolysis transforms 1 [ton] of GFRP into .46 [tons] medium quality rGF and .19 [tons] low quality rGF. The .35 [tons] polymer matrix are recovered energetically based on the yield rate (70 [%]) and the reduction in tensile strength (48 [%]). Note that this provides additional information than Fig. 2, in which we present only the material transformation with regard to the highest quality, neglecting the low

Table 1: Technology specific characteristics.

Technology	Investments	Variable costs	Fixed costs	Capacity	Yield (GF/CF)	Quality	
						GF	CF
Pre-diminishing	250	100	15	15	95		
Milling	250	100	15	4	58	78	50
Voltage fragmentation	2.450	6.120	294	0.1	60	88	83
Pyrolysis	900	1.100	108	1	70	52	78
Fluidized bed	1.000	10.000	120	1	44 (rGF) 90 (rCF)	50	75
Solvolysis	6.400	1.500	768	1	100	58	95

qualitative rejects (1-yield rate). The lowest quality rGF are combusted in incineration plants. The lowest quality rCF are co-processed in the calcium carbide industry after briquetting with light packaging material (see next section).

2.3. Recovery of GFRP and CFRP

In addition to the recycling options, few other recovery options are available. Herein, waste streams can either be treated in the process industry, replacing other materials such as fossil fuels. However, the material specific properties of GFRP and CFRP impact the choice of the recovery options (cf. Lange, 2018; Nagle et al., 2020; Stockschläder et al., 2018; Walter, 2017). While GFRP can be co-processed in cement clinker industry, CFRP can be coprocessed in calcium carbide industry. However, blending with paper rejects (GFRP) and briquetting with light packaging materials CFRP) in a ratio of 1 : 1 is required due to the process structures in these industries (Lange, 2018; Stockschläder, 2019). These co-processing options partly account for recycling (downcycling) and partly for energy recovery (European Parliament and Council of the European Union, 2008, art. 3 (15, 17)).

In addition to the co-processing options, GFRP can also be combusted in (hazardous) incineration plants. However, plant operators accept only limited amounts of GFRP due to possible vitrification of the furnaces. The combustion of CFRP in (hazardous) incineration plants is impossible, since the carbon fibers are not destructed (Stockschläder et al., 2018, 2019).

2.4. Assessment and comparison of recycling and recovery options

Table 1 presents information on economic parameters and material yields for the technologies depicted in Fig. 2. Herein, the investments, operational and fixed costs are depicted in [ths.€/unit], [€/t] and [ths.€/unit], respectively. We assume 12 and 6 [%] for the advanced technologies and the simple mechanical treatment technologies of the investments as fixed costs. The capacity is depicted in [ths. tons/a]. We determined the

Table 2: Transformed material and sink specific costs.

Transformed material	Sink	Costs	Capacity	Recycling	Circularity
Milled CFRP (high)	Lightweight	+2.500	-	1	0
Milled CFRP	Calcium carbide	−100	8.000	1	0
Milled GFRP (high)	Lightweight	+250	-	1	0
Milled GFRP	Incineration	−100		0	0
rGF (high)	Textile	+250	-	1	1
rGF	Incineration	−100		0	0
rCF (high)	Textile	+8.000	-	1	1
rCF (medium)	Textile	+5.000		1	1
rCF	Calcium carbide	−100	8.000	1	0
rP	Chemical	+1.500	-	1	1
	Incineration	−100		0	0
Blended GFRP	Cement clinker	−100	60.000	Fiber part	0
Briquetted CFRP	Calcium carbide	−100	8.000	Fiber part	0
Crushed GFRP	Incineration	−100	-	0	0

capacities of pyrolysis, solvolysis and fluidized bed process according to (Geldermann, 2014): Investments (I_1) in capacity (K_1) can be anticipated by $I_1 = I_0 \left(K_0/K_1\right)^\beta$ with known investments I_0 and capacity K_0 of one capacity module. The known capacity module information was compiled from Selfrag AG (2015), Pickering et al. (2000) and Vo Dong et al. (2018). We assume a β of .67 for pyrolysis and the fluidized bed process, which is a typical value for chemical processes (Geldermann, 2014). Due to the early research state of solvolysis, we assume a β of .5. For solvolysis and the high voltage fragmentation we indicate the early research state by italic font.

Additionally, we present information on each transformed material in Table 2. Herein, the costs are provided in [*e*/t] and the values are estimated based on information given in Vo Dong et al. (2018). The future development of secondary markets is uncertain for most of the output materials (Liu et al., 2019). Therefore, future capacities are also uncertain and are subject to analysis in Section 4. However, capacities were provided by the plant operators in personal communication for the cement clinker and the calcium carbide industry in the EU-28. Here, only one cement clinker and calcium carbide plant accepts blended GFRP and briquetted CFRP. In Table 2, different material-sink combinations are listed to account for the specific treatment of high- and low quality materials. We also indicate in Table 2, whether a material-sink combination accounts for recycling with respect to the definition in European Parliament and Council of the European Union, 2008, art. 3 (15, 17) or even for requirements of circularity.

2.5. Research questions

The aim of this publication is to develop a decision support system to systematically design and evaluate optimal recycling and recovery infrastructures for GFRP and CFRP from end-of-life rotor blades of wind power plants. By scenario analyses of potential regulatory measures and development of secondary markets, we aim at deriving insights for political decision makers to decide on further actions, e.g. implementation of circularity and recycling quotas or subsidies on recycled materials. With this paper, we want to answer the following four research questions RQ):

1. RQ1: Which recycling and recovery options are optimal for the considered materials and where and when should capacities of which technology be installed when aiming at minimizing the total system costs for the recycling and recovery of GFRP and CFRP in the EU?

2. RQ2: What is the impact of potential recycling quotas on the choice of recycling and recovery options and on the total costs for the recycling and recovery of GFRP and CFRP waste from end-of-life rotor blades, i.e. what is the trade-off of recycling quotas and total system costs?

3. RQ3: What is the impact, if downcycling is no longer accepted by political decision makers and circularity of secondary materials is enforced to establish a circular economy, i.e., what is the trade-off of circularity quotas and total system costs?

4. RQ4: What is the impact of the uncertain market development for recycled fibers and milled FRP on the choice of recycling and recovery options and the total system costs?

In the following, we present the method that we applied to answer these questions.

3. Methodology for the design of recycling and recovery infrastructures

Mathematical optimization is frequently applied to design and analyze future recycling and recovery infrastructures. In the following, we give an overview on approaches developed for comparable planning problems (Section 3.1). Afterwards, we derive model requirements that have to be fulfilled in order to answer the research questions stated above (Section 3.2). Finally, we present a generic model for the design of recycling and recovery infrastructures in Section 3.3. The model is then applied to a specific regional data set in Section 4.

3.1. Optimization of recycling and recovery infrastructures

Research on the design of recycling and recovery infrastructures is extensive. In the last three decades researchers developed approaches for a variety of waste materials and regions based on the early works of Bloemhof-Ruwaard et al., 1996, Fleischmann et al., 1997, Kroon and Vrijens, 1995, Spengler et al., 1997 and Thierry et al., 1995. The interested reader is referred to the extensive reviews of de Brito et al., 2005, Govindan and Soleimani, 2017 and Govindan et al., 2015 for a detailed overview.

Govindan et al., 2015 review 265 articles that report research on activities related to recycling and recovery infrastructures. Of the 72 papers that focus on the design and planning of such infrastructures, 70 [%] use mathematical optimization as the method of choice. Herein, mathematical optimization is a prescriptive approach that allows for ex-ante analyses of the outcome of future infrastructure decisions, e.g. investment decisions and legal steering measures, while aiming at performance criteria such as the minimization of total system costs or the maximizing of the net present value. Mathematical optimization models represent real-world planning problems through three components: decision variables, constraints and one or more objective functions. The decision variables represent the planning decisions to be taken, i.e., the location, technologies and capacities of future recycling and recovery plants. However, the decisions that can be taken are restricted by a set of constraints, i.e., technological restrictions on capacities or legal restrictions on material flows and recycling quotas. The objective function represents the target that is achieved by the design of the recycling and recovery infrastructure, i.e., minimize total system costs or maximize net present value. By solving the optimization model, the value of all decision variables is determined such that the solution is optimal with regard to the objective function and feasible with regard to all real-world restrictions (Domschke et al., 2015; Fleischmann, 2000; Govindan et al., 2015).

A multitude of models were developed for the design of recycling and recovery infrastructures. While some papers present generic mathematical optimization models that can be applied to a variety of cases (Hasani et al., 2012; Salema et al., 2007; Zeballos et al., 2014), other approaches were developed and applied for specific cases. For instance, specific approaches were presented for the design of recycling and recovery infrastructures for returnable containers in the Netherlands (Kroon and Vrijens, 1995), for construction waste focusing on sand in the Netherlands (Barros et al., 1998), for carpets in the United States (Realff et al., 1999), for end-of-life batteries in Germany (Schultmann et al., 2003), for refrigerators in Western Europe (Krikke et al., 2003), for electrical and electronical waste (Quariguasi et al., 2010), and for perishable goods (Hasani et al., 2012). In all of these papers decisions were endogenously taken by the optimization model on the locations of recycling and recovery plants, on the technologies to be selected and on the capacities to be installed. Model extensions also integrate product design decisions (Krikke et al., 2003). Other approaches develop hybrid approaches (Schultmann et al., 2003) including also flow-sheeting process models in order to simulate potential recycling options.

Regarding the advantages of mathematical optimization that allows for a prescriptive design and analyses of future recycling and recovery infrastructures, we develop a mathematical optimization model to plan recycling and recovery infrastructures for GFRP and CFRP from end-of-life rotor blades of wind power plants in the following.

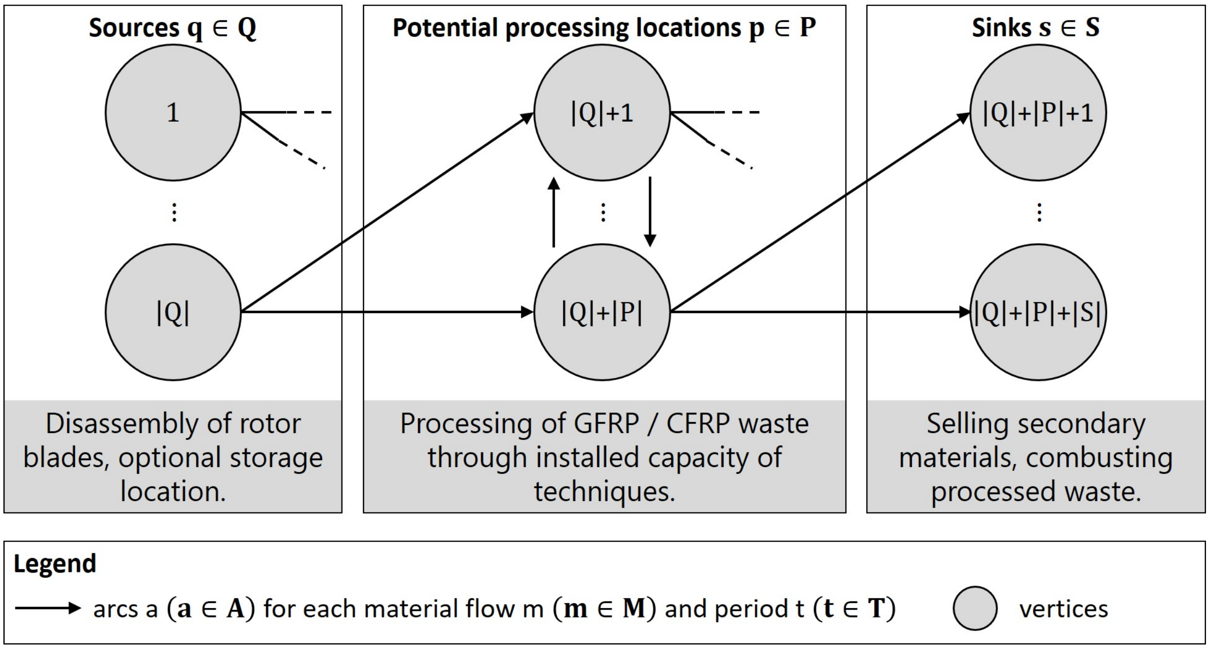
3.2. Model requirements

The aim of the mathematical model is to determine the cost minimal recycling and recovery infrastructures to treat end-of life GFRP and CFRP waste from rotor blades of wind power plants while satisfying technical and legal restrictions. In line with this, we want to formulate a material flow based mathematical model that decides on technologies, capacities, processing locations as well as material flows and transformations. To do so, we first have to derive the model requirements.

Several modeling requirements have to be fulfilled such that the mathematical model adequately represents the planning problem. A multi-period formulation is required as increasing GFRP and CFRP waste over time demand for a long-term analysis. A multi-product representation is required in order to account for the different input and output materials of the recycling and recovery processes. Moreover, a multi-echelon model formulation is necessary as most recycling and recovery options consist of a sequence of transformation processes. The model should also allow for temporary storage options at sources of the recycling and recovery infrastructure since temporary storage is permitted by European law (cf. European Parliament and Council of the European Union, 2008, art. 3 (10)) if waste is pending for further treatment. To take future technologies into account, different research states have to be considered as well. Also, capacity classes of technologies and scale effects have to be represented. Within the processing plants, capacity sharing must be modeled as most technologies can treat GFRP as well as CFRP waste masses. However, this requires that waste material specific bills of materials must be modeled, since the processing of GFRP is represented by different input materials, yields and output materials than the processing of CFRP, even if the same technology is applied. Regarding the output materials, limited capacities of secondary markets and final sinks as well as revenues and disposal costs of output materials have to be regarded, since transformed materials are either sold to industries, co-processed in industrial processes or combusted in incineration plants. Finally, circularity and recycling quotas must be accounted for in accordance with current and potential future European regulations (European Commission, 2011a).

Concluding, the strategic planning problem of designing recycling and recovery infrastructures for GFRP and CFRP waste from end-of-life rotor blades of wind power plants is a multi-echelon, multi-period, multi-product material flow based integrated technology and capacity selection problem. In the following section, we present the mathematical optimization model that represents this strategic planning problem.

Figure 3: Underlying graph of the optimization model.



3.3. Optimization model

In this section we formulate a mathematical optimization model for the design and analysis of recycling and recovery infrastructures for GFRP and CFRP. The model is developed for the GFRP and CFRP material flows regarding the requirements discussed in Section 3.2. However, the model is generic in the sense that it can be applied to different regions, extended by other technologies or applied to GFRP and CFRP material flows of other industries. The mathematical model is filled with the data of a specific application case in Section 4.

The complete optimization model with its constraints and objective as well as a summary of the notation can be found in the appendix. In the following, we present the underlying graph, parameters and decision variables of the model.

The directed graph G is defined by a quadruple ($G = (\mathcal{V}, \mathcal{A}, \mathcal{M}, \mathcal{T})$) (cf. Fig. 3). Sources q ($q \in \mathcal{Q}$), potential processing location for the installation of technologies p ($p \in \mathcal{P}$) as well as sinks s ($s \in \mathcal{S}$) represent set $\mathcal{V}$. Set $\mathcal{A}$ represents the union of all vertex specific outgoing $\delta\,(q/p/s)^{-}$ and incoming $\delta\,(q/p/s)^{+}$ arcs a ($a \in \mathcal{A}$) at the vertices. Sets $\mathcal{M}$ ($m \in \mathcal{M}$) and $\mathcal{T}$ ($t \in \mathcal{T}$) are mappings of $\mathcal{A}$ and represent different transportation flows considering the transported material m and time period t.

At sources, occurring material masses (N_{qmt}) can be stored in any time period or transported on arcs towards potential processing locations and subsequently towards sinks. Continuous decision variables l_{qmt} represent the masses of material m that is stored at source q in time period t regarding holding costs $c^{\mathcal{Q}}_{qm}$. Continuous decision variables x_{amt}

represent the masses of material m transported on arc a in time period t with transportation costs $c^{\mathcal{A}}_{am}$. The amount of material m that is transported towards sinks s of G can be sold, co-processed or incinerated for revenues or final treatment costs $c^{\mathcal{S}}_{sm}$. Following the European Commission's Decision (European Commission, 2011a), recycling and circularity quotas have to be measured at the final treatment step of the waste masses, hence at the sinks of the network. Herein, parameters α_{sm} define the share of material m being recycled, while β_{sm} represent the share of material m being circulated at sinks s. Parameters $S^{\max}_{smt}$ define the maximum capacity at sink s for material m in time period t. These can either represent restrictions for the processing of materials at sinks or limitations of potential secondary markets.

Capacity modules are installed at potential processing locations. Integer decision variables z_{prkt} represent the number of installed capacity modules of capacity class k $(k \in \mathcal{K}_r)$ of technology r $(r \in \mathcal{R})$ at a potential processing location p in time period t. Herein, parameters $K^{\max}_{rk}$ define the specific production capacity for each capacity module of capacity class k and technology r installed. Investments $\left(c^{K,invest}_{rk}\right)$ as well as variable $\left(c^{K,var}_{rk}\right)$ and fixed $\left(c^{K,fix}_{rk}\right)$ costs are regarded with respect to each capacity module of capacity class k and technology r. Parameters t^*_r represent the earliest time period in which a technology r is fully developed and available for installation. Two bills of materials b $(b \in \mathcal{B}_{rk})$ are modeled for each technology r and capacity module of capacity class k describing the possible transformation processes for GFRP and CFRP. Each bill of materials b is represented by a vector of transformation coefficients for each material m $(m \in \mathcal{M})$, with input materials having negative and output materials having positive signs, i.e. each bill of material is a vector of length $|\mathcal{M}|$. Parameters γ_{bmrk} depict the material specific transformation coefficients of material m in bill of materials b, capacity class k and technology r. Continuous decision variables λ_{bprkt} represent the amount of capacity that is utilized at potential processing locations p with regard to technology r and capacity module of capacity class k for the transformation process with regard to bill of material b in time period t.

In summary, the recycling and recovery infrastructures are designed by the installation of treatment capacities at potential processing locations. Such installation is steered by upcoming waste masses that must be treated and by potential political regulations as well as influenced by sink specific capacities. The material flows and transformation activities are decided accordingly. So far, the model is generic in that no specific region, technologies or time horizon is specified.

In the next section, we first introduce the specific data set of our case study, and present results of our planning approach and scenario analyses to gain managerial insights.

4. Results and discussion – Design of GFRP/CFRP recycling and recovery infrastructures in the EU-28

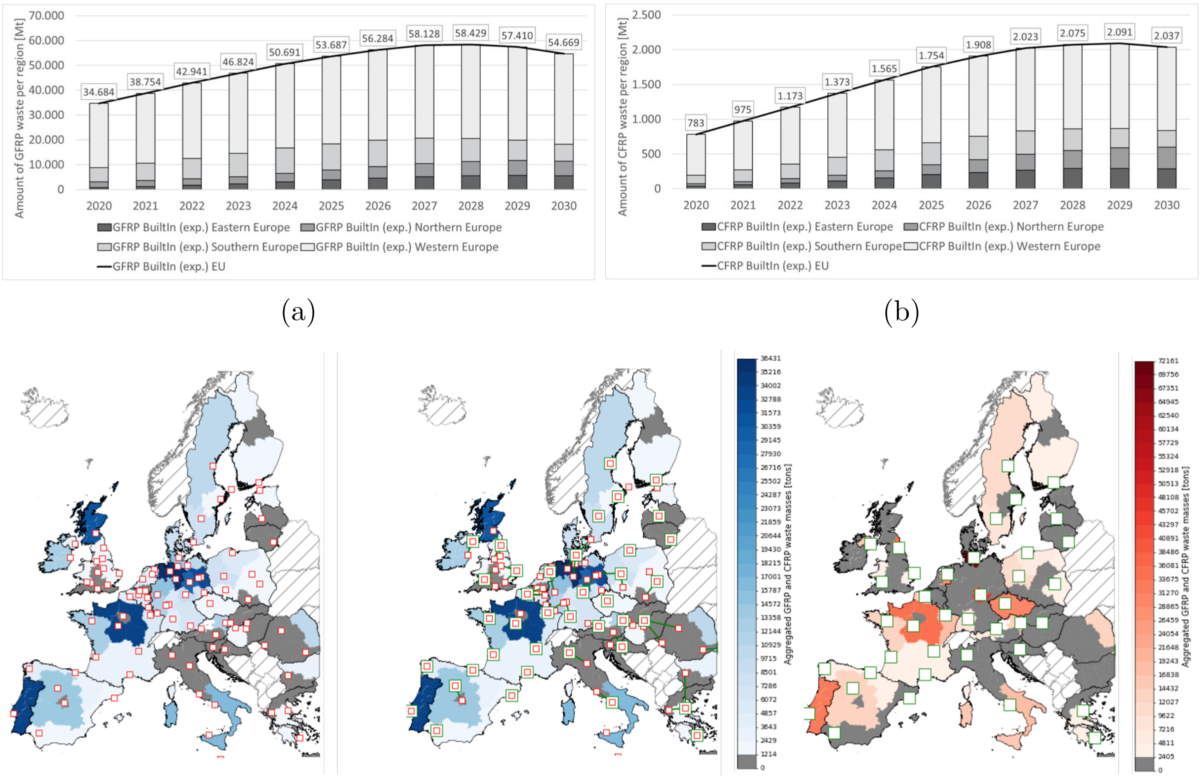
In the following, we apply the mathematical optimization model to a specific real-world data set of GFRP and CFRP waste of end-of-life rotor blades from wind power plants. We first introduce the data in Section 4.1. To answer the research questions, we present the results for a number of scenario analyses in Section 4.2. Insights from the analyses are highlighted in Section 4.3. We further place our results into the context of relevant literature on the recycling and recovery of GFRP and CFRP waste in Section 4.4.

4.1. Data and assumptions

We focus on the EU-28 as a system with a cohesive regulatory framework. To achieve a circular economy, harmonized legal environmental regulations are needed and economic advantages must be exploited, i.e., allowing for economies of scale of advanced recycling technologies with high investment and fixed costs by aggregating waste streams. Moreover, secondary markets for recycled materials demand for aggregated quantities of materials in order to be competitive against globalized primary materials that are available in high amounts. Therefore, we analyze optimal European-wide recycling and recovery infrastructures, i.e., we determine the optimal design of recycling and recovery infrastructures to derive recommendations for political decision makers on future (harmonized) regulations and to draw conclusions on the impact of legal regulations on total system costs as well as on the advantage of secondary market development.

We regard for annual GFRP and CFRP waste of 60.000 operating wind power plants in the EU-28 using the data set of (Sommer et al., 2020). Based on the approach of (Sommer et al., 2020), we forecast the future GFRP and CFRP waste streams in the EU-28 from 2020 to 2030. The forecasting horizon equals the planning horizon of this case study, i.e. $\mathcal{T} = \{2020, ..., 2030\}$. Fig. 4(a) and (b) shows the increase of GFRP and CFRP waste masses over time. The decrease at the end of the planning horizon is subject to limited data availability (cf. Sommer et al., 2020). We further aggregate GFRP and CFRP waste streams to 40 locations within the EU-28, which we depict in Fig. 4(e): We first aggregate the waste masses at Nuts-1 level in dependence of the wind power plant's geographic location. Herein, the capital of each Nuts-1 level serves as a reference location where the nearby waste masses are aggregated. Fig. 4(c) shows the distribution of waste masses and the Nuts-1 specific reference locations within the EU. From the set of Nuts-1 level capitals, we chose 40 locations as final reference locations on which the nearby waste masses are allocated to. Fig. 4(d) shows the allocation of waste masses to the final reference locations, and Fig. 4(e) shows the final graph with the adjusted

Figure 4: Calculation of waste masses based on Sommer et al., 2020 and further aggregation.



(a) (b)

(c) (d) (e)

waste mass heat map. The final reference locations represent sources ($\mathcal{Q} = \{1, ..., 40\}$) at which annual GFRP and CFRP waste masses occur. Since separation, cutting and first crushing processes take place at the construction sites of wind power plants and nearby scrap yards (cf. Sommer et al., 2020), we assume that homogeneous and crushed GFRP and CFRP are further transported to processing plants. Each of the final reference locations represents a potential processing location ($\mathcal{P} = \{41, ..., 80\}$) at which the treatment technologies can be installed (cf. Table 1). As the high voltage fragmentation is dominated by the solvolysis technology (see Table 1), we abstain from modeling this technology. While we assume that investments, operational and fixed costs of mechanical treatment technologies develop in a linear manner in relation to the installed capacity, we assume that economies of scale exist for the advanced processing technologies pyrolysis, fluidized bed process and solvolysis. For these technologies, we consider two capacity classes to account for scale effects. Besides the capacity class that is depicted in Table 1, we assume a second capacity class with an annual processing capacity of 2.000 [t/a]. We generated the corresponding investments and costs as described in Section 2, i.e. applying $I_1 = I_0\,(K_0/K_1)^{\beta}$ (Geldermann, 2014). Moreover, we assume that solvolysis will be available from 2023 on.

For each technology and capacity class, we determine two bills of materials to account for the independent treatment of GFRP and CFRP while sharing the installed capacity. Herein, we consider the different yield rates and assume the ratio of the polymer matrix and the fiber share to be .35 : .65 (in accordance with (Lefeuvre et al., 2019)). We consider secondary markets for rGF, rCF, rP and milled GFRP/CFRP in the textile, chemical and lightweight industry, as well as co-processing in cement clinker, calcium carbide and incineration plants. The annual capacity of the cement clinker and calcium carbide plants accepting blended GFRP and briquetted CFRP is restricted to 60.000 and 8.000 [tons/a], respectively, i.e. co-processing of GFRP and CFRP is limited (expert interviews). The blending and briquetting ratio of 1 : 1 the annual treatment capacity of GFRP and CFRP leads to even lower amounts of 30.000 and 4.000 [tons/a], respectively, that are accepted for co-processing. Since incineration plants are widely available, we assume that the corresponding capacity is not restricted. Since the development of markets for secondary materials is uncertain (Ginder and Ozcan, 2019; Liu et al., 2019), we consider the secondary material demand through scenario analyses.

We assume that incineration plants are available within the close neighborhood of each location and thus neglect transportation for this treatment option. In contrast, we explicitly consider the transportation towards cement clinker and calcium carbide plants with an average transportation costs factor of .14 [e/t*km] for heavy duty vehicles in the EU (European Commission, 2006) as only very few companies accept GFRP and CFRP materials and thus transportation distances might be high. Since the locations of customers for rGF, rCF, rP and milled GFRP/CFRP are unknown, we consider average transportation costs of 28 [e/t], herein assuming an average distance of 200 [km]. Transportation processes between waste sources and processing sites are explicitly considered based on the average transportation costs factor stated above, the distance and the transported masses.

The revenues and acceptance costs for each material and corresponding sink are depicted in Table 2. Since rotor blades can be stored without infrastructure investments, the annual inventory holding costs are assumed to be negligible. Interest rates are set to be 5 [%/a].

4.2. Experimental design and results

With regard to the four research questions, we analyze the impacts of potential regulations and the uncertain development of secondary markets. We define a reference scenario that represents the current political situation, hence no recycling quotas (0 [%]) and a conservative assumption on the secondary market development, hence lack of secondary markets (NoM). We denominate the reference scenario NoM-0. We further define a SecM-

Table 3: Scenario denomination within the analyses.

	No target	Recycling target						Circularity target					
		15	30	45	60	75	95	15	30	45	*60*	75	95
NoM	-0	-15r	-30r	-45r	-60r	-75r	-95r	Not feasible					
SecM	-0	-15r	-30r	-45r	-60r	-75r	-95r	-15c	-30c	-45c	-60c	-75c	-95c

0 scenario that explicitly considers secondary markets for recycled fibers and milled FRP (SecM) and also represents the current political situation (0 [%]). We adjust the NoM-0 and SecM-0 scenarios by annual recycling (15r,..., 95r) and circularity (15c,..., 95c) quotas that must be satisfied from 2025 on. As circularity quotas can only be fulfilled if secondary markets exist, we do not analyze NoM-15c, ..., NoM-95c as these optimization runs are infeasible. The scenarios are denominated as displayed in Table 3. The referred figures are displayed in the supplementary e-component.

In Section 4.2.1, we describe the results of the NoM scenarios (NoM-0, ..., NoM-95r). In Section 4.2.2, we describe the results of the SecM scenarios (SecM-0, ..., SecM-95c). Herein, each scenario is defined by a recycling and recovery infrastructure. We display the choice of recycling and recovery options for GFRP and CFRP, the installation of recycling and recovery capacities within the EU-28 and the total system costs divided into the costs factors described by Eqs. 15–17 of the mathematical model (as found in the Appendix).

4.2.1. No secondary markets

First, we analyze the results of the reference scenario (NoM-0). Fig. 5a) shows the choice of recycling and recovery options and indicates the installed treatment capacities. Fig. 5b) shows the spatial installation of treatment capacities within the EU-28. Fig. 5c) shows the distribution of costs with regard to investments, net flow costs and process costs. It can be seen that GFRP is incinerated, whereas CFRP is co-processed in the calcium carbide industry. As a result, pre-diminishing capacities are installed in central Europe to an extent that allows for the transformation of CFRP into briquetted CFRP that are further transported towards the calcium carbide plant located in Southern Germany. The net flow costs, which consist of transportation costs for briquetted GFRP as well as acceptance fees at incineration plants (GFRP) and at the calcium carbide plant (briquetted CFRP) are the main contributors to the negative net present value. Investments and process costs are comparably low.

We adjust the reference scenario by implementing annual recycling quotas to be fulfilled from 2025 on. Herein, we allow for a storage of waste masses until the end of 2024. Fig. 6 summarizes the results of the scenarios NoM-0, ..., NoM-95r with regard to the cost distribution. It can be seen that the net present value decreases linearly for recycling quotas up to 30 [%], and disproportionately for recycling quotas up to 45 [%]. As can be seen, the net flow costs and especially the investments increase strongly if recycling quotas of more than 30 [%] have to be fulfilled. The strong increase in investments and process costs results from the installation of advanced recycling technologies. Recycling quotas higher than 45 [%] leads to infeasibility, i.e., these recycling quotas cannot be achieved as secondary markets are missing. Figs. 7 and 8 show the choice of recycling and recovery options and capacity distribution within the EU-28 for NoM-30r, NoM-45r. Concerning NoM-30r, the results are similar to NoM-0 with the exception that GFRP is now partly co-processed instead of being incinerated. The impact on the capacity distribution and on the net present value is small. Regarding the NoM-45r scenario, the high recycling quotas can only be achieved if some of the waste masses are chemically recycled by solvolysis, since the annual co-processing capacity of GFRP in the cement clinker plant is already fully depleted. While rP can be sold to sales markets, the recycled fibers have to be incinerated as secondary fiber markets are missing. CFRP is also recycled by solvolysis exploiting the unused capacity of the installed plants. High investments in solvolysis capacities are required.

4.2.2. Development of secondary markets

First, we analyze the results of the secondary market scenario with the current political situation (SecM-0), i.e. no recycling quotas. Fig. 9 shows the results of SecM-0 with regard to the cost distribution. As can be seen, the net flow costs are now positive, but the overall net present value remains negative. CFRP is chemically recycled through solvolysis, and rCF as well as rP masses are sold to secondary markets (Fig. 10, top left). In line with this, solvolysis capacity is installed in central Europe (Fig. 11, top left). GFRP waste masses are incinerated as in the NoM-0 scenario, indicating that the existence of secondary markets does not affect the choice of recycling and recovery options for GFRP.

We adjust the SecM-0 scenario by implementing annual recycling quotas to be met from 2025 on. Again, we allow for a storage of waste masses until the end of 2024. Fig. 9 summarizes the results of the scenarios SecM-15r, ..., SecM-95r with regard to the cost distribution. It can be seen that the net present value decreases almost linearly up to recycling quotas of 45 [%] and decreases disproportionately if recycling quotas of 60 [%] and higher are required. In the following, we describe the recycling and recovery infrastructures of SecM-45r, SecM-60r, SecM-95r to present the impacts of increasing recycling quotas (see Figs. 10 and 11). For a recycling quota of 45 [%] (SecM-45r), large parts of GFRP are milled and sold to the lightweight industry in order to satisfy the recycling quota. The remaining GFRP waste is incinerated. CFRP is treated as in the

SecM-0 scenario. With regard to the capacity distribution, additional pre-diminishing and milling technologies are installed throughout Europe to treat the GFRP waste masses (cf. Fig. 11, bottom left). For a recycling quota of 60 [%] (SecM-60r), the recycling quota can no longer be met by milling GFRP, since the overall yield of the milling technology is 55 [%] (cf. Table 1). Few GFRP waste masses are co-processed in the cement clinker industry. CFRP is treated as in SecM-0. For a recycling quota of 95 [%] (SecM-95r), recycling of GFRP through solvolysis becomes necessary due to the high yield rates. CFRP is treated as in the SecM-0 scenario.

Additionally, we analyze the impact of potential circularity quotas. Fig. 12 shows the results of SecM-15c, ..., SecM-95c with regard to the cost distribution. It can be seen that circularity instead of recycling quotas result in lower net present values that develop linearly with the quotas. In accordance with Table 2, GFRP waste can no longer be co-processed or milled, but is now chemically recycled by solvolysis. Herein, the increasing quotas determine the decreasing net present value. Since we assumed fix transportation costs to customers, the net present value develops linearly. CFRP is treated as in the SecM-0 scenario.

4.3. Managerial insights

Based on the previous analyses, we find answers to the research questions derived in Section 2.5.

Regarding the recycling and recovery of GFRP, incineration is the most preferred recovery option from an economic perception (RQ1). If political regulations steer recycling of GFRP, coprocessing is preferred if secondary markets for milled GFRP are missing (RQ2, RQ4). However, if secondary markets exist, the GFRP waste is milled and further sold to sales markets (RQ4). If circularity instead of recycling quotas must be satisfied, GFRP waste is recycled by solvolysis at low revenues but high process costs and investments (RQ3).

Regarding the recycling and recovery of CFRP, co-processing of CFRP in the calcium carbide industry is the preferred option if secondary markets for rCF do not exist (RQ1, RQ4). In contrast, CFRP waste is chemically recycled through solvolysis if secondary markets for rCF exist (RQ4). Herein, the high quality and high yields of the solvolysis technology is decisive for the choice of recycling and recovery option, even if no recycling or circularity target must be satisfied (RQ2, RQ3).

The price of potential political regulations, i.e., the requirement of recycling and circularity quotas, and the economic potential of secondary markets can be derived from the figures in the supplementary e-component. Analyzing these results allows to derive the economic value of potential subsidies on secondary materials.

4.4. Discussion and implications in the research context

In the following, we place our results in the literature, discuss consensus and highlight the contributions of our research.

So far, literature is often merely regarding technical characteristics and is often focusing on a separate evaluation of selected recycling options. While literature on the feasibility and characteristics of selected technologies is more frequent (e.g. Pickering et al., 2000; Piñero-Hernanz et al., 2008; Stockschläder et al., 2019; Stockschläder, 2019; Walter, 2017), literature on the comparison of different recycling and recovery options is still scarce and there are only selected publications that state preferred recycling and recovery options for GFRP and CFRP (Liu et al., 2019; Oliveux et al., 2015). Our paper provides valuable information in this context as it presents an integrated analysis particularly focusing on the development of secondary markets and regulatory requirements.

We highlighted co-processing of GFRP in the cement clinker industry as the preferred recovery option as long as legal requirements on recycling quotas are non-existent or small. With regard to CFRP, the potential high value of the recycled material can support the installation of advanced recycling technologies if markets for recycled materials develop. These findings are conform with the findings of Oliveux et al., 2015 who review the status of recycling and recovery of GFRP and CFRP focusing on the technological feasibility as well as on the economic viability. The authors state that all studies focusing on GFRP recycling lead to the conclusion that co-processing in cement kilns is the most preferred treatment, since the treatment costs of recycling GFRP is too high and the quality of the recycled GFs is too low, i.e., no process can provide rGF with the same characteristics as GFs at a competitive price. This is also confirmed by other studies that state that chemical recycling of GFRP is unlikely due to high recycling costs in comparison to low primary production costs as well as low quality of recycled (Ginder and Ozcan, 2019; Liu et al., 2019; Pickering et al., 2000; Rouholamin et al., 2014). Our results concerning the treatment of GFRP support these statements.

Concerning the treatment of CFRP, Oliveux et al., 2015 state that solvolysis and pyrolysis appear to be more applicable due to the higher value of the recycled material. Thus, the recycling of CFRP is expected to be economically efficient due to the high value of CFs, the high costs within its primary production and the stronger resistance to thermo-chemical recycling processes. However, this requires little loss of tensile strength and recycled fibers of a certain length (cf. Job et al.) as well as the development of secondary markets to exploit these benefits. We find supporting evidence for these statements in our analysis. Also, our analysis is in line with Liu et al., 2019 that state that besides technological issues, successful composite recycling requires political incentives, infrastructures and market commitment, i.e. the design of a recycling and recovery infrastructures depends not only on technological availability but also on the development of secondary markets and political incentives.

However, our research not only supports the common opinions, but contributes to existing literature. By applying real-world data in a regional context, in particular future GFRP and CFRP waste masses in the EU-28, we are able to derive insights into future requirements of recycling and recovery capacities. We show that capacities for the co-processing of GFRP in the cement clinker plants are insufficient. Also, our analysis allows for a quantification of the total end-of-life treatment costs for GFRP and quantifies the value of secondary markets for CFRP. Based on our research, political decision makers could decide on incentivize the cement industry to increase the acceptance of GFRP waste, on promoting research to overcome technological challenges as well as to foster secondary market development. This research thus provides insights with high value to political decision makers.

5. Conclusion

Within this publication, we analyze the recycling and recovery of GFRP and CFRP waste from rotor blades of wind power plants. We developed a decision support system based on a mathematical optimization model to systematically analyze the future design of recycling and recovery infrastructures for GFRP and CFRP waste from 60.000 wind turbines within the EU-28. We considered the recycling and recovery options for both waste streams and analyzed the impacts of secondary market development and potential political regulations on the choice of technologies and the installation of treatment capacities. Based on the EU-28 case study, we draw managerial insights on the recycling and recovery of GFRP and CFRP from rotor blades of wind power plants. We further compare our results to the common opinion in the relevant literature and highlight additional insights that result from our study. We show that our results are in line with the common opinion on the recycling and recovery of GFRP and CFRP.

Moreover, our studies contribute to the existing literature in that it allows to **determine the minimum total system costs** for recycling and recovery infrastructures for a given region, that it supports decisions on the integrated **selection of optimal treatment options** for GFRP and CFRP **in dependence on potential political regulations and secondary market development**. Additionally, our approach enables the derivation and quantification of potential political measures and incentives.

In the future, this work could be extended regarding several aspects: A common consideration of GFRP and CFRP waste from other industries would allow to exploit fully intra-industrial potentials. Robust planning approaches could be promising to account for uncertain planning parameters, like the upcoming waste masses (see Sommer et al., 2020), the bills of materials (see Liu et al., 2019) or the technology development. Moreover, current European regulations show a trend towards a sustainable material management (European Parliament and Council of the European Union, 2018). Thus, the developed mathematical optimization model could be extended to adequately consider uncertain parameters and to explicitly consider ecological and/or social criteria.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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A. Appendix: Mathematical Model

Table 4 in the supplementary e-component (Appendix B) states the complete notation of the mathematical model.

A.1. Constraints

Constraints (1) enforce that occurring masses of material m at sources q in time period t (N_{qmt}) are stored ($l_{qm,t-1} - l_{qmt}$) or transported towards (final) treatment $\left(\sum_{a\in\delta(q)^-} x_{amt}\right)$ in dependence of the waste management option (cf. figure 2).

$$N_{qmt} + l_{qm,t-1} - l_{qmt} = \sum_{a\in\delta(q)^-} x_{amt} \qquad \forall q \in \mathcal{Q}, m \in \mathcal{M}, t \in \mathcal{T} \quad (1)$$

Constraints (2) enforce that no material m is stored at any source q at the end of the planning horizon ($\max(\mathcal{T})$).

$$l_{qm,\max(\mathcal{T})} = 0 \qquad \forall q \in \mathcal{Q}, m \in \mathcal{M} \quad (2)$$

Constraints (3) depict the mass balance for each material m and time period t at each potential processing location p. By multiplying the bill of material b and the amount of capacity utilized $\left(\sum_{r\in\mathcal{R}} \sum_{k\in\mathcal{K}_r} \sum_{b\in\mathcal{B}_{rk}} \lambda_{bprkt}\gamma_{bmrk}\right)$ with respect to the capacity module of capacity class k of technology r in time period t at potential processing location p, the incoming $\left(\sum_{a\in\delta(p)^+} x_{amt}\right)$ and outgoing $\left(\sum_{a\in\delta(p)^-} x_{amt}\right)$ masses of m at potential processing location p in time period t are defined (in accordance to Spengler et al. (1997); Dyckhoff and Spengler (2007)).

$$\sum_{a\in\delta(p)^-} x_{amt} = \sum_{a\in\delta(p)^+} x_{amt} + \sum_{r\in\mathcal{R}} \sum_{k\in\mathcal{K}_r} \sum_{b\in\mathcal{B}_{rk}} \lambda_{bprkt}\gamma_{bmrk} \qquad \forall p \in \mathcal{P}, m \in \mathcal{M}, t \in \mathcal{T} \quad (3)$$

Constraints (4) enforce that the total capacity utilized $\left(\sum_{b\in\mathcal{B}_{rk}} \lambda_{bprkt}\right)$ cannot exceed the maximum production capacity of the corresponding technology r at a potential processing location p ($K^{\max}_{rk} z_{prkt}$).

$$\sum_{b\in\mathcal{B}_{rk}} \lambda_{bprkt} \leq K^{\max}_{rk} z_{prkt} \qquad \forall p \in \mathcal{P}, r \in \mathcal{R}, k \in \mathcal{K}_r, t \in \mathcal{T} \quad (4)$$

Constraints (5) enforce the number of installed capacity modules k of technology r (z_{prkt}) to increase or remain unchanged.

$$z_{prk,t-1} \leq z_{prkt} \qquad \forall p \in \mathcal{P}, r \in \mathcal{R}, k \in \mathcal{K}_r, t \in \mathcal{T}\setminus \min(\mathcal{T}) \quad (5)$$

Constraints (6) prohibit the installation of technology r (z_{prkt}) if the technology is not available (t^*_r).

$$z_{prkt} = 0 \qquad \forall p \in \mathcal{P}, r \in \mathcal{R}, k \in \mathcal{K}_r, t \in \mathcal{T} | t < t^*_r \quad (6)$$

Constraints (7) enforce that the total amount of material m transported towards sink s $\left(\sum_{a \in \delta(s)^+} x_{amt}\right)$ cannot exceed the maximum capacity at s with regard to m within any time period t ($S^{\max}_{smt}$).

$$\sum_{a \in \delta(s)^+} x_{amt} \leq S^{\max}_{smt} \qquad \forall s \in \mathcal{S}, m \in \mathcal{M}, t \in \mathcal{T} \quad (7)$$

Following European Commission (2011a) art. 2 (1) "*Member states shall verify compliance with* [..] *targets* [...] *by calculating the weight of waste streams which are generated and the waste streams which are* [...] *recycled or have undergone other material recovery in one calendar year.*". Moreover, "*The weight of the waste* [...] *recycled or materially recovered shall be determined by calculating the input waste used in* [...] *the final recycling or other final material recovery processes.*" (European Commission (2011a) Art. 3). Consequentially, the waste masses that are recycled and those that are recycled and not downcycled should be measured at the final sinks of the network in order to comply with potential recycling and circularity quotas. Thereby, the annual achieved recycling and circularity quotas are defined as the ratio between the occurred waste masses and the total amount of waste that has been sent towards sinks. Constraints (8) and (9) enforce annual recycling and circularity quotas, respectively. The left-hand sides describe all occurring waste masses in time period t $\left(\sum_{m \in \mathcal{M}} \sum_{q \in \mathcal{Q}} N_{qmt}\right)$. A pre-defined ratio of these waste masses must be recycled (α) and recycled without being downcycled (β). The right-hand sides describe all material masses sent towards sinks within time period t $\left(\sum_{m \in \mathcal{M}} \sum_{s \in \mathcal{S}} \sum_{a \in \delta(s)^+} x_{amt}\right)$ factorized with a material and sink specific percentage accounting for the weight share of material m being recycled (α_{sm}) or recycled without being downcycled (β_{sm}) at sink s.

$$\alpha \sum_{m \in \mathcal{M}} \sum_{q \in \mathcal{Q}} N_{qmt} \leq \sum_{m \in \mathcal{M}} \sum_{s \in \mathcal{S}} \sum_{a \in \delta(s)^+} x_{amt} \alpha_{sm} \qquad \forall t \in \mathcal{T} \quad (8)$$

$$\beta \sum_{m \in \mathcal{M}} \sum_{q \in \mathcal{Q}} N_{qmt} \leq \sum_{m \in \mathcal{M}} \sum_{s \in \mathcal{S}} \sum_{a \in \delta(s)^+} x_{amt} \beta_{sm} \qquad \forall t \in \mathcal{T} \quad (9)$$

Constraints (10)-(13) define the domains of each decision variable, excluding the auxiliary variables (R_t, I_t, P_t) introduced in the following section.

$$l_{qmt} \in \mathbb{R}^+ \qquad \forall q \in \mathcal{Q}, m \in \mathcal{M}, t \in \mathcal{T} \quad (10)$$

$$\lambda_{bprkt} \in \mathbb{R}^+ \qquad \forall p \in \mathcal{P}, r \in \mathcal{R}, k \in \mathcal{K}_r, b \in \mathcal{B}_{rk}, t \in \mathcal{T} \quad (11)$$

$$x_{amt} \in \mathbb{R}^+ \qquad \forall a \in \mathcal{A}, m \in \mathcal{M}, t \in \mathcal{T} \quad (12)$$

$$z_{prkt} \in \mathbb{N}^0 \qquad \forall p \in \mathcal{P}, r \in \mathcal{R}, k \in \mathcal{K}_r, t \in \mathcal{T} \quad (13)$$

A.2. Objective

The net present value is maximized. It comprises of annual net revenues from material flows ($R_t \in \mathbb{R}$, $\forall t \in \mathcal{T}$), annual investments ($I_t \in \mathbb{R}^+$, $\forall t \in \mathcal{T}$) and process costs ($P_t \in \mathbb{R}^+$, $\forall t \in \mathcal{T}$) discounted by interest rate i (equation 14)[1]. Constraints (15)-(17) define the individual cost terms and determination of the corresponding auxiliary variables R_t, I_t and P_t. Herein, the net revenues (R_t) within time period t result from the achievable revenues and final treatment costs. The total investments (I_t) within time period t result from investments in technology capacities at potential processing locations. The total process costs (P_t) within time period t result from fixed and operational costs, as well as inventory and transportation costs.

$$\max \sum_{t \in \mathcal{T}} \frac{R_t - I_t - P_t}{(1+i)^{1+t-\min(\mathcal{T})}} \quad (14)$$

$$R_t = \sum_{m \in \mathcal{M}} \sum_{s \in \mathcal{S}} \sum_{a \in \delta(s)^+} x_{amt} c^{\mathcal{S}}_{sm} \qquad \forall t \in \mathcal{T} \quad (15)$$

$$I_t = \begin{cases} \sum_{p \in \mathcal{P}} \sum_{r \in \mathcal{R}} \sum_{k \in \mathcal{K}_r} \left(z_{prk,t} - z_{prk,t-1} \right) c^{\mathcal{K}, \text{ invest}}_{rk} & \text{, if } t \neq \min(\mathcal{T}) \\ \sum_{p \in \mathcal{P}} \sum_{r \in \mathcal{R}} \sum_{k \in \mathcal{K}_r} z_{prkt} c^{\mathcal{K}, \text{ invest}}_{rk} & \text{, else} \end{cases} \qquad \forall t \in \mathcal{T} \quad (16)$$

[1]Note that the annual net revenues from material flows can be positive or negative depending on whether revenues are achieved or final treatment costs are paid with respect to a material-sink (sm) combination, i.e. $c^{\mathcal{S}}_{sm}$ takes either positive values for revenues or negative values for final treatment costs.

$$P_t = \sum_{p\in\mathcal{P}} \sum_{r\in\mathcal{R}} \sum_{k\in\mathcal{K}_r} z_{prkt} c_{rk}^{\mathcal{K},\text{ fix}} + \sum_{p\in\mathcal{P}} \sum_{r\in\mathcal{R}} \sum_{k\in\mathcal{K}_r} \sum_{b\in\mathcal{B}_{rk}} \lambda_{bprkt} c_{rk}^{\mathcal{K},\text{ var}} + \sum_{q\in\mathcal{Q}} \sum_{m\in\mathcal{M}} l_{qmt} c_{qm}^{\mathcal{Q}} + \sum_{a\in\mathcal{A}} \sum_{m\in\mathcal{M}} x_{amt} c_{am}^{\mathcal{A}} \quad \forall t\in\mathcal{T} \quad (17)$$

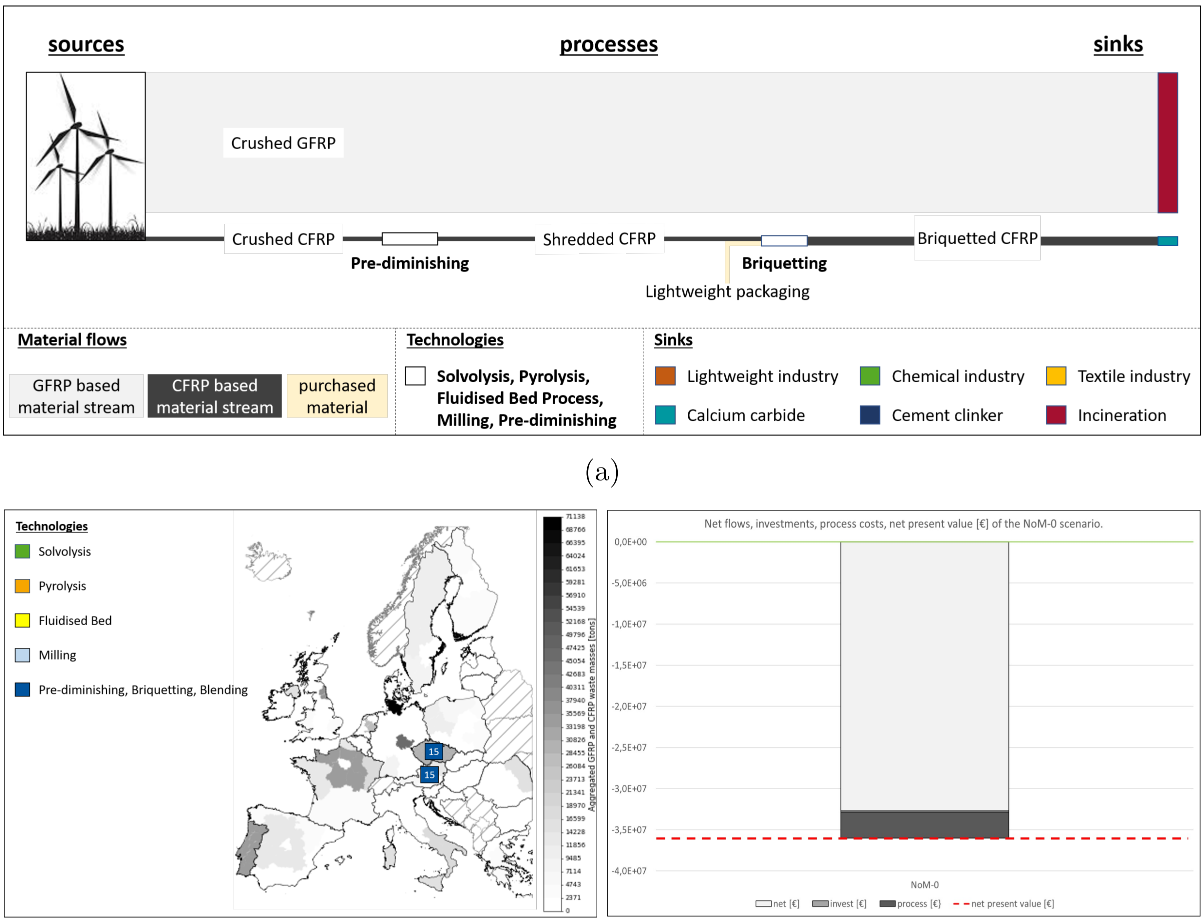
B. E-Component: Tables and Figures

Table 4: Notation of the optimization model.

$\mathcal{K}_r$	indexset of capacity modules for technology r	$k \in \mathcal{K}_r$
$\mathcal{M}$	indexset of materials	$m \in \mathcal{M}$
$\mathcal{Q}$	indexset of sources	$q \in \mathcal{Q}$
$\mathcal{R}$	indexset of technologies	$r \in \mathcal{R}$
$\mathcal{P}$	indexset of potential processing locations for technologies	$p \in \mathcal{P}$
$\mathcal{S}$	indexset of sinks	$s \in \mathcal{S}$
$\mathcal{T}$	indexset of time periods	$t \in \mathcal{T}$
$\mathcal{B}_{rk}$	indexset of bills of material at capacity module k of technology r	$b \in \mathcal{B}_{rk}$
$\delta(q/p/s)^-$	indexset of outgoing arcs at vertex q, p, s	$a \in \delta(q/p/s)^-$
$\delta(q/p/s)^+$	indexset of incoming arcs at vertex q, p, s	$a \in \delta(q/p/s)^+$
$\mathcal{A}$	indexset of arcs	$a \in \mathcal{A}$
α	defined recycling quota	[%/a]
α_{sm}	weight share of material m being recycled at sink s	[-]
β	defined circularity quota	[%/a]
β_{sm}	weight share of material m being recycled and not downcycled at sink s	[-]
$c_{sm}^{\mathcal{S}}$	revenues or final treatment costs of material m at sink s	[€/tons]
$c_{am}^{\mathcal{A}}$	transportation costs of material m on arc a	[€/tons]
$c_{rk}^{\mathcal{K},\text{ invest}}$	investments for capacity module k of technology r	[€/pcs.]
$c_{rk}^{\mathcal{K},\text{ fix}}$	fixed process costs for capacity module k of technology r	[€/pc.]
$c_{rk}^{\text{K, var}}$	variable process costs for capacity module k of technology r	[€/tons]
c_{qm}^{Q}	inventory holding costs for material m at source q	[€/tons]
γ_{bmrk}	bill of material b at capacity module k of technology r with regard to material m	[-]
i	interest rate	[-]
$K_{rk}^{\max}$	production capacity of capacity module k of technology r	[tons]
$S_{smt}^{\max}$	capacity of sink s with regard to material m	[tons]
N_{qmt}	amount of occurring waste masses of material m at source q	[tons]
t_r^*	time period of availability for technology r	[-]
I_t	auxiliary variable: total investments	[€] (continuous)
l_{qmt}	stored amount of material m at source q	[tons] (continuous)
λ_{bprkt}	used capacity of capacity module k of technology r at potential processing location p concerning bill of material b	[tons] (continuous)
P_t	auxiliary variable: total process costs	[€] (continuous)
R_t	auxiliary variable: total revenues / final treatment costs	[€] (continuous)
x_{amt}	transportation amount of material m on arc a	[tons] (continuous)
z_{prkt}	number of capacity module k of technology r at potential processing location p	[pc.] (integer)

The table is separated into indexsets, parameters, decision variables. Index t states that a parameter or decision variable is modeled for each time period $t \in \mathcal{T}$.

Figure 5: Results NoM-0: Choice of waste management options (a), regional distribution of capacities (b) and cost distribution (c).



(a)

(b) (c)

Figure 6: Results NoM-0, ..., NoM-95r: cost distribution.

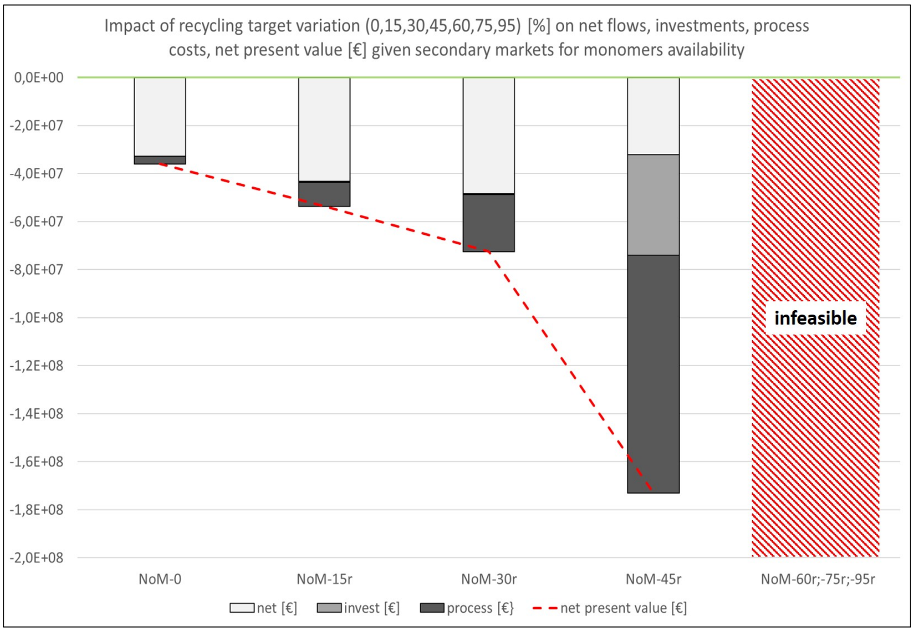


Figure 7: Waste management options: NoM-30r (left), NoM-45r (right).

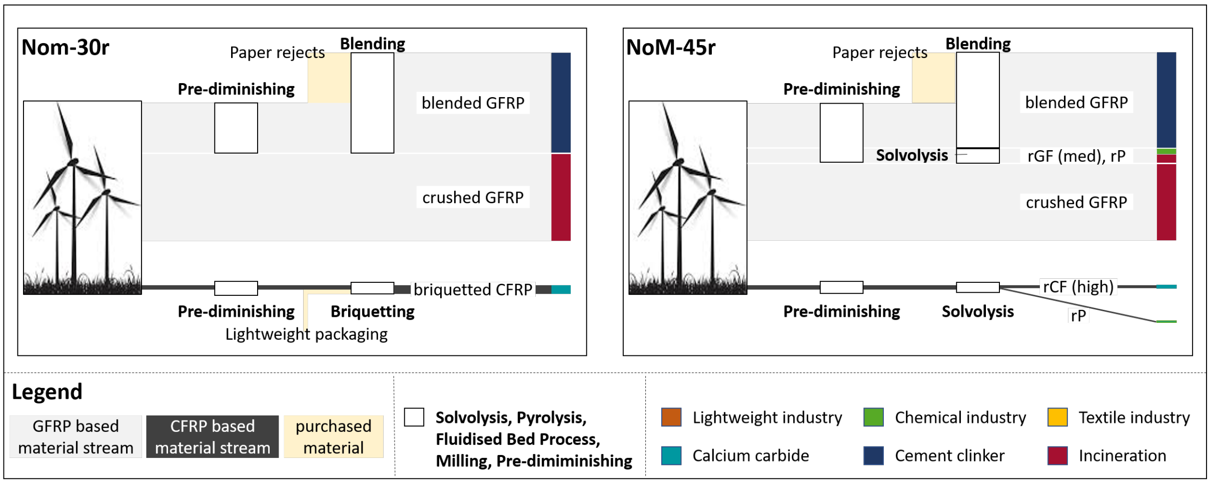


Figure 8: Capacity distribution: NoM-30r (left), NoM-45r (right).

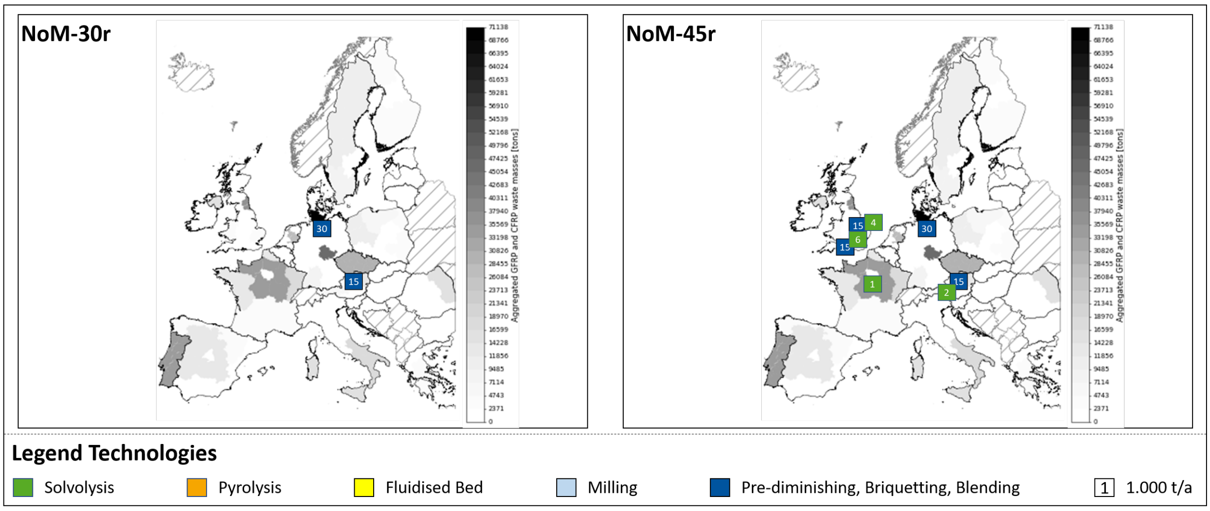


Figure 9: Results recycling target variation considering secondary markets: cost distribution.

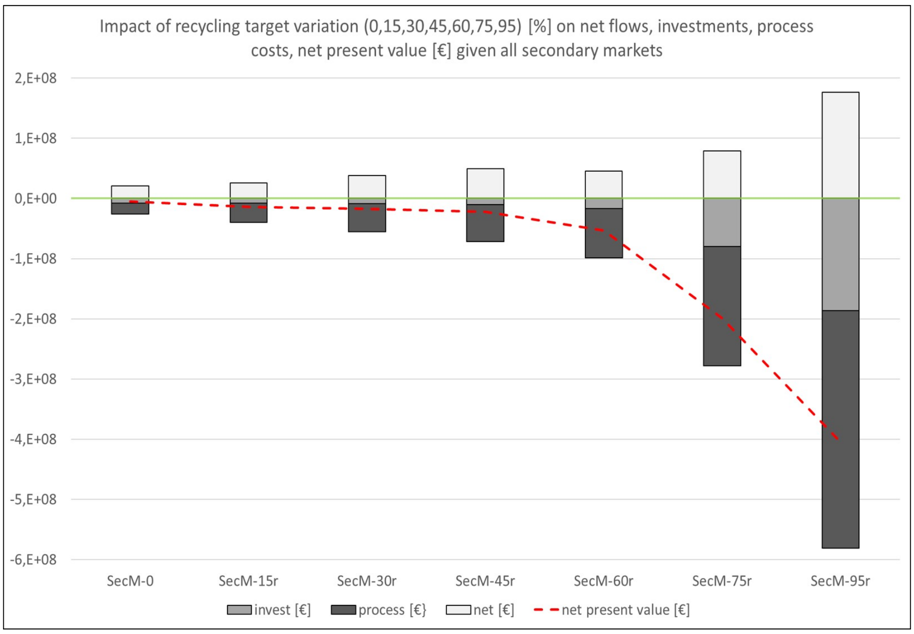


Figure 10: Comparison waste management options: SecM-0 (top left), SecM-45r (top right), SecM-60r (bottom left), SecM-95r (bottom right).

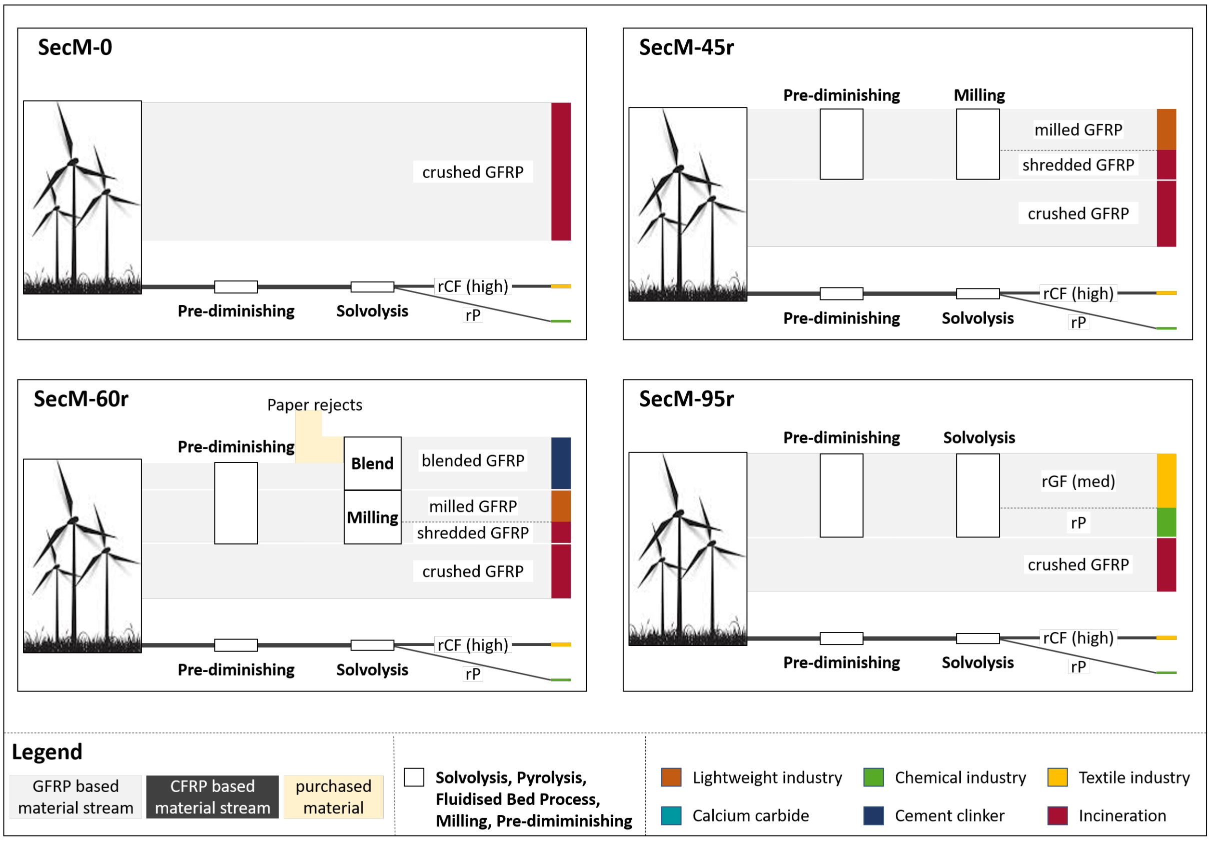


Figure 11: Comparison capacity distribution: SecM-0 (top left), SecM-45r (top right), SecM-60r (bottom left), SecM-95r (bottom right).

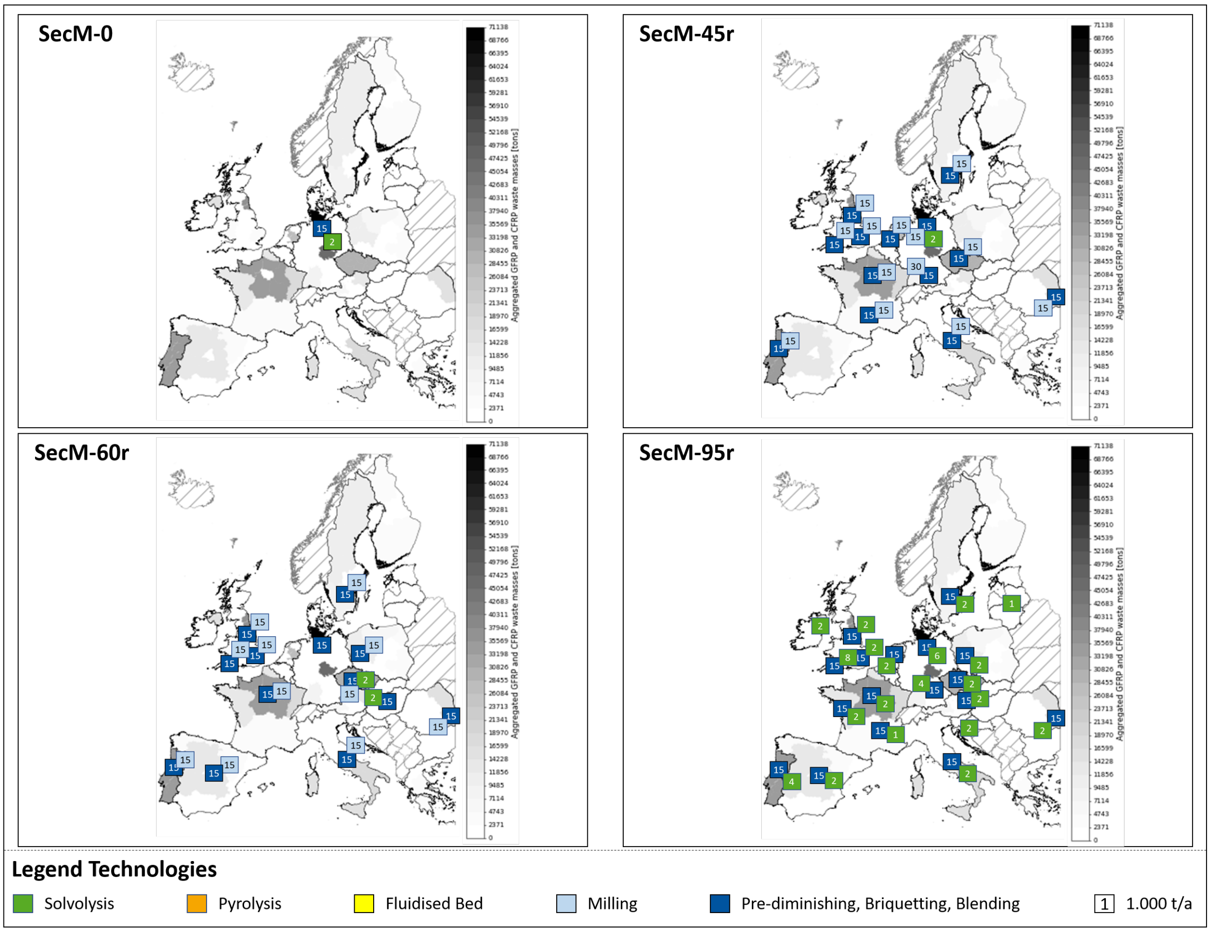
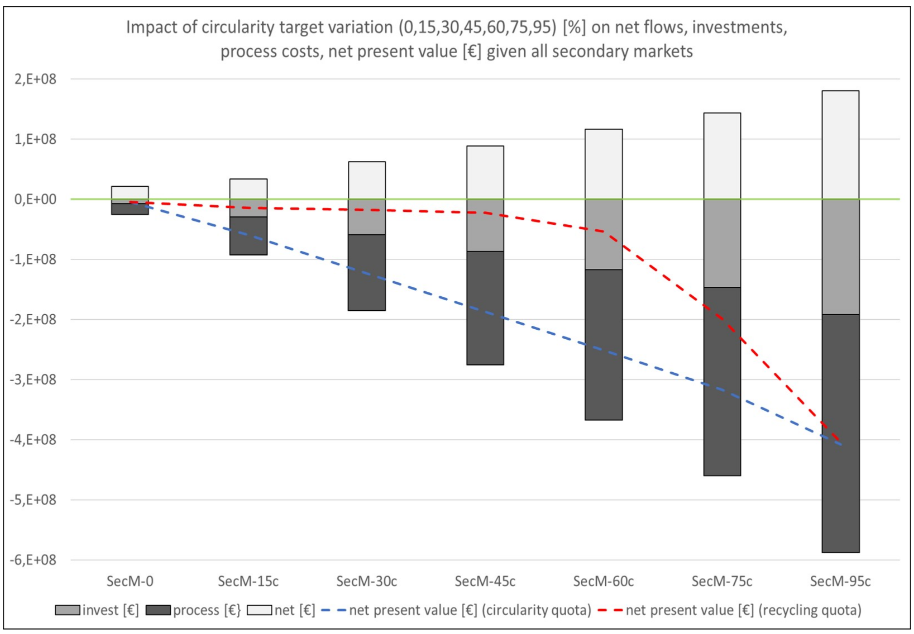


Figure 12: Results circularity target variation considering secondary markets: cost distribution.



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6. Steering Sustainable End-of-Life Treatment of Glass and Carbon Fiber Reinforced Plastics Waste from Rotor Blades of Wind Power Plants

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Abstract

In the European Union, recycling quotas are the measure of choice to regulate the end-of-life treatment of waste. In addition to accomplishing the circularity of resources, it is implicitly assumed that the environmentally most favored recycling system will be established. However, in dependence of the waste material as well as the local treatment and infrastructural conditions, the impacts of political regulations on the total system differ in terms of the environmental as well as economic outcomes. Against this background, we analyze the impact of political regulations on the economic and environmental burden of the necessary treatment infrastructure for end-of-life glass and carbon fiber reinforced plastic waste. We first conduct Lifecycle Impact Assessments to quantify the environmental impact of several end-of-life treatment paths. In addition, we developed a decision support tool based on mathematical optimization to systematically analyze the impact of political regulations on the design of the required treatment infrastructures. Herein, we focus on economic and environmental objectives to demonstrate the trade-off between the two evaluation criteria. We apply our methodological approach to a case study on end-of-life glass and carbon fiber reinforced plastic waste from rotor blades of wind power plants in the European Union. We found that up to a certain degree (<60%) recycling quotas lead to the desired environmental benefit in exchange for higher costs. However, when recycling quotas above 60% are demanded the effect is reversed. In addition, we found that the impact of setting recycling quotas differs in dependence of the material.

Keywords: Waste management, economic and environmental impacts of political regulations, mathematical optimization, LCA, recycling of glass and carbon fiber reinforced plastics, rotor blades of wind power plants

1. Introduction

The use of glass and carbon fiber reinforced plastic (GFRP/CFRP) has received strong attention in recent years in the lightweight industry (Ehrenstein, 2006; Mallick, 2007; Sapuan, 2017; Sauer, 2019). While GFRP/CFRP show advantages in the usage phase of respective applications, the end-of-life treatment of GFRP/CFRP, particularly the recycling, still reveals technological challenges. However, as the primary production of GFRP/CFRP is cost-, energy- and resource-intensive, recycling and further re-use of the materials might be economically and environmentally beneficial (Deng, 2014; Gutiérrez and Bono, 2013; Kaur et al., 2016).

The expected increase in GFRP/CFRP waste streams has provoked a discussion among academics, businesses, and government officials on the future treatment of GFRP/CFRP end-of-life waste (e.g. Oliveux et al., 2015; Sommer and Walther, 2020; Vo Dong et al., 2018; Zotz et al., 2019). So far, the technological challenges within the end-of-life treatment, particularly the potential performance loss of recycling materials, affect the reputation of the secondary materials' quality, which leads to a lack of market commitment. Without secondary markets, though, there are no economic incentives to invest in recycling infrastructures. In line with this, Liu et al. (2019b) state that legal measures are required to steer the installation of the necessary recycling infrastructures such that potential economic and environmental benefits can be exploited.

On a European level, the directive on waste calls for an efficient utilization of natural resources and an implementation of circular economy principles (European Parliament and Council of the European Union, 2018). Herein, recycling/recovery quotas are seen as legal measures to steer the installation of the required recycling infrastructures and the choice of end-of-life treatment (European Parliament and Council of the European Union, 2000, 2006; European Commission, 2011, 2018, e.g. for end-of-life vehicles, batteries and plastics). These measures base on the assumption that recycling is the environmentally most favored end-of-life treatment option after product re-use (European Parliament and Council of the European Union, 2008, (7, 31)), and that recycling targets stimulate the development of the economically and environmentally most favored recycling system. However, recycling might not always be the option that reveals the lowest environmental impact and thus, end-of-life treatment options must be evaluated with regard to their overall environmental impact. However, this is a complex task that requires information on the complete process paths and material flows, potential secondary utilization of materials and substituted materials, available processing capacities, and the energy mix applied in the analyzed system.

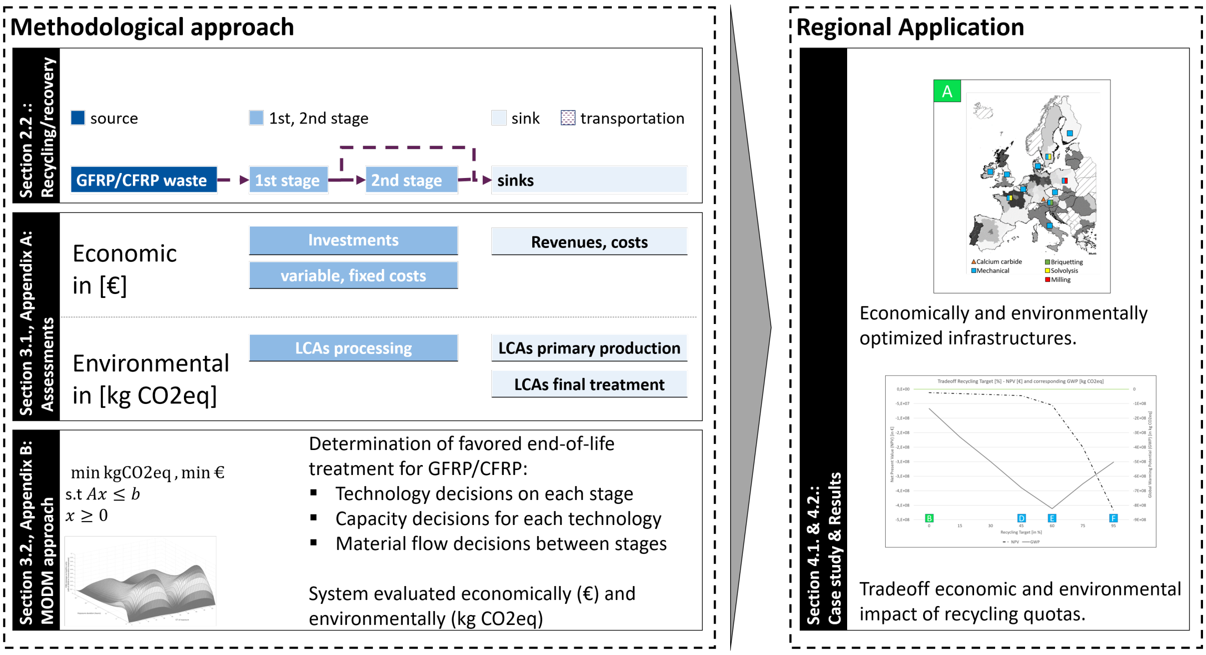
Previous research on the economic and environmental impact of GFRP/CFRP recycling often focuses on individual technological processes. Only few studies model the interplay of processes and material flows, herein encompassing also the utilization of the secondary materials (e.g. Liu et al., 2019b; Oliveux et al., 2015; Vo Dong et al., 2018, 2015). However, these studies do not provide an analysis of the steering effects of recycling targets, nor do they regard the complete (future) recycling system with its infrastructural preconditions, potential economies of scale, limited capacities of recycling processes and material sinks, and resulting overall material flows and material substitution effects.

Moreover, environmental assessments are often based on average EU-level data (e.g., average EU electricity mix). This is only of limited value as the end-of-life treatment of GFRP/CFRP depends on the specific regional characteristics of the waste material flows with their underlying treatment capacities, logistics, energy mix and resulting material substitution. For example, there might be environmental benefits from providing a high-value secondary material as result of a sophisticated recycling process. This benefit might be offset by the high energy demand of the recycling process if the energy mix carries a large environmental burden (e.g. coal-based electricity mix), while the same process might be overall beneficial if the energy mix carries a low environmental burden (e.g., renewable-based electricity mix). Besides, the specific characteristics of GFRP/CFRP call for sophisticated treatment processes (e.g., co-processing in the calcium carbide industry), which results in limited regional treatment capacities.

Concluding, average environmental and economic analyses are not sufficient to evaluate GFRP/CFRP end-of-life treatment paths. Instead, it is necessary to develop an evaluation approach that is able to model the complete (future) recycling system with its economies of scale and the interrelations of technologies, material flows and transformed secondary materials. Moreover the approach must be able to take into account specific regional and logistical aspects, i.e. electricity mixes, limited sink capacities as well as economic and ecological evaluation criteria to identify the most beneficial end-of-life treatment. Against this background, we develop a methodological approach that allows the assessment of the end-of-life treatment options of GFRP/CFRP based on an ex-ante design of regional recycling infrastructures for GFRP/CFRP end-of-life waste.

To achieve this target, we proceed as shown in Figure 1. First, we describe the end-of-life treatment options with their material flows, recycling potential and technological feasibility (Section 2.2). Afterwards, we evaluate the overall economic benefits and burdens of the different recycling paths, and conducted life cycle impact assessments (LCIA), including the generation of detailed and regionalized life cycle inventories (LCI), to evaluate the overall environmental burden/benefits of these treatment paths (Section 3.1). We then present a multi-objective decision making (MODM) model that allows to design a future recycling system. With this model, we are able to account for regional and logistical infrastructural aspects and to regard economic and environmental criteria simultaneously

Figure 1: Overview methodological approach.



(Section 3.2). The model is generic in its regional applicability, but specific with regard to the treatment of the GFRP/CFRP waste streams. We apply our approach to a European case study, calculate optimal solutions from an environmental and an economic perspective (Section 4.1), and explore the trade-offs between the extreme solutions and the impact of potential recycling quotas on the design of the end-of-life treatment system (Section 4.2). Finally, we generate insights for political decision makers for the decision of legal measures and their impact on the choice of the adequate end-of-life treatment with the accompanying design of regional recycling infrastructures.

The remaining publication is structured as follows: Section 2 provides information on GFRP/CFRP and their end-of-life treatment. Section 3 presents our methodological approach. In Section 4, we apply our methodological approach to a European case study and generate insights for European decision makers. In Section 5, we conclude our work.

2. Materials

In the following section, we describe the materials GFRP/CFRP with their respective production and recycling processes. For this, in Section 2.1, we introduce the materials of interest and highlight the economic and environmental benefits of the recycling and material re-use of GFRP/CFRP end-of-life waste. In Section 2.2, we introduce the end-of-life treatment options for GFRP/CFRP waste and discuss differences in terms of their classification as recycling/recovery.

2.1. Production of primary GFRP/CFRP

Primary GFRP/CFRP are produced by embedding a glass fiber (GF)/carbon fiber (CF) based reinforcement in a polymer matrix. In the following, we introduce the production processes of GF, CF and epoxy resin as polymer matrix, with respect to their economic and environmental burdens. Note that throughout the course of this paper, particularly in the case study in Section 4, the focus is on GFRP/CFRP End-of-Life waste from rotor blades of wind power plants. The most commonly applied polymer matrix in GFRP/CFRP End-of-Life waste from rotor blades of wind power plants is epoxy resin (Liu and Barlow, 2017).

The production process of GFs involves large amounts of natural resources. Silica (SiO_2), limestone (rich in CaO), aluminum (Al_2O_3), soda-ash (high in Na_2O) are blended, melted and processed into single fibers, rovings and textile products (Dai et al., 2015; US National Renewable Energy Lab, 2002). While the raw materials consumption for GF is high and can lead to the scarcity of silica sand, limestone, and alumina (Gutiérrez and Bono, 2013), the production costs for GFs are low in comparison to CFs.

The production process of CFs involves the processing of carbon-rich precursors, mostly polyacrylonitrile. The precursor refinement in pyrolysis processes is very energy-intensive resulting in substantial cumulative embodied energy (CED) and greenhouse gas (GHG) emissions in production (Ehrenstein, 2006; Oliveux et al., 2015). Besides the large energy input, the overall production costs for CFs are high, which motivates the re-use as recycled CFs not only from an environmental but also from an economic perspective. In addition, the carbon-rich precursors are primarily produced from finite fossil-fuel-based resources.

Epoxy resin is the most commonly used polymer matrix in the production of GFRP/CFRP (Martins et al., 2017). Although the cross-linked structure of the thermosetting epoxy resin improves the thermal and mechanical stability of GFRP/CFRP, the separation of the GFs/CFs based reinforcement and the epoxy resin at the materials' end-of-life is technologically challenging. Moreover, Bisphenol A as essential organic compound for the production of epoxy resins is co-produced from finite fossil-fuel-based resources. Thus, consumption of epoxy resin accelerates resource depletion (Tao et al.,

Table 1: Summary of the manufacturing burden of constituent materials in terms of environmental and economic metrics based on Deng (2014); Gutiérrez and Bono (2013); Kaur et al. (2016).

Component	CED $\left[\frac{MJ}{kg}\right]$	GHG emissions $\left[\frac{kg\ CO2eq}{kg}\right]$	Market price $\left[\frac{€}{kg}\right]$
Glass Fiber	45	2.6	1.8
Carbon Fiber	183 – 286	22.4 – 31	24
Epoxy resin	76 – 137	4.7 – 8.1	4.4

2020).

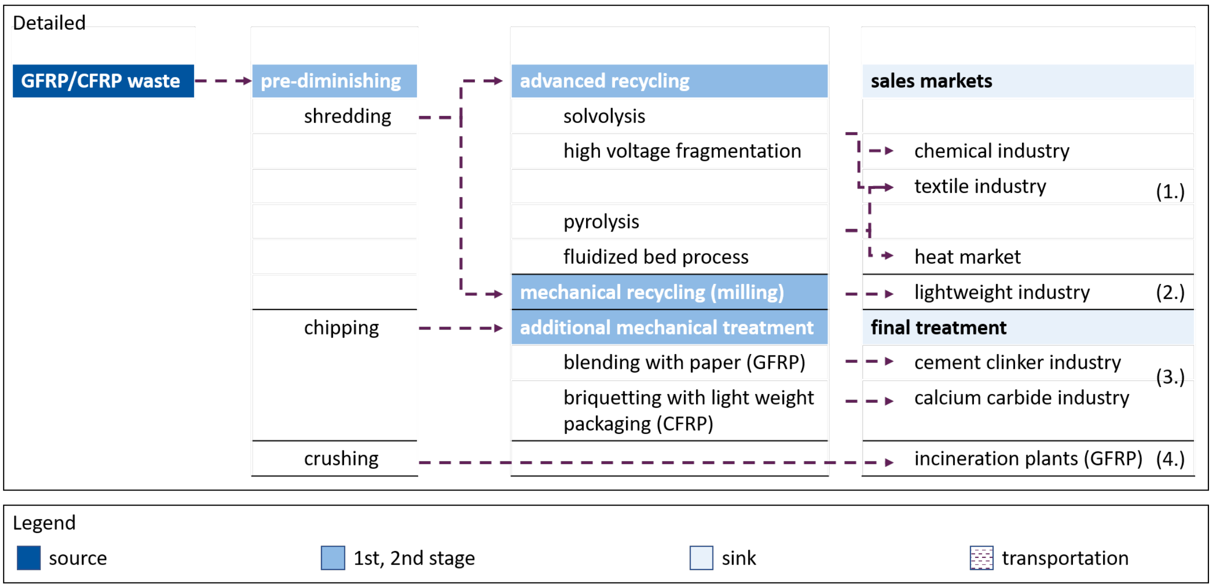
Table 1 summarizes the component specific CED, GHG emissions, raw material extraction and market price based on Deng (2014); Gutiérrez and Bono (2013); Kaur et al. (2016), providing an indication for the potential economic and environmental benefits of recycling GFRP/CFRP end-of-life waste and use of secondary materials, i.e. from cradle to cradle. The following Section 2.2 introduces the end-of-life treatment options for GFRP/CFRP waste.

2.2. Recycling/recovery treatment options for GFRP/CFRP end-of-life waste

Figure 2 shows an overview of the end-of-life treatment options for GFRP/CFRP waste compiled and adapted from literature (Ginder and Ozcan, 2019; Hahn, 2017; Holcim, 2019; Howarth et al., 2014; Lange, 2018; Liu et al., 2019b; Nagle et al., 2020; Oliveux et al., 2015; Pickering et al., 2000; Pickering, 2006; Piñero-Hernanz et al., 2008a,b; Selfrag AG, 2015; Sommer and Walther, 2020; Stockschläder et al., 2019; Vo Dong et al., 2018; Walter, 2017). Each end-of-life treatment option is a two stage process, finalized by either selling recycled materials to secondary markets or combusting transformed waste materials at industrial and waste incineration plants. At the 1st stage, GFRP/CFRP end-of-life waste is diminished by mechanical treatment processes and further transported to the 2nd stage. At the 2nd stage, the diminished GFRP/CFRP end-of-life waste takes one of the following paths depending on the subsequent final point of sale or combustion process: 1. advanced chemical and thermal recycling through solvolysis, high voltage fragmentation, pyrolysis or the fluidized bed process; 2. mechanical recycling; 3. co-processing of GFRP through combustion in the cement clinker industry and of briquetted CFRP in the calcium carbide industry; 4. combustion of GFRP in waste incineration plants.

The advanced chemical and thermal recycling technologies (1.) separate the GF/CF based reinforcement from the epoxy resin matrix. While solvolysis and high voltage fragmentation allows to recycle the fiber reinforcement as well as the epoxy resin matrix, the

Figure 2: Overview of end-of-life treatment options.



thermal recycling processes pyrolysis and the fluidized bed process only allow for recycling of the fiber reinforcement and energy recovery of the epoxy resin matrix. In mechanical recycling (2.), GFRP/CFRP are milled into a fiber and polymer matrix rich powder that substitutes primary epoxy resin in the production of primary GFRP/CFRP. Co-processing (3.) in the cement clinker (GFRP) and the calcium carbide industry (CFRP) allows to use the fiber reinforcement as a substitute for natural mineral resources and fossil fuels. Lastly, the combustion of GFRP in waste incineration plants (4.) allows for a substitution of natural fossil resources for heat and electricity generation.

End-of-life treatment options might account for recycling for the same purpose, recycling for other purposes and recovery regarding the definitions of *recycling/recovery* in (European Parliament and Council of the European Union, 2008, art. 3 (15) and (17)). Herein, the secondary materials from the advanced recycling paths (1.) are able to substitute primary materials with the same initial purpose. The mechanical recycling (2.) represents a recycling for other purposes as the output materials cannot be reused for the same initial purpose. This holds also for certain material components that are co-processed in industrial processes (3.). However, co-processing of the remaining components (3.) and the waste combustion in incineration plants (4.) is classified as recovery (of energy) as it substitutes fossil fuels.

3. Methodological approach

In Section 3.1, we provide details on the technologies and the environmental and economic characteristics of the end-of-life treatment paths. While the economic metrics are mainly taken from literature, the environmental metrics are based on LCIA studies, which we conducted based on official data sources (see Appendix A). In 3.2, we introduce our methodological approach aiming at the design of an optimized GFRP/CFRP recycling system from an economic and/or environmental perspective.

3.1. Economic and environmental assessments

As shown in Figure 2, each GFRP/CFRP end-of-life treatment option consists of a pre-diminishing 1st stage, followed by recycling or mechanical treatment as a 2nd stage, and by either the sale of recycled material at secondary markets or the combusting of the processed waste material at industrial processes or waste incineration plants as a 3rd stage. While the environmental impacts and economic costs at the 1st and 2nd stage mainly arise from the installation, maintenance and operation of the treatment processes (Table 2), the environmental impacts of the 3rd step depend on the utilization of the transformed material and the substitution of other materials or energy within the sinks (Table 3). For example, the chemical recycling of CFRP waste requires the installation and operation of pre-diminishing capacities (1st stage) and solvolysis capacities (2nd stage) with respective costs and environmental impacts. The sale of the recycled carbon fibres on secondary markets might result in revenues (economic benefit) and substitute primary carbon fibres (environmental benefit, c.f. Section 2.1). Thus, the overall evaluation of an the end-of-life treatment option must consider the complete processing paths, i.e., the 1st and 2nd stage processes as well as the substitution effects at the final treatment step. Note that any additional processing step, e.g. the demolition or disassembly of GFRP/CFRP End-of-Life waste from vehicles or rotor blades as well as additional production of textile products after selling recycled fibers to sales markets is not considered -even if recycled fibers are unlike in the form of virgin fibers. The considered systems starts with the occurred waste streams and ends with the final treatment step.

Table 2 presents results of the analysis of the 1st and 2nd step processes. Herein, the efficiency of the technologies is characterized by yield and quality. While the yield rate describes the ratio of the GFRP/CFRP end-of-life waste with regard to the share of the fiber that is transformed into the specified quality, the quality refers to the remaining tensile strength after the advanced recycling processes. For example, CFRP end-of-life waste that is processed in a fluidized bed process results in 90 [%] of the CF-based reinforcement being transformed into rCF of high quality (only 25 [%] reduction in tensile strength in comparison to primary CF), while the remaining material of lower quality is reject and must be treated otherwise. Within this paper we assume that GFRP of low quality is combusted in waste incineration plants, while CFRP of low quality is combusted in calcium carbide plants. The yield rate com-

Table 2: Environmental, economic and technical parameterization of treatment technologies.

	Environmental parameter [1]		Economic parameter				Efficiency				Data
Technology	GWP burden $\left[\frac{kg\ CO2eq}{kg}\right]$	GWP benefit[2] $\left[\frac{kg\ CO2eq}{kg}\right]$	Invest $\left[\frac{mil.€}{\#}\right]$	Variable $\left[\frac{1,000€}{t}\right]$	Fix $\left[\frac{mil.€}{\#a}\right]$	Capacity $\left[\frac{1,000t}{\#}\right]$	Yield [%] GF	Yield [%] CF	Quality [%] GF	Quality [%] CF	
Diminishing[3]	17.64	-	0.25	0.1	15	15	95	95	-	-	[1,2]
Briquetting[4]	443.35	-	-	-	-	-	-	-	-	-	[1,3]
Blending[4]	62.3	-	-	-	-	-	-	-	-	-	[1,4]
Milling	47.7	-	0.25	0.1	15	4	58	58	78	50	[1,5]
HVF[5]	10,592	-	2.45	6.12	294	0.1	60	60	88	83	[1,6]
Pyrolysis	3,902	648	0.9	1.1	108	1	70	70	52	78	[1,7]
Fluidized bed	1,862	648	1	10	120	1	44	90	50	75	[1,8]
Solvolysis	4,370	-	6.4	1.5	768	1	100	100	58	95	[1,7]

[1]: Liu et al. (2019b), Vo Dong et al. (2018), Sommer and Walther (2020); [2]: Andritz AB (2019), Vecoplan AG (2019); [3]: AGEB (2019); [4]: Potgieter (2014); [5]: Howarth et al. (2014); [6]: Mativenga et al. (2016); [7]: Pillain et al. (2019); [8]: Meng et al. (2018);
[1] Based on the German Energy mix.
[2] Due to the heat recovery by the thermal recycling processes.
[3] Diminishing means crushing, shredding, chipping in dependence of the recycling/recovery path.
[4] For the economic and efficiency parameter part of pre-diminishing.
[5] High voltage fragmentation.

prises important information for the economic and environmental evaluation as well as for the calculation of recycling quotas (Sommer and Walther, 2020; Liu et al., 2019b).

The economic parameters presented in Tables 2 and 3 were gathered from literature and from personal communication with experts (Lange, 2018; Liu et al., 2019b; Sommer and Walther, 2020; Stockschläder, 2019; Vo Dong et al., 2018). The environmental parameters presented in Tables 2 and 3 were gathered performing detailed LCIAs following the life cycle assessment (LCA) frameworks ISO 14040 and ISO 14044 (ISO, a,b). The corresponding life cycle inventories (LCIs) were derived based on data from literature, the Ecoinvent v.3.5 database and the European Reference Life Cycle Database (ELCD) v.3.2. We modeled each product system, i.e., the complete processing path of 1st and 2nd step technologies and substitution of primary materials at the 3rd step, in openLCA software. Each LCI system was further assessed using the IPCC 2013 GWP 100a method (GWP, engl. Global Warming Potential), hence the potential impact of carbon dioxide equivalents in [kg CO2eq] emissions in a time frame of 100 years in line with Dauguet et al. (2015); Khalil (2018); La Rosa et al. (2016); Liu et al. (2019b); Meng et al. (2018); Nunes et al. (2018); Pillain et al. (2019); Shuaib and Mativenga (2017); Stocker et al. (2014); Vo Dong et al. (2018). The list of energy mixes, major materials and processes considered for each process path is provided in the Appendix A.

Besides the specification of the 1st and 2nd stage processes and the material specific final treatment, the geographical processing location is crucial due to different regional

Table 3: Environmental and economic parameters of each material-sink combination.

		Environmental		Economic		Data
Material	Sink	Burden $\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$	Benefit $\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$	Revenue $\left[\frac{€}{\text{t}}\right]$	Costs $\left[\frac{€}{\text{t}}\right]$	
Blended GFRP	cement clinker	686	1,150	-	100	[1,2]
Briquetted CFRP	calcium carbide	1,884	2,226	-	100	[1,3]
Crushed GFRP	incineration	610	742	-	100	[1,4]
Milled GFRP	lightweight	0	3,910	250	-	[1,5]
Milled CFRP	lightweight	0	3,910	2,500	-	[1,5]
rP	chemical	0	3,910	1,500	-	[1,5]
rGF	textile	0	2,225	250	-	[1,5]
rCF	textile	0	23,430	8,000	-	[1,6]

[1]: in accordance with Sommer and Walther (2020) and Vo Dong et al. (2018); [2]: Bundesverband WindEnergie e.V., Hahn (2017); [3]: AGEB (2019); [4]: Job (2013); Hedlund-Åström (2005); [5]: Ecoinvent v.3.5; [6]: Pillain et al. (2019), ELCD (2015);

and logistical aspects, e.g. availability of waste material, regional energy mixes, limitation of industrial process capacities. To fully answer the research question of the most favored environmental and economic end-of-life treatment of GFRP/CFRP waste, we integrate the results of the detailed LCIAs (Appendix A), the economic and technological parameters as well as regional characteristics into a mathematical optimization model, which plans recycling infrastructure in a given system regarding for these spatial characteristics.

3.2. MODM approach

The aim of this publication is to evaluate the most favored end-of-life treatment system for GFRP/CFRP waste considering not only technological and material specific aspects, but regarding the overall recycling system including regional aspects, logistics, (limited) capacities and infrastructures. To do so, we develop a mathematical optimization model that decides on treatment capacities as well as transformation and transportation activities while applying an evaluation that simultaneously regards for economic as well as environmental criteria. Herein, we implicitly decide on the economically and environmentally favored end-of-life treatment system for GFRP/CFRP waste. In the following Section, we introduce the concept of mathematical optimization, our developed mathematical model and multi-objective-decision-making (MODM) approach.

Mathematical optimization models are widely applied to plan logistic infrastructures (e.g. Govindan and Soleimani, 2017; Govindan et al., 2015; Dekker et al., 2004; Melo et al., 2009). Such models endogenously decide on the location and capacities of treatment processes, the processed material amounts and the materials flows between the processing stages of a system, while evaluating the system in accordance to one or several objectives.

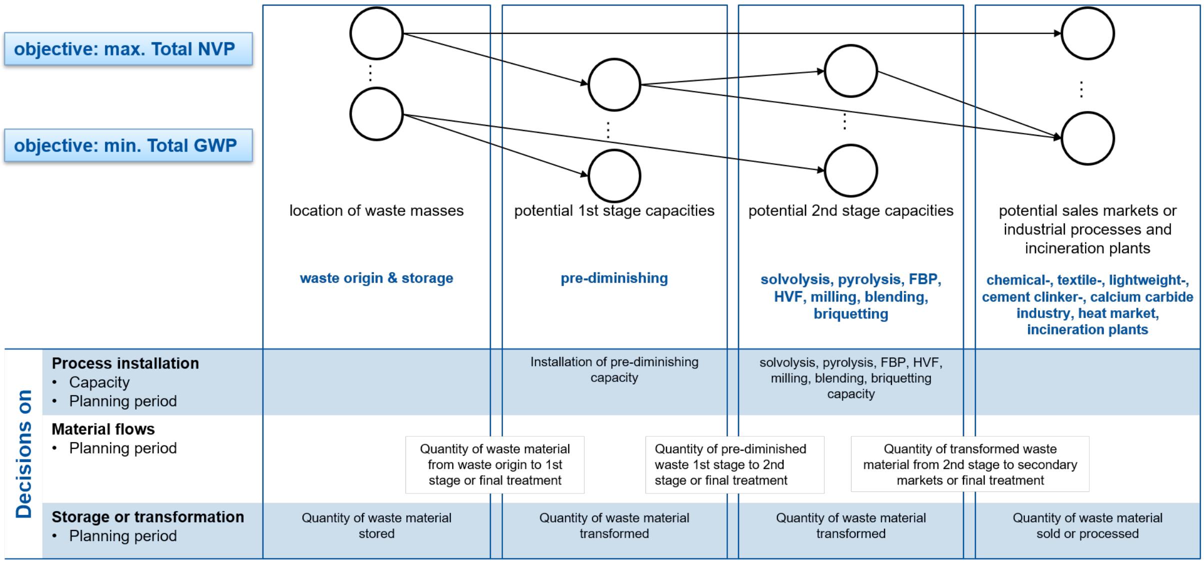
Herein, different metrics can be used as objective, i.e. economic or environmental criteria as well as combinations (e.g. Altmann and Bogaschewsky, 2014; Amin and Zhang, 2014, 2013a, 2012; Garg et al., 2015; PATI et al., 2008; Pishvaee et al., 2010; Quariguasi Frota Neto et al., 2009; Talaei et al., 2016). If several criteria have to be considered simultaneously, this leads to multi-objective decisions, which can be tackled applying MODM approaches like the lexicographic method (e.g. PATI et al., 2008), the weighted sum method (e.g. Amin and Zhang, 2014, 2013b) or the ϵ-constraint method (e.g. Talaei et al., 2016).

In the following, we present a bi-objective mathematical optimization model to decide on the end-of-life treatment of GFRP/CFRP waste and the corresponding recycling infrastructure evaluated by the net present value (NPV) in [€] and the Global Warming Potential (GWP) in [kg CO2eq]. The NPV consists of discounted investments in processing capacities, revenues for sold secondary materials, acceptance costs for transformed waste materials, annual fixed costs for installed processing capacities, variable processing costs, and transportation costs. The GWP consists of environmental impacts from the processing and transportation activities as well as of environmental benefits from re-use of secondary materials (cf. Tables 2 and 3). Taking into account both objectives simultaneously, we consider a comprehensive economic and environmental evaluation. To overcome the issue of comparing the corresponding metrics, we implement an ϵ-constraint approach that generates pareto-optimal solutions, i.e., solutions that can not be improved for one objective without compromising the other objective (e.g. Frota Neto et al., 2008).

In the specified region, sources represent GFRP/CFRP waste origins, sinks represent locations at which recycled materials can be sold and re-used or at which transformed GFRP/CFRP waste is combusted. Decisions are taken on regional locations and capacities for the 1st and 2nd stage processes as well as regional processing amounts and transportation activities. Potential processing locations represent locations at which capacities for the 1st and 2nd stage technologies can be installed and at which GFRP/CFRP end-of-life waste is transformed. Decision on transportation activities between all network entities are taken. Figure 3 shows the graphical representation of the decision problem. Besides the decisions to be taken, the planned recycling infrastructures must satisfy political and technical restrictions: The mathematical optimization model allows to demand the fulfillment of annual recycling quotas following European Commission (2011). Besides, capacity limitations are considered at sinks as well as for each installed technology and storage, and material balances are implemented at each stage.

The complete mathematical model, with its underlying graph, notation, constraints and objectives can be found in the Appendix B. In the following Section 4, we apply our developed methodological approach to a European case study.

Figure 3: Graphical representation and verbal description of the mathematical model.



4. Treatment of GFRP/CFRP waste from rotor blades of wind power plants

Section 4.1 introduces case specific regional information, i.e. information on sources, potential processing locations and sinks. In section 4.2, we define our case study to test the impact of potential recycling quotas on the design of the required recycling infrastructures and present the results. In Section 4.3, we relate our results to the relevant literature on the end-of-life treatment of GFRP/CFRP waste.

4.1. Regional Characteristics: European Case Study from Wind Energy Industry

Against the background of increasing GFRP/CFRP end-of-life waste from rotor blades of wind power plants, political stakeholders like the German Environmental Agency demand for an ex-ante analysis of the potential future recycling infrastructures considering the overall economic burden and potential environmental benefits, herein taking also into account the technological capabilities and limitations (Zotz et al., 2019). In this regard, our aim is to determine the economically and environmentally optimized recycling infrastructure for the treatment of GFRP/CFRP. To account for targeted harmonization of legal regulation and recycling within the EU and to allow for economies of scale, we carry out this analysis for the whole EU-28. However, European member states differ in their infrastructural conditions, especially with respect to the country specific energy mix (cf. Table 4 in the Appendix A). Hence, we account for these regional aspects by regarding

NUTS-2 resolution data. In the following, we further define the regional system, in particular the GFRP/CFRP end-of-life sources, the sinks and chosen transportation modes.

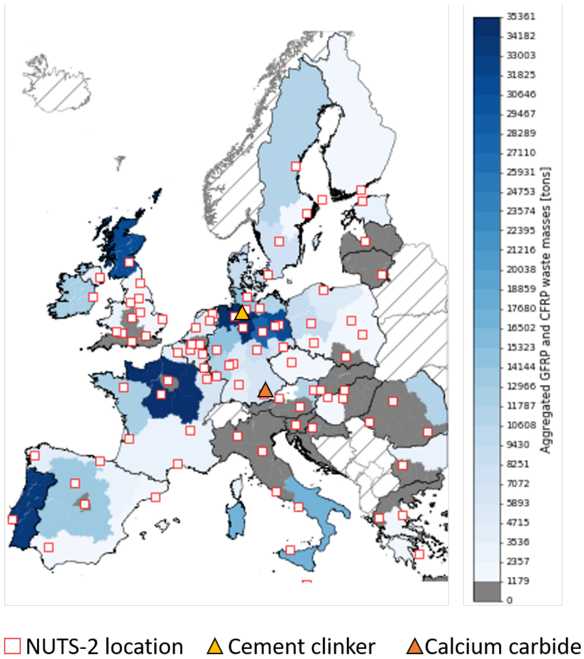
Sources: Lefeuvre et al. (2019), Liu and Barlow (2017) and Sommer et al. (2020) estimate future GFRP/CFRP end-of-life waste from rotor blades of wind power plants in the EU. Figure 4 shows the expected GFRP/CFRP end-of-life waste amount from 2020 until 2030 in the EU, with the red bordered rectangles representing the geographical locations, hence waste origins, at NUTS-2 level. On an annual basis, GFRP End-of-Life masses from rotor blades of wind power plants are increasing over time from approximately 34.000 [t] in 2020 to 52.000 [t] in 2030, whereas respective CFRP End-of-Life masses increases from approximately 600 [t] in 2020 to 1.700 [t] in 2030 (Sommer et al., 2020; Sommer and Walther, 2020, based on information provided by).

Sinks: For materials that can be sold at general sales markets (e.g. like recycled fibers or polymers), we assume that an average transportation of 200 $\left[\frac{\text{km}}{\text{t}}\right]$ takes place within the subsequent transportation step after processing the respective material amount [t] (cf. Sommer and Walther, 2020). For materials that can only be utilized by selected technologies at specific locations, we consider the specific transportation distance. This holds for the combustion of blended GFRP at cement clinker plants and briquetted CFRP at calcium carbide plants as these processes are not yet widely established due to technological challenges. Currently, only one cement clinker plant in Northern Germany provides processing capacities for $60,000$ [t] of blended GFRP per year, and one calcium carbide plant in Southern Germany provides processing capacities for $8,000$ [t] of briquetted CFRP annually (Holcim, 2019; Lange, 2018; Nagle et al., 2020; Stockschläder, 2019; Walter, 2017). Assuming a blending and briquetting ratio of $1:1$, the overall capacity for GFRP and CFRP is only 30.000 $\left[\frac{\text{t}}{\text{a}}\right]$ and 4.000 $\left[\frac{\text{t}}{\text{a}}\right]$. With regard to the upcoming masses, it can be stated that the overall capacity for the co-processing of GFRP in cement clinker industry is already too low considering only the End-of-Life waste from rotor blades of wind power plants. Concerning the combustion of crushed GFRP in waste incineration plants, we assume infinite capacity and neglect the additional transportation since incineration plants are widely distributed in the EU. However, we explicitly consider country specific GWP of waste incineration processes (cf. Appendix A).

Transportation: Concerning the European wide transportation, we implemented real-world road distances using data from OpenStreetMap and assume that all logistical processes are executed by lorries. Herein, transportation results in costs of .14 $\left[\frac{€}{\text{tkm}}\right]$ (European Commission, 2006) and environmental impacts of .16149 $\left[\frac{\text{kg CO2eq}}{\text{tkm}}\right]$ (Ecoinvent v.3.5 database: freight transport with lorry 16-32 metric ton), respectively.

We chose one geographical reference for each country as source of waste masses and **potential location for the installation of transformation processes** (waste origins, potential locations for 1st and 2nd stage capacities). The locations directly impact the process related GWP (cf. Appendix A). Figure 4 displays the locations.

Figure 4: Aggregated GFRP/CFRP end-of-life waste streams from [2020, ..., 2030] in the EU based on the approach described in (Sommer et al., 2020).



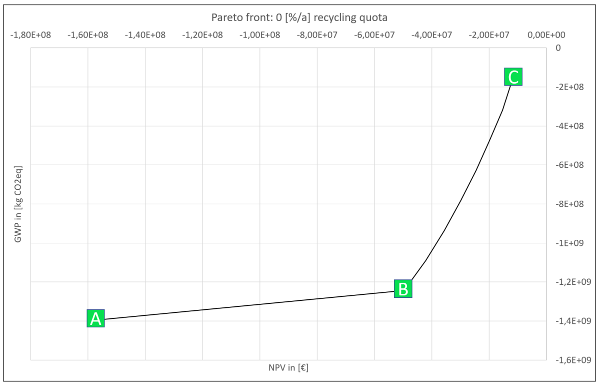
4.2. Results and insights

In the following Sections, we present results on optimal recycling infrastructures in the EU for the treatment of GFRP/CFRP waste from the wind energy industry from an economic as well as environmental perspective. Herein, we first analyze the favored end-of-life treatment of GFRP/CFRP without recycling quotas in Section 4.2.1 as a base scenario. Afterwards, we analyze the impact of recycling quotas on the system in Section 4.2.2.

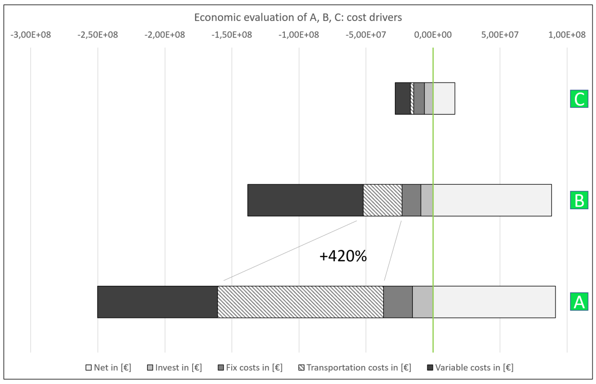
4.2.1. Base scenario

Figure 5 summarizes the results for the base scenario, i.e. objectives (Figure 5a), cost drivers (Figure 5b), and resulting recycling infrastructures (Figure 5c-e) that result if no recycling quotas have to be fulfilled. All results are given for 3 solutions: solution A represents a purely environmental perspective (Minimization of GWP [kg CO2eq]), solution B represents a purely economic perspective (Maximization of NPV [€]). In between, environmental/economic trade-off solutions generate a Pareto front as shown in Figure 5a. From this Pareto front, we select solution C for the following analysis as it represents the solutions at which a large decrease in GWP can be achieved by only a relatively small increase in NPV.

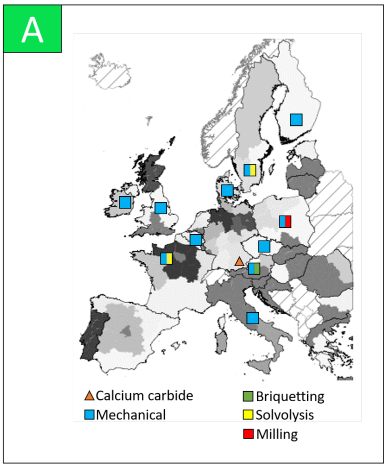
Figure 5: Results Base Scenario.



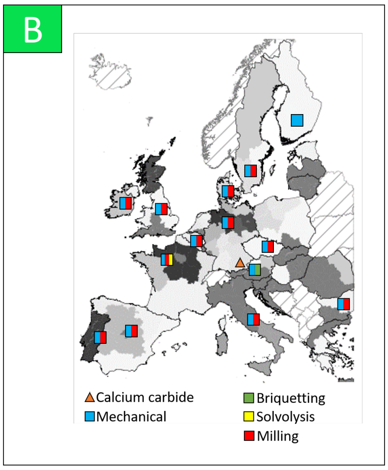
(a) Pareto front at 0 [%/a] recycling quota.



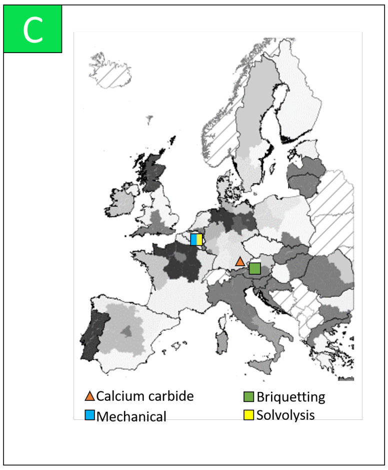
(b) Economic evaluation of A, B, C.



(c)



(d)



(e)

A **Environmental perspective: Minimization of GWP.**
GFRP: centralized mechanical recycling through milling in Poland. Large environmental benefits are generated through the substitution of primary epoxy resin. GFRP rejects are combusted in incineration plants at which energy mix is partly substituted. Substitution of energy mix is most beneficial in Poland. Large additional transportation costs are accepted for small additional environmental benefit (Figure (a), (b) development from C to A).
CFRP: centralized chemical recycling through solvolysis in Sweden and France. Large economic and environmental benefits are generated through the re-using of rCF. Sweden and France show the best energy mix, hence, the energy intensive processes are installed. CFRP rejects are co-procressed in calcium carbide plant, located in Southern Germany. Taking this into account, the geographical distribution of mechanical treatment technologies is explained.

B **Economic perspective: Maximization of NPV.**
GFRP: regional waste incineration as the economically most preferred treatment. No investments, no transportation costs (by assumption) and little acceptance costs. Environmental benefits are neglected.
CFRP: As in A and B, but solvolysis takes only place in Belgium. Belgium has a low-GWP energy mix. Although this energy mix is a little higher in GWP than France it is still preferred due to the more beneficial geographical location considering the occurring waste masses as well as the distance to the calcium carbide plant.

C **Both objectives are taken into account.**
GFRP: decentralized mechanically recycling through milling. Large environmental benefits are generated through the substitution of primary epoxy resin. Choice of locations based on the trade-off between transportation costs/ emissions and generated environmental benefits from incineration.
CFRP: As in A, but solvolysis takes only place in France due to the lower GWP in the energy mix compared to Belgium.

The following general insights were obtained:

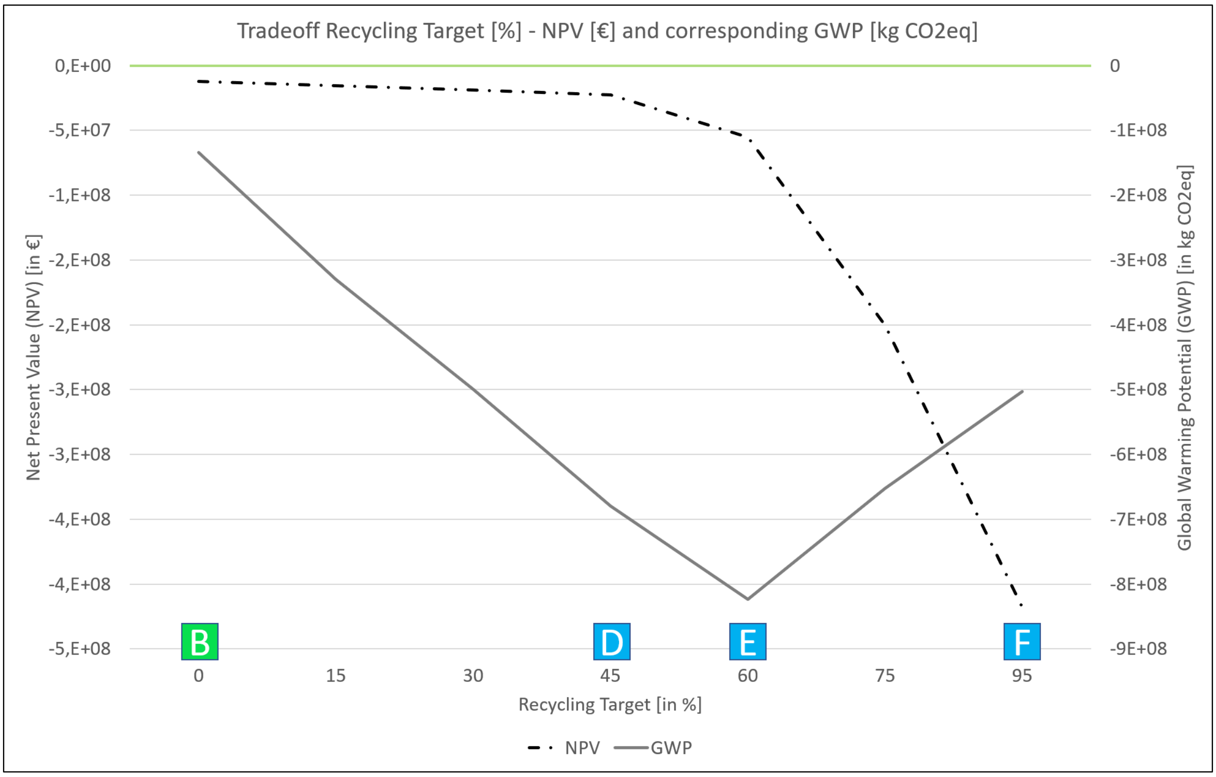
1. From an economic and environmental perspective, **CFRP** is chemically recycled due to large economic as well as environmental benefits of re-using rCF and rP as secondary material if the respective secondary markets are available (cf. Tables 2 and 3). The energy intensive recycling processes are installed in countries with low-GWP energy mixes such as France, Belgium or Sweden.
2. If following a purely economic target, **GFRP** is sent to regional waste incineration plants.
3. If following an environmental perspective, **GFRP** is mechanically recycled. Herein, small additional investments and low operational costs go along with large environmental benefits through the substitution of primary epoxy resin (see high gradient in Figure 5 (a) from solution B to solution C).
4. The GWP can still be decreased (from solution C to solution A), if the **GFRP** recovery processes are performed within countries with a high-GWP energy mix. Herein, the low-quality GFRP rejects, which are produced through mechanical recycling besides the epoxy resin (cf. Table 2), are combusted in waste incineration plants. As this combustion partly accounts for energy recovery (Appendix A) this substitutes the local energy mix. Thus, the calculated energy recovery is the higher, the higher the GWP of the substituted local energy mix is. Thus, the gradient from solution C to solution A represents an increasing transportation of material to countries with a high-GWP energy mix. In the extreme solution A, a centralized mechanical recycling of GFRP is performed in Poland. The resulting high transportation costs (and respective GWP) of transportation are calculational substituted by the recovery of energy and thus the substitution of the local high-GWP energy mix.

As can be seen, favored end-of-life treatment solutions for GFRP/CFRP depend on the overall target, i.e., if the aim is to minimize GWP or to maximize the NPV. Small additional investments that allow for recycling of the epoxy resin can result in high environmental benefits.

4.2.2. Varying recycling quotas

In the following, we analyze into what direction recycling quotas steer the treatment system, i.e., we test if and to what extent recycling quotas that enforce the circularity of materials, change the installed treatment capacities and material flows, and test the impact on the NPV and GWP. Herein, we account for the current regulation in the European Union, in which the design and operation of recycling systems is based on economic decisions of investors and recycling companies, but the system is initialized and steered by

Figure 6: Trade-off between recycling quotas and economic effort with corresponding environmental benefit.



recycling targets as is the case for WEEE, batteries or plastics (European Parliament and Council of the European Union, 2000, 2003, 2006). The underlying implicit assumption herein is that circulation of materials and recycling is per se advantageous.

In our analysis, we require that specific recycling quotas $\left(15, 30, 45, 60, 75, 95\left[\frac{\%}{\mathrm{a}}\right]\right)$ must be satisfied at minimal NPV. To regard for this in our model, we minimize the economic objective and add recycling quotas as new constraints. We then analyse the impact on the choice of end-of-life treatment and accompanying recycling infrastructures as well as the impact on the environmental objective.

Figure 6 represents the results of our experimental study. The required recycling quotas $\beta\left[\frac{\%}{\mathrm{a}}\right]$ are displayed on the x-axis. The NPV [€] is displayed on the left y-axis and represented by the dashed line, while the GWP [kg CO2eq] is displayed on the right y-axis and represented as straight line. We apply a lexicographic optimization. First, we optimize the economic value, i.e. minimize NPV, for each recycling quota $\left(0, 15, 30, 45, 60, 75, 95\left[\frac{\%}{\mathrm{a}}\right]\right)$. Subsequently, we optimize the environmental objective at the given economic value and recycling target. Note that Point B in Figures 5 and 6 represents the same scenario, i.e., the minimal NPV that can be achieved if no recycling quota exists (recycling quota of $0\left[\frac{\%}{\mathrm{a}}\right]$).

As can be seen in Figure 6, increasing recycling targets demand for increasing economic efforts and thus a lower NPV results. However, additional economic effort is rather low up to a recycling quota of 45 $\left[\frac{\%}{a}\right]$ (cf. dashed line between Point B and D), but increases more rapidly for recycling targets between 45 and 60 $\left[\frac{\%}{a}\right]$ (cf. dashed line Point D and E), and sharply for recycling quotas above 60 $\left[\frac{\%}{a}\right]$ (cf. dashed line between Point E and F).

While the NPV continuously decreases with increasing recycling quotas, the GWP behaves differently. Up to a recycling quota of 60 $\left[\frac{\%}{a}\right]$, the additional economic effort leads to additional environmental benefits (cf. straight line Point B and E). However, recycling quotas of more than 60 $\left[\frac{\%}{a}\right]$ even result in increasing environmental impact despite (very) high additional economic efforts (cf. straight line Point E and F).

The developments of the NPV and corresponding GWP can be explained by the chosen end-of-life treatment. For all recycling quotas, CFRP is chemically recycled through solvolysis, which allows to fulfil high recycling quotas at high revenues and low environmental impacts, but requires high investments (cf. Tables 2 and 3). As already discovered for the base case, the differences in the NPV and GWP for different recycling quotas result from the treatment of GFRP: As stated in the previous section, GFRP is incinerated if political regulations respectively recycling quotas are missing (Point B). Up to recycling quotas of 60 $\left[\frac{\%}{a}\right]$, the amount of GFRP that is mechanically recycled continuously increases at the expense of the amount of incinerated GFRP. This increase requires only small additional investments, but allows to exploit high environmental benefits (Tables 2 and 3). Accordingly, the NPV (dashed line) decreases only slightly, while the GWP (straight line) decreases strongly. However, if recycling quotas above 60 $\left[\frac{\%}{a}\right]$ are required, GFRP have to be chemically recycled by solvolysis as mechanical recycling through milling cannot meet the high recycling rates due to technology-specific yield rates, assuming that the status quo prevails (cf. Table 2). However, the environmental benefits of the resulting secondary materials from chemical recycling of GFRP are not able to outweigh the additional environmental impacts of the energy-intensive solvolysis. Therefore, the NPV decreases rapidly, while the GWP even increases compared to recycling targets of less than 60 $\left[\frac{\%}{a}\right]$.

Concluding, chemical recycling of CFRP seems to be an advantageous solution from both economic and environmental perspective. However, uncertainties within the technological development and reservations against the quality of the secondary materials might hinder the development of recycling infrastructure. Thus, recycling targets might promote and speed up the development. Mechanical recycling of GFRP seems also to be beneficial from an environmental perspective, but requires small additional investments. Here, recycling quotas might steer the system such that the environmental benefits can be exploited at little additional effort. Too high recycling targets might even steer the system into an unintended direction as there is a trade-off between circularity and GWP.

4.3. Discussion of results and contribution

In this paper, we analyze the economically and environmentally favored end-of-life treatment of GFRP/CFRP. In contrast to existing literature (Liu et al., 2019a; Oliveux et al., 2015; Sommer and Walther, 2020; Vo Dong et al., 2018, e.g.), we focuse on a holistic system view by designing the required recycling infrastructure to be able to state the most beneficial end-of-life treatment applying an MODM approach. We conducted detailed LCIAs of each end-of-life treatment path, herein focusing not only on environmental burdens from operating treatment technologies and potential environmental benefits through the substitution of natural resources and fossil fuels, but also regarding regional differences with respect to the technologies and final treatment system (cf. the Appendix A).

We conclude that the favored treatment for CFRP is chemical recycling, herein agreeing with previous studies. The findings indicate that the favored treatment for GFRP is mechanical recycling, but political regulations are necessary to fully exploit the environmental and economic potential. In general, the geographical location of any treatment is decisive for the environmental perspective, affecting whether energy intensive solvolysis processes are operated or energy recovery through combustion of GFRP is exploited.

However, we want to critically reflect the results as well as point out few assumptions, which might have an impact on the results. As indicated in Table 1 of this publication, the environmental burden of the primary production of carbon fibre and epoxy resin show a certain range of values (cf. Table 1). Concerning the primary production of carbon fibers, we considered an environmental burden of $23,430 \left[\frac{\text{kg CO2eq}}{t}\right]$ (cf. Appendix A2.7), which is very close to the lower end of the depicted range in Table 1. With respect to the conducted analysis, the lower the value, the more conservative is the approach, i.e., the higher the environmental burden of the primary production, the higher the environmental benefit if rCF substitutes virgin fibers. Since our results show that CFRP is already recycled under this most conservative approach, the chosen recycling path for CFRP would not change if a higher value were considered. Considering the primary production of epoxy resin, Table 1 shows a range between 4.7 and 8.1 $\left[\frac{\text{kg CO2eq}}{t}\right]$ based on literature. We based our analysis on data from Ecoinvent v.3.5 database, which even states a total environmental burden for the primary production of epoxy resin as low as 3.9 $\left[\frac{\text{kg CO2eq}}{t}\right]$. Since the value is even lower than the depicted values from other literature, we again followed a very conservative approach similar to the carbon fiber production, i.e., the results would not change with higher values for production.

It is well known that economies of scale might have an influence on the viability of business models but also on the overall environmental performance of a waste management system due to increased efficiency in the treatment of waste streams (e.g. Sommer and Walther, 2020). In this regard, we regarded various capacity modules for the advanced chemical recycling technologies in our case study. Herein, we considered economies of scale in the investments and variable processing costs (cf. Sommer and Walther, 2020, for the considered capacity modules). However, we did not regard for capacity dependent processing emissions, i.e., a larger capacity module is similar to a smaller capacity module of the same treatment technology from an environmental perspective. As can be seen in Appendix A, we modeled each treatment technology based on recent literature. Most of the technologies discussed in the cited literature were of small capacities. Assuming that larger capacity modules are more efficient not only from an economic but also from an environmental perspective, the conducted analyses are again conservative and hence the overall results are reliable.

5. Conclusion

Within this publication, we analyzed the design of recycling infrastructures, respectively the choice of end-of-life treatment, for GFRP/CFRP waste regarding environmental and economic objectives simultaneously. We motivated the necessity for an analysis by the increasing GFRP/CFRP application and resulting waste masses, the potential economic and environmental benefits from high quality recycling as well as by the demand for environmentally and economically viable treatment of waste and the current implementation schemes that might not be successful in this sense. We aimed at analyzing the trade-off between economically and environmentally favored end-of-life treatment, and analysed the impact of potential recycling quotas to support political decision makers. We found that depending on the specific waste stream the choice of legal measures might steer the recycling system. However, especially implementing too high recycling quotas might not be effective. We further highlighted that political decision makers require ex-ante analyses on the treatment of innovative and in the future relevant waste stream to implement the appropriate instruments. At the end of this publication, we want to stress that the results clearly depend on the underlying assumptions and specific economic and environmental values used within the analysis. However, the aforementioned discussion gives an indication that the most conservative values were applied such that the statements seem to be reliable and resilient.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

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A. Detailed Life Cycle Impact Assessments

A.1. LCIAs related to the transformation technologies

The results are summarized in Tables 1 and 2 in the manuscript. The following Sections describe the detailed LCIs and LCIAs with respect to the transformation technologies shown in Figure 2. For the values in Tables 1 and 2, we present the GWP resulting from energy production with respect to the German energy mix for the sake of simplicity. In the case study, we adjusted the environmental benefits/burdens with respect to the country specific energy mixes displayed in Table 4, which are based on Ecoinvent v.3.5 database. The displayed GWP burdens are from energy production in the respective country.

Table 4: Country specific GWP burdens with respect to the energy mixes.

Country	GWP $\left[\frac{\text{kg CO2eq}}{\text{MJ}}\right]$
Germany	.1766
Finland	.0670
Spain	.0942
Italy	.1187
United Kingdom	.1474
Poland	.2846
Croatia	.1056
Belgium	.0748
Sweden	.0114
Romania	.1232
Greece	.2669
Netherlands	.1737
France	.0154
Latvia	.1690
Hungary	.1283
Bulgaria	.1759
Denmark	.1008
Austria	.0872
Czech Republic	.2157
Luxembourg	.1548
Lithuania	.1728
Portugal	.1000
Slovenia	.0886
Slovakia	.1251
Estonia	.2448
Ireland	.1456

A.1.1. Pre-diminishing

Pre-diminishing is an essential process before recycling and recovering of GFRP/CFRP. During this process, the use of a single shaft shredder and a universal cross-flow shredder was considered, based on consultations with industrial experts in pre-diminishing of GFRP/CFRP from rotor blades of wind power plants (Lange, 2018). A selection of specific machines used in this phase is presented in Table 5. The technical data of each shredding machine, including energy consumption and process duration, were obtained from the brochures of the companies (Andritz AB, 2019; Vecoplan AG, 2019). To compute the GWP impact due to the pre-diminishing process, the energy consumption ([kWh]) for each process was calculated based on the machine data. Accordingly, the GWP impact associated with the pre-diminishing process was found to be 17.64 $\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$ (Table 5).

Table 5: Machine selection of the pre-diminishing process.

Process	Machine	Demand $\left[\frac{\text{kW}}{\text{t}}\right]$	Duration $\left[\frac{\text{h}}{\text{t}}\right]$	Consumption $\left[\frac{\text{kWh}}{\text{t}}\right]$	Reference
Single shaft shredder	Vecoplan VAZ 2000	247	0.04	9.88	Vecoplan AG (2019)
Cross-flow shredder	Andriz QZ 2000	250	0.067	16.75	Andritz AB (2019)

A.1.2. Briquetting - co-processing CFRP

Further mechanical process is required after the pre-diminishing processes stated in Section A.1.1 to enable the CFRP waste to be co-processed due to technical reasons (Stockschläder, 2019). During this process, the pre-diminished CFRP is pressed into briquettes by an extrusion briquetting machine assuming BPE Shimada Extruder Briquetting Press, which consumes energy of 90 [kWh] (Nielsen, 2019). For the production of briquettes, light package material is used as matrix to cover CFRP, in a ratio of 1 : 1, matrix to CFRP (Stockschläder, 2019). For the transportation of lightweight packaging material, we assume an average distance of 150 [km]. The output briquettes can be co-processed in the calcium carbide industry, which is environmentally assessed in detail in Section A.2.3. The GWP impact associated with this process were calculated by using three parameters: extruder briquetting press, lightweight packaging material and transportation. Consequently, the entire briquetting process produces a GWP burden of 443.35 $\left[\frac{\text{kg CO2 eq}}{\text{t}}\right]$ (Table 6).

A.1.3. Blending - co-processing GFRP

To enable the GFRP waste to be co-processed, further mechanical processing is required after the pre-diminished processes stated in Section A.1.1 due to required calorific values in the cement clinker industry (Lange, 2018). During this process, the pre-diminished GFRP

Table 6: Inventory data and GWP impact of the briquetting process.

Process/Material	Amount	Data	GWP burden $\left[\frac{kg\ CO2eq}{t}\right]$
Extruder briquetting press	90 [kWh]	market for electricity, medium voltage	435.35
Lightweight packaging material	1 [t]	market for waste polyethylene, for recycling, sorted (Europe without Switzerland)	
Transportation of LWP	150 [tkm]	transport, freight, lorry 16-32 metric ton, EURO6 - RER	

are blended, which consumes energy of 6.6 [kWh] (Potgieter, 2014). For the production of blended GFRP, pre-diminished GFRP is blended with paper waste in a ratio of 1 : 1 (Lange, 2018; Holcim, 2019). For the transportation of waste paper, we assume an average distance of 150 [km]. The output of blended GFRP can then be co-processed in the cement clinker industry, which is environmentally assessed in detail in Section A.2.2. As shown in Table 7, total GWP burden associated with the pre-processes for co-processing of GFRP in cement industry includes three parameters: the energy consumption of the blending process, the emissions caused by waste paper generation and the transportation of waste paper to the cement kiln. Consequently, the GWP impact due to the co-processing in the cement industry process was calculated as 62.3 $\left[\frac{kg\ CO2eq}{t}\right]$ (Table 7).

Table 7: Inventory data and GWP impact of the co-processing in cement industry.

Process/Material	Amount	Data	GWP burden $\left[\frac{kg\ CO2eq}{t}\right]$
Blending process	6.6 [kWh]	market for electricity, medium voltage	62.3
Waste paper	1 [t]	waste paper, unsorted	
Transportation of waste paper	150 [tkm]	transport, freight, lorry 16-32 metric ton, EURO6 - RER	

A.1.4. Milling - mechanical Recycling GFRP/CFRP

The primary purpose of milling is to enhance mechanical recycling of GFRP/CFRP waste. Herein, materials are milled into a coarse fraction (rich in fibre content) and fine fractions (resin-rich powder). Both parts can further be used as material substitution of primary epoxy resin in the production of virgin GFRP/CFRP (Howarth et al., 2014), which results in environmental benefits (Section A.2.4). The energy consumption of the milling process was obtained from Howarth et al. (2014) with 270 $\left[\frac{MJ}{t}\right]$. With this amount of energy consumption, the mechanical recycling process results in a GWP burden of 47.7 $\left[\frac{kg\ CO2eq}{t}\right]$ (cf. Table 8).

Table 8: Inventory data and GWP impact of the milling process (Howarth et al., 2014).

Process/Material	Amount	Data	GWP burden $\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$
Electricity	270 [MJ]	market for electricity, medium voltage | Cutoff, U - DE	47.7

A.1.5. Pyrolysis - thermal recycling of GFRP/CFRP

The primary purpose of the pyrolysis process is to separate the fiber reinforcement from the polymer matrix, hence recycle GFRP/CFRP into its components. The exposed fiber reinforcement can then substitute virgin fibers, hence substitutes the primary production of fibers (cf. Section A.2.6 and A.2.7). The energy of the polymer matrix is recovered within the process itself. To collect the inventory data for recycling of CFRP and GFRP waste by pyrolysis, the relevant studies were reviewed. Of the reviewed studies, Pillain et al. (2019) and Khalil (2018) were the only ones that include nitrogen gas, an essential element for the pyrolysis process, within the LCI input data. Using the LCI data provided by the two studies, the GWP impact due to the pyrolysis recycling process for each case study was calculated. As the emissions based on the LCI data provided by Pillain et al. (2019) resulted in a higher value, their LCI data was applied in this study, herein taking a conservative approach.

As considered by the literature (Meng et al., 2018; Pillain et al., 2019), the potential GWP benefits achieved by the heat recovery process using the epoxy resin from the pyrolysis process were also quantified. This heat recovery credit is accounted as a negative burden and leads to a reduction in the overall GWP burden of the pyrolysis process. In this case study, the pyrolysis by-product compensates the use of natural gas for heating purposes. Using the GWP emission factor of .05608 $\left[\frac{\text{kg CO2 eq}}{\text{MJ}}\right]$ (the market for heat, district or industrial, natural gas, Germany) and the epoxy resin's calorific value $33,000 \left[\frac{\text{MJ}}{\text{t}}\right]$ (Merkisz-Guranowska, 2018), the heat recovery credit for the pyrolysis process was obtained as $647.72 \left[\frac{\text{kg CO2 eq}}{\text{t}}\right]$. The total GWP impact is calculated as $3,254.28\,(3,902 - 647.72) \left[\frac{\text{kg CO2 eq}}{\text{t}}\right]$ (Table 9).

A.1.6. Fluidized bed process - thermal recycling of GFRP/CFRP

The primary purpose of the fluidized bed process is to recycle GFRP/CFRP waste by separation of the fiber reinforcement from the epoxy resin by pyrolyzing the latter. The exposed fiber reinforcement can further substitute virgin fibers, hence substitutes the primary production of fibers (cf. Sections A.2.6 and A.2.7). The energy of the polymer matrix is recovered within the process itself. The LCI data for the fluidized bed process

Table 9: Inventory data and GWP impact of the pyrolysis process (Pillain et al., 2019).

Process/Material	Amount	Data	GWP impact $\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$
Electricity	$21,125\,[\text{MJ}]$	market for electricity, medium voltage | Cutoff, U - DE	3,902
Nitrogen	$.699\,[\text{t}]$	market for nitrogen, liquid | nitrogen, liquid | Cutoff, U - RER	
Heat recovery	$33,000\,\left[\frac{\text{MJ}}{\text{t}}\right]$	the market for heat, district or industrial, natural gas, Germany	647.72

was extracted from the studies of Meng et al. (2018) and Pickering (2006).

As considered in the previous LCI (Section A.1.5), the potential GWP benefits achieved by the heat recovery process using epoxy resin from the fluidized bed process were also quantified. This heat recovery credit is counted as a negative burden and reduces the overall GWP burdens of the fluidized bed process. In this case study, the fluidized bed by-product compensates the use of natural gas for heating purposes. Using the GWP emission factor of $.05608\left[\frac{\text{kg CO2 eq}}{\text{MJ}}\right]$ (the market for heat, district or industrial, natural gas, Germany) and the epoxy resin's calorific value, $33,000\left[\frac{\text{MJ}}{\text{t}}\right]$ (Merkisz-Guranowska, 2018), the heat recovery credit for the fluidized bed process was obtained $647.72\left[\frac{\text{kg CO2 eq}}{\text{t}}\right]$. The total GWP impact is calculated as $1,214\,(1,862-647.72)\left[\frac{\text{kg CO2 eq}}{\text{t}}\right]$ (Table 10).

Table 10: Inventory data and GWP impact of the fluidized bed process (Meng et al., 2018).

Process/Material	Amount	Data	GWP impact $\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$
Electricity	$4,020\,[\text{MJ}]$	market for electricity, medium voltage | Cutoff, U - DE	1,862
Natural Gas	$1,300\,[\text{MJ}]$	market for heat, district or industrial, natural gas | Cutoff, U - Europe without Switzerland	
Heat recovery	$33,000\,\left[\frac{\text{MJ}}{\text{t}}\right]$	the market for heat, district or industrial, natural gas, Germany	647.72

A.1.7. High Voltage Fragmentation - chemical recycling of GFRP/CFRP

The primary purpose of the high voltage fragmentation is to recycle GFRP/CFRP waste by separation of the fiber reinforcement from the epoxy resin applying electrical pulses. The exposed fiber reinforcement can further substitute virgin fibers, hence substitutes the primary production of fibers (cf. Sections A.2.6 and A.2.7). The epoxy resin can further substitute virgin epoxy resin, hence substitutes the primary production of epoxy resin (cf. Section A.2.5). The basic input parameter used to model the high voltage fragmentation recycling process was solely based on the energy demand required to generate a total of

$1,500$ numbers for electrical pulses resulting in $60\left[\frac{\text{MJ}}{\text{kg}}\right]$ waste material (Mativenga et al., 2016). In accordance to the authors, the GWP impact associated with the high voltage fragmentation process was calculated as $10,592\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$ (Table 11).

Table 11: Inventory data and GWP impact of the HVF process (Mativenga et al., 2016).

Process/Material	Amount	Data	GWP burden $\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$
Electricity	$60,000$ [MJ]	market for electricity, medium voltage | Cutoff, U - DE	$10,592$

A.1.8. Solvolysis - chemical recycling of GFRP/CFRP

The primary purpose of solvolysis is to recycle GFRP/CFRP waste by separation of the fiber reinforcement from the epoxy resin using high/low temperature and pressure. The exposed fiber reinforcement can further substitute virgin fibers, hence substitutes the primary production of fibers (cf. Sections A.2.6 and A.2.7). The epoxy resin can further substitute virgin epoxy resin, hence substitutes the primary production of epoxy resin (cf. Section A.2.5). In this study, the solvolysis treatment method considered is the supercritical water solvolysis method. In the recent study conducted by Pillain et al. (2019), CFRP waste recycling process via supercritical water solvolysis was evaluated. The authors provided primary LCI data, which includes the water and energy consumption required for the supercritical water solvolysis process. Based on the water consumption data obtained from the experiments, the authors calculated the required energy to heat the water to the supercritical state.

Although primary LCI data of the supercritical water solvolysis process were found from other reviewed literature (Khalil, 2018; Vo Dong et al., 2018), the LCI data presented in these publications were based on less recent literature (Knight, 2013) and the publications lack in sufficient explanations, in particular the conversion of the original units in which the primary data were measured by Knight (2013). Due to the lack of clarity in these LCI data, the GWP burden of supercritical water solvolysis process was assessed using only the LCI data provided by Pillain et al. (2019). The inventory data and the GWP impact due to the supercritical water solvolysis process adapted to this study lead to a GWP of $4,370\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$ (Table 12).

A.2. LCIs related to the potential sink options and their associated GWP

The following Sections describe the detailed LCIs and LCIA with respect to the potential sink options, i.e. the GWP impact of the final treatment and sales of transformed waste

Table 12: Inventory data and GWP impact of the solvolysis process (Pillain et al., 2019).

Process/Material	Amount	Data	GWP burden $\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$
Electricity	$24,700$ [MJ]	market for electricity, medium voltage | Cutoff, U - DE	$4,370$
Deionized water	$10,000$ [L]	market for water, deionized, from tap water, at user | Cutoff, U - Europe without Switzerland	

materials with regard to the recycling and recovery paths shown in Figure 7 (a). The information is summarized in Table 3.

A.2.1. Crushed GFRP (potential sink: incineration)

The GWP burden of $610\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$ associated with the incineration process of GFRP waste was obtained from Job (2013), Hedlund-Åström (2005) and Vo Dong et al. (2015). Based on the calorific value of GFRP waste considered in this study $12\left[\frac{\text{MJ}}{\text{kg}}\right]$ (Hedlund-Åström, 2005; Job, 2013), the energy recovered in waste incineration was considered as $12,000\left[\frac{\text{MJ}}{\text{t}}\right]$. The generated heat is further converted to electricity with a $35\,[\%]$ electricity generation, hence $4,200\left[\frac{\text{MJ}}{\text{t}}\right]$. Country-specific electricity grid mixes were considered. For Germany with an emissions factor (electricity, medium voltage, Germany) of $.17675\left[\frac{\text{kg CO2eq}}{\text{MJ}}\right]$, the GWP impact associated with the electricity recovery via incineration was calculated as $742.35\,(4,200\cdot .17675)\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$. Hence, the overall GWP benefit is $132.35\,(742.35-610)\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$

A.2.2. Blended GFRP (potential sink: cement clinker)

Blended GFRP (cf. Section A.1.3) is co-processed in the cement industry as a substitute for fossil fuels and raw materials. Neocomp GmbH, a German company, specializes in the co-processing of GFRP waste and produces an alternative fuel by blending shredded GFRP with waste paper. By combusting $1,000$ [t] of GFRP waste in the cement clinker plant, 450 [t] of coal, 200 [t] of sand (silicon dioxide – SiO_2) and 200 [t] of chalk (calcium oxide – CaO) are substituted (Bundesverband WindEnergie e.V.).

In this study, the GF components in the blended GFRP serve as raw material substitution (CaO, SiO_2 and Al_2O_3 + Fe_2O_3), and the polymers (epoxy resin) in the GFRP are considered to serve as fuel (coal) substitute. GFRP composite is assumed to consist of $65\,[\%]$ GF and $35\,[\%]$ epoxy resin (Lefeuvre et al., 2019). Table 13 shows the average percentage of material components of GF in rotor blades and raw material components required for cement production. As the only cement clinker plant accepting blended GFRP is currently located on soil that contains 98[%] chalk (Nagle et al., 2020), the replacement of CaO using blade waste was not considered in this study.

Table 13: The average ratio of GF components and cement production materials (Hahn, 2017).

Material component	GF component [%]	Cement clinker production requirement [%]	[%] of each material blade waste (GF – 65 [wt%]) [%]	Raw material replaced with 1 [t] blade waste [kg]
CaO	35	70	22.75	227.5
SiO_2	55	20	35.75	357.5
$Al_2O_3 + Fe_2O_2$	10	10	6.5	65

Using the ratio presented in Table 13, the amount of each substituted raw material in the cement clinker production is calculated. As previously stated, at neocomp GmbH, 450 [t] of coal substitute can be produced by using 1,000 [t] of GFRP; thus a substitution of 450 [kg] of coal (out of 1 [t] of GFRP waste) was considered. These values were used as an input to compute the GWP impact responsible for the entire production of the raw materials, which gives 328.48 $\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$ (Table 14).

Table 14: Inventory data for raw materials and GWP avoided in the cement industry.

Raw material	Raw material replaced with 1 [t] blade waste [kg]	LCI	GWP benefit $\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$
Coal	450	market for hard coal | hard coal | Cutoff, U - RoW	328.48
Limestone (CaO)	0	limestone production, crushed, for mill| Cutoff, U - CH	
Silica sand (SiO_2)	357.5	silica sand production | silica sand | Cutoff, U - DE	
Aluminium oxide (Al_2O_3)	65	market for aluminium oxide | aluminium oxide | Cutoff, U - GLO	

Since only the epoxy resin fraction (.35 · .5 [t]) is used as surrogate fuel and the blending ratio of GFRP and paper is 1:1, the heat energy produced for 1 [t] of blended GFRP is calculated as follows: 35 [%] of 0.5 [t] of GFRP is the amount of epoxy resin with a calorific value of 33,000 $\left[\frac{\text{MJ}}{\text{t}}\right]$ (Merkisz-Guranowska, 2018) plus 0.5 [t] of paper reject with a calorific value of 15,000 $\left[\frac{\text{MJ}}{\text{t}}\right]$ (Rezaei et al., 2020). The heat energy produced was obtained as 13,250 (.35 · .5 · 33,000 + .5 · 15,000) [MJ]. Similar to the incineration pathway, the generated heat is further converted to electricity with a 35 [%] transformation coefficient, which leads to the produced electricity of 4,646 [MJ]. For Germany, based on the emissions factor (electricity, medium voltage, Germany) of .17675 $\left[\frac{\text{kg CO2eq}}{\text{MJ}}\right]$, the GWP impact associated with the electricity recovery via the cement clinker industry was calculated as $824.18\,(4,646 \cdot .17675)\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$. Thus, the overall eco-credit obtained in the cement clinker industry is given as $1,149.66\,(328.48 + 824.18)\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$.

In contrast to the overall eco-credit, the GWP burden associated with the combustion of GFRP waste was obtained as in the previous LCI $\left(610\left[\frac{\text{kg CO2eq}}{\text{t}}\right]\right)$ based on (Job, 2013; Hedlund-Åström, 2005; Vo Dong et al., 2018). The calorific value of GFRP waste is $12,000\left[\frac{\text{MJ}}{\text{t}}\right]$. The GWP burden associated with the combustion of paper waste is $762.5\left[\frac{\text{kg CO2eq}}{\text{t}}\right]\left(610 \cdot 1.25\left[\frac{\text{kg CO2eq}}{\text{t}}\right]\right)$ based on the 1.25 times higher calorific value of paper waste $\left(15,000\left[\frac{\text{MJ}}{\text{t}}\right]\right)$ in comparison to GFRP $\left(12,000\left[\frac{\text{MJ}}{\text{t}}\right]\right)$. Taking the components ratio into account, the GWP burden due to the combustion of blended GFRP in the cement clinker process is obtained as $686.23\,((610 + 762.5) \cdot .5)\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$. Thus, the overall environmental benefit obtained by co-processing blended GFRP in the cement clinker industry is $464,43\,(1,149.66 - 686.23)\left[\frac{\text{kg CO2 eq}}{\text{t}}\right]$.

A.2.3. Briquetted CFRP (potential sink: calcium carbide)

Similar to the co-processing of blended GFRP in the cement clinker industry, co-processing of briquetted CFRP (1 : 1 CFRP and light weight package material) in the calcium carbide industry is a promising option (Stockschläder, 2019; Walter, 2017). Herein, the CF constituent $\left(.65\left[\frac{\text{t}}{\text{t}}\right] \cdot .5\right)$ is used as a substitute of coke, while the epoxy resin constituent $\left(.35\left[\frac{\text{t}}{\text{t}}\right] \cdot .5\right)$ is used as a surrogate fuel in combination with light weight package material $(1 \cdot .5)$ assumed to consist of low-density polyethylene (LDPE) materials, which contributes to the energy recovery at a later stage in the process. The whole calcium carbide recovery option was made based on consultation with an academic expert (Stockschläder, 2019). To assess the eco-credit achieved in the calcium carbide industry, the CF part of briquetted CFRP was considered to substitute coke with the calorific value of $28.7\left[\frac{\text{MJ}}{\text{t}}\right]$ (Davies, 2004) and multiplied by the GWP emissions factor for coke (see Table 15).

Table 15: Inventory data for raw material and GWP avoided in the calcium carbide industry.

Material component	Raw material replaced with 1 [t] CFRP waste [kg]	GWP Emission factor $\left[\frac{\text{kg CO2eq}}{\text{MJ}}\right]$	calorific value $\left[\frac{\text{MJ}}{\text{kg}}\right]$	GWP benefit $\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$
Coke	325	.02467	28.7	221.26

Using the calorific value of epoxy resin of $33,000\left[\frac{\text{MJ}}{\text{t}}\right]$ (Merkisz-Guranowska, 2018), and the calorific value of LDPE of $41,700\left[\frac{\text{MJ}}{\text{t}}\right]$ (Sonawane et al., 2017), the heat energy produced was obtained as $32,400\,((33,000 \cdot .35 + 41,700) \cdot .5)$ [MJ]. Similar to the incineration pathway, the generated heat is further converted to electricity with a 35 [%] transformation coefficient, which leads to the produced electricity of $11,340$ [MJ]. For Germany with the emissions factor (electricity, medium voltage, Germany) of $.17675 \left[\frac{\text{kg CO2eq}}{\text{MJ}}\right]$, the GWP impact associated with the electricity recovery via the calcium carbide industry was calculated as $2,004.35\,(11,340 \cdot .17675) \left[\frac{\text{kg CO2eq}}{\text{t}}\right]$. Thus, the environmental benefits obtained by co-processing briquetted CFRP in the calcium carbide industry is $2,225.61\,(221.26 + 2,004.35) \left[\frac{\text{kg CO2eq}}{\text{t}}\right]$.

To calculate the GWP impact due to the final treatment emissions in the calcium carbide industry, i.e. the emissions of the combustion of the epoxy resin and the LDPE material, at first, the GWP burden associated with the incineration process of CFRP waste was obtained from Vo Dong et al. (2015), Hedlund-Åström (2005) and Job (2013) $\left(3.39 \left[\frac{\text{kg CO2eq}}{\text{kg}}\right]\right)$. Based on that value, we obtain $.1069 \left[\frac{\text{kg CO2eq}}{\text{MJ}}\right]$ as a factor for epoxy resin. In addition, the GWP burden due to the combustion of LDPE material was obtained from Mendoza et al. (2019) $\left(2,500 \left[\frac{\text{kg CO2eq}}{\text{kg}}\right]\right)$. The final treatment emissions associated with combusting epoxy resin and LDPE are $1,884.18\,(33,900 \cdot .35 + 2,500) \cdot .5 \left[\frac{\text{kg CO2eq}}{\text{t}}\right]$.

Thus, the overall environmental benefit obtained by co-processing briquetted CFRP in the calcium carbide industry is $341,43\,(2,225.61 - 1,884.18) \left[\frac{\text{kg CO2eq}}{\text{t}}\right]$.

A.2.4. Milled CFRP/GFRP (potential sink: lightweight industry)

Since the outcome of mechanical milling, the ground matrix-rich powder, can be used as a substitute for epoxy resin, this study considered that the ground matrix powder displaces the primary production of epoxy resin (Howarth et al., 2014). The GWP impact associated with the production of virgin epoxy resin is presented in Table 16 (based on the inventory data of epoxy resin production available in Ecoinvent v.3.5, see also Section A.2.5).

Table 16: Raw material substituted and GWP avoided through the milling process.

Material	Replaced raw material	LCI	GWP benefit $\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$
Matrix rich powder	Epoxy resin	market for epoxy resin, liquid | Cutoff, U	$3,910.17$

A.2.5. rP (potential sink: chemical industry)

This study considers that the recycled epoxy resin (rP) replaces the equivalent quantity of virgin materials with the equivalent quality; thus, the GWP impact associated with the production of virgin epoxy resin is avoided (based on Oliveux et al., 2015, assuming that the composition of the polymer matrix is known, which holds as usually epoxy resin is applied in rotor blades from wind power plants (Liu and Barlow, 2017)). As shown in Table A.16, the production of epoxy resin yields a GWP of $3,910.17 \left[\frac{\text{kg CO2 eq}}{\text{t}}\right]$, which are represented as the environmental benefits through the sales of rP.

Table 17: Raw material substituted and GWP avoided of epoxy resin production.

Material	Replaced raw material	LCI	GWP benefit $\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$
Matrix rich powder	Epoxy resin	market for epoxy resin, liquid | Cutoff, U	$3,910.17$

A.2.6. rGF(high) (potential sink: textile industry)

As indicated, we assume that using rGF instead of vGF substitutes the primary production of GF. In line with this, the recycling benefit is equal to the GWP impact of vGF productions including the material and energy usage. Based on LCI data (glass fibre production | glass fibre | Cutoff, U-RER) we assessed the eco-credit to $2,224.66 \left[\frac{\text{kg CO2eq}}{\text{t}}\right]$ (Table 18).

Table 18: Inventory data and the GWP of GF production.

Material	Replaced raw material	LCI	GWP benefit $\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$
rGF	vGF	glass fibre production | glass fibre | Cutoff, U-RER	$2,224.66$

A.2.7. rCF (high/medium) (potential sink: textile industry)

As indicated, we assume that using rCF instead of vCF substitutes the primary production of CF. Although the inventory for the production of CF is not available in the Ecoinvent v.3.5 database, the dataset of polyacrylonitrile (PAN), a precursor for producing CF, is available in the European Reference Life Cycle Database (ELCD). With a combination of the PAN dataset from the ELCD as input parameter and the inventory dataset obtained from the reviewed literature (La Rosa et al., 2016; Meng et al., 2018; Khalil, 2018; Pillain et al., 2019; Vo Dong et al., 2018), the GWP impact associated with the production of virgin CF was modelled via openLCA. In addition, the following scenario was considered for the carbon fibre supply chain in this study:

- European companies purchase CF from the U.S. based company Toray (Decatur, U.S.) which has one of the highest CF manufacturing capacities in the world (Das et al.)
- The produced CF are transported by lorry from Decatur to the port of Savannah (with a distance of 724 [km]). They are further shipped to the port of Bremen with a travel distance of approximately $4,125\,[\text{nm}] = 7,640\,[\text{km}]$.

The GWP burden due to the carbon fibre manufacturing process (including the transportation emissions of vCF from the U.S. to Europe) was in the range $23,227$ to $34,210 \left[\frac{\text{kg CO2eq}}{\text{t}}\right]$ of vCF production; a similar emissions range $22,400$ to $31,000 \left[\frac{\text{kg CO2eq}}{\text{t}}\right]$ was found in the literature review conducted by Deng (2014).

The selection of input parameters to model the manufacturing process of CF is following a conservative approach by using the lowest [CO2eq] from the reviewed literature (Pillain et al., 2019); Herein, the emissions of CF production represents the recycling benefit, i.e., the lower the emissions are, the less benefit is obtained by avoiding vCF manufacturing process. As a result, the GWP impact associated with vCF production including transportation emissions was calculated as $23,430 \left[\frac{\text{kg CO2eq}}{\text{t}}\right]$ (see Table 19, note that negative and positive values indicate input and output materials.).

Table 19: LCI data and GWP impact associated with the virgin carbon fibre production (Supply Chain: US-Germany) (Pillain et al., 2019).

Input/Ouput[1]	Amount	Unit	GWP burden $\left[\frac{\text{kg CO2eq}}{\text{t}}\right]$
sulfuric acid	$-.02$	[t]	
polyacrylonitrile fibres (PAN)	-1.816	[t]	
heat, from steam, in chemical industry	-2.63	[GJ]	
tap water	-2.88	[t]	
nitrogen, liquid	-1	[t]	
market for electricity, medium voltage | Cutoff, U - NPCC, US only	-6.98	[GJ]	
Virgin carbon fibres (vCF)	1	[t]	$23,227$
Carbon monoxide	.003	[t]	
Carbon dioxide	1.013	[t]	
Hydrogen cyanide	.016	[t]	
Ammonia	.001	[t]	
Nitrogen dioxide	.00067	[t]	
Ethane	.000101	[t]	
Sulfuric acid	.01	[t]	
Land freight transportation (US inland)	724	[tkm]	203.2
Maritime transportation (US – Germany)	$7,640$	[tkm]	

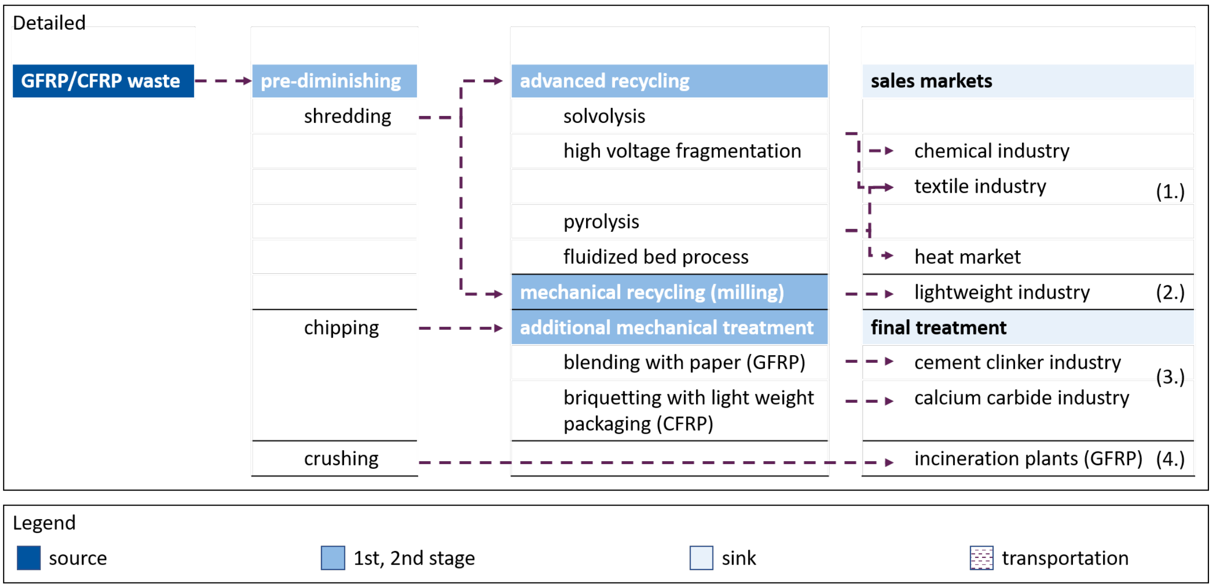
[1] Input and output indicated by negative and positive sign with respect to the amount.

B. Multi-Objective-Decision-Making Approach

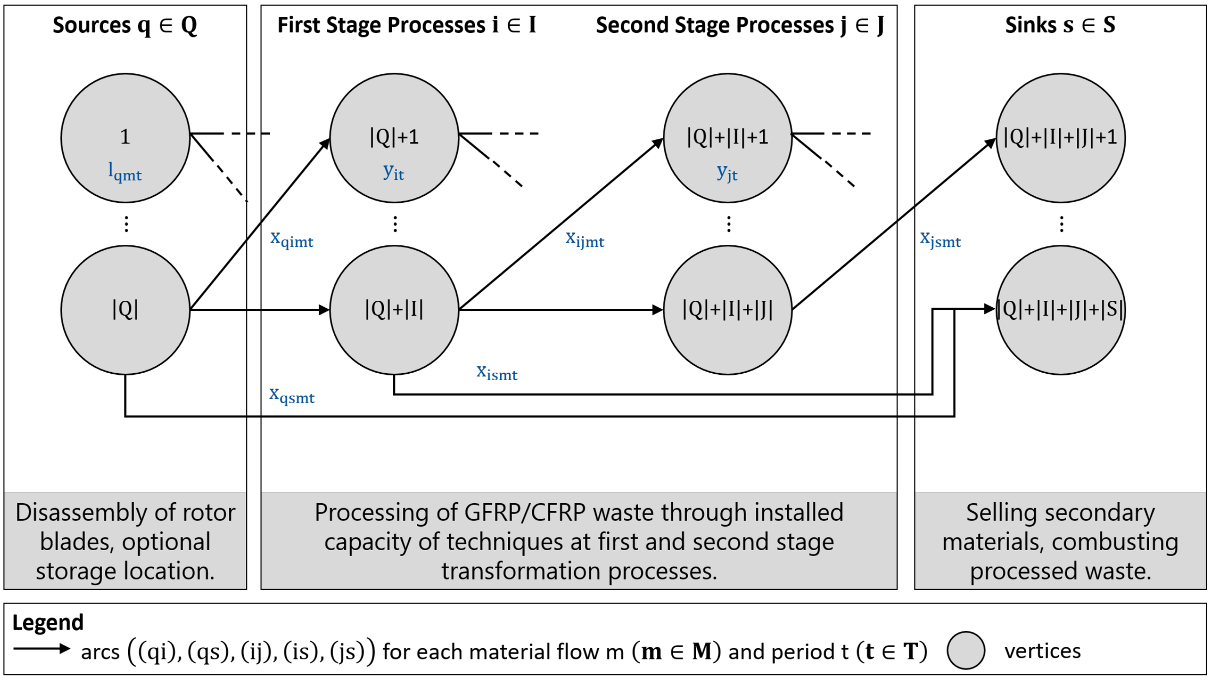
B.1. Bi-Objective Optimization Model

The planning and optimization of feasible recycling and recovery infrastructures for the treatment of GFRP/CFRP waste streams requires the mathematical representation of the real-world situation. Based on this representation, the mathematical model endogenously decides on the installation and locations of treatment capacities, transformation and transportation of waste materials while considering technical constraints.

Figure 7: (a) Overview recycling and recovery paths. (b) Graph G with vertices representing stages of each recycling and recovery path as well as transportation arcs and decisions.



(a)



(b)

Figure 7 (b) shows the underlying graph of the mathematical optimization model. At sources q ($q \in \mathcal{Q}$) GFRP/CFRP waste masses occur. To account for scale effects, waste masses can be stored at sources q. At the first stage, mechanical pre-treatment i ($i \in \mathcal{I}$), and at the second stage, advanced recycling technologies j ($j \in \mathcal{J}$) transform GFRP/CFRP waste masses. At sinks s ($s \in \mathcal{S}$) (transformed) GFRP/CFRP waste can be finally treated or sold depending on the material (cf. Section 2.2). At each processing stage, transformation processes take place where materials m ($m \in \mathcal{M}$) are processed. Between the process stages transportation takes place. Each transformation and transportation process might take place within each planning period t ($t \in \mathcal{T}$).

Decisions are taken endogenously by the mathematical model with respect to the decision variables' domains. The decisions to be taken are the installation of treatment capacities on each processing stage, indicated by y, the transportation amounts between sources, first stage, second stage and sinks, indicated by x, as well as storage amounts at sources, indicated by l.

Parameters that further define the real-world system are the information on future waste masses (N_{qmt}) in [t], information on the investments at the first $\left(C_{it}^{IN}\right)$ and at the second $\left(C_{jt}^{IN}\right)$ stage in $\left[\frac{€}{\#}\right]$, information on the respective capacities of each installed treatment technology (K_i, K_j) in [t], information on the variable environmental impacts, variable and fixed costs at the first $\left(C_{it}^{var,econ}, C_{i}^{var,env}, C_{it}^{fix,econ}\right)$ and at the second $\left(C_{jt}^{var,econ}, C_{j}^{var,env}, C_{jt}^{fix,econ}\right)$ stage in $\left[\frac{€}{\mathrm{t}}\right]$ and $\left[\frac{\mathrm{kg\ CO2eq}}{\mathrm{t}}\right]$ respectively in $\left[\frac{€}{\#}\right]$, information on the transportation costs and environmental impacts due to transportation processes between each stage $\left(c_{qimt}^{econ}, c_{qsmt}^{econ}, c_{ijmt}^{econ}, c_{jsmt}^{econ} c_{qim}^{env}, c_{qsm}^{env}, c_{ijm}^{env}, c_{jsm}^{env}\right)$ in $\left[\frac{€}{\mathrm{t}}\right]$ and $\left[\frac{\mathrm{kg\ CO2eq}}{\mathrm{t}}\right]$ including the transportation specific distances, information on material specific revenues and GWP at sinks ($r_{mst}^{econ}, r_{ms}^{env}$) in $\left[\frac{€}{\mathrm{t}}\right]$ and $\left[\frac{\mathrm{kg\ CO2eq}}{\mathrm{t}}\right]$, information on material specific acceptance costs and environmental impact at sinks ($i_{mst}^{econ}, i_{ms}^{env}$) in $\left[\frac{€}{\mathrm{t}}\right]$ and $\left[\frac{\mathrm{kg\ CO2eq}}{\mathrm{t}}\right]$. All economic related parameters carry an additional index for each time period, since we evaluate the recycling and recovery infrastructures economically by the net present value (NPV) and annual discounting of the economic parameters in dependence on interest rates become necessary. Table 20 summarizes the indexsets, parameters and decision variables.

B.1.1. Constraints: Feasible Solutions

Constraints 1 represent the conservation of mass at sources q of the graph. The amount of occurred materials (N_{qmt}) must be either stored ($l_{qmt} - l_{qmt-1}$), transported to the first stage ($\sum_{i \in \mathcal{I}} x_{qimt}$) or sinks ($\sum_{s \in \mathcal{S}} x_{qsmt}$) in dependence of the recycling and recovery path (cf. Figure 7 (a)).

$$N_{qmt} = l_{qmt} - l_{qmt-1} + \sum_{i \in \mathcal{I}} x_{qimt} + \sum_{s \in \mathcal{S}} x_{qsmt} \qquad \forall q \in \mathcal{Q}; m \in \mathcal{M}; t \in \mathcal{T} \quad (1)$$

Constraints 2 represent the conservation of mass at the first stage transformation processes i ($i \in \mathcal{I}$). The amount of transported material m towards the first stage transformation processes $\left(\sum_{q \in \mathcal{Q}} x_{qimt}\right)$ factorized with a process and material specific transformation parameter, representing the bill of material ($\gamma_{im'm}$), is equal to the amount of transformed

Table 20: Notation of the optimization model.

$\mathcal{M}$	indexset of materials	$m \in \mathcal{M}$
$\mathcal{Q}$	indexset of sources	$q \in \mathcal{Q}$
$\mathcal{I}$	indexset of potential processing locations for technologies at the first stage	$i \in \mathcal{I}$
$\mathcal{J}$	indexset of potential processing locations for technologies at the first stage	$j \in \mathcal{J}$
$\mathcal{S}$	indexset of sinks	$s \in \mathcal{S}$
$\mathcal{T}$	indexset of time periods	$t \in \mathcal{T}$
$\mathcal{A}$	indexset of all transportation arcs	$a \in \mathcal{A}$
β	defined recycling quota	[%/a]
β_{sm}	weight share of material m being recycled at sink s	[-]
r^{econ}_{mst}	revenues of material m at sink s	[€/t]
r^{env}_{ms}	environmental benefit of material m at sink s	[kg CO2eq/t]
i^{econ}_{mst}	acceptance costs of material m at sink s	[€/t]
i^{env}_{ms}	environmental burden of material m at sink s	[kg CO2eq/t]
c^{econ}_{amt}	economic transportation costs of material m on arc a	[€/t]
c^{env}_{am}	environmental burden due to transportation of material m on arc a	[kg CO2eq/t]
C^{IN}_{it}	investments in transformation capacity at i	[€/#]
C^{IN}_{jt}	investments in transformation capacity at j	[€/#]
$C^{\text{fix, econ}}_{it}$	fixed process costs for capacity at i	[€/#]
$C^{\text{fix, econ}}_{jt}$	fixed process costs for capacity at j	[€/#]
$C^{\text{var, econ}}_{it}$	variable process costs for transformation at i	[€/t]
$C^{\text{var, env}}_{i}$	variable environmental burden for transformation at i	[kg CO2eq/t]
$C^{\text{var, econ}}_{jt}$	variable process costs for transformation at j	[€/t]
$C^{\text{var, env}}_{j}$	variable environmental burden for transformation at j	[kg CO2eq/t]
$\gamma_{m'mi}$	bill of material at transformation vertex i with regard to input material m in output material m'	[-]
$\gamma_{m'mj}$	bill of material at transformation vertex j with regard to input material m in output material m'	[-]
K_i	production capacity at transformation vertex i	[t]
K_j	production capacity at transformation vertex j	[t]
K_{sm}	capacity of sink s with regard to material m	[t]
N_{qmt}	amount of occurring waste masses of material m at source q	[t]
z	interest rate	[%]
l_{qmt}	stored amount of material m at source q	[t] (continuous)
x_{amt}	transportation amount of material m on arc a	[t] (continuous)
y_{it}	number of capacity modules installed at i	[#] (integer)
y_{jt}	number of capacity modules installed at j	[#] (integer)

The table is separated into indexsets, parameters, decision variables. Index t states that a parameter or decision variable is modeled for each time period $t \in \mathcal{T}$.

material m' transported to either second stage transformation processes $\left(\sum_{j\in\mathcal{J}} x_{ijm't}\right)$ or sinks $(\sum_{s\in\mathcal{S}} x_{ism't})$ in dependence of the recycling and recovery path (cf. Figure 7 (a)).

$$\sum_{q\in\mathcal{Q}} x_{qimt}\gamma_{im'm} = \sum_{j\in\mathcal{J}} x_{ijm't} + \sum_{s\in\mathcal{S}} x_{ism't} \qquad \forall i \in \mathcal{I}; m', m \in \mathcal{M}, t \in \mathcal{T} \quad (2)$$

Constraints 3 are similar to Constraints 2 for the conservation of mass at the second stage transformation processes j $(j \in \mathcal{J})$ in dependence of the recycling and recovery path (cf.

Figure 7 (a)).

$$\sum_{i \in \mathcal{I}} x_{ijmt} \gamma_{jm'm} = \sum_{s \in \mathcal{S}} x_{jsm't} \qquad \forall j \in \mathcal{J}; m^{'}, m \in \mathcal{M}, t \in \mathcal{T} \quad (3)$$

Constraints 4 represent the technical restriction that the amount of transformation capacity at first stage transformation processes i ($i \in \mathcal{I}$), available in period t $\left(\sum_{t' \in \mathcal{T}[:t]} K_i y_{it'}\right)$, must be sufficient to transform any transported material $\left(\sum_{q \in \mathcal{Q}} x_{qimt}\right)$ in dependence of the recycling and recovery path (cf. Figure 7 (a)).

$$\sum_{q \in \mathcal{Q}} x_{qimt} \leq \sum_{t' \in \mathcal{T}[:t]} K_i y_{it'} \qquad \forall i \in \mathcal{I}; t \in \mathcal{T} \quad (4)$$

Constraints 5 are similar to Constraints 4 for the transformation capacity at the second stage transformation processes j ($j \in \mathcal{J}$) in dependence of the recycling and recovery path (cf. Figure 7 (a)).

$$\sum_{i \in \mathcal{I}} x_{ijmt} \leq \sum_{t' \in \mathcal{T}[:t]} K_j y_{jt'} \qquad \forall j \in \mathcal{J}; t \in \mathcal{T} \quad (5)$$

Constraints 6 represent the capacity limitation at sinks s ($s \in \mathcal{S}$) for material m ($m \in \mathcal{M}$). The left hand side describes all incoming masses from sources q ($q \in \mathcal{Q}$), first stage transformation i ($i \in \mathcal{I}$) and second stage transformation j ($j \in \mathcal{J}$) processes in a specific time period t ($t \in \mathcal{T}$), which is limited by the available capacity K_{sm}.

$$\sum_{1 \in \mathcal{Q}} x_{qsmt} + \sum_{i \in \mathcal{I}} x_{ismt} + \sum_{j \in \mathcal{J}} x_{jsmt} \leq K_{sm} \qquad \forall s \in \mathcal{S}; m \in \mathcal{M}; t \in \mathcal{T} \quad (6)$$

Constraints 7 represent potential political steering measures in accordance to (European Commission, 2011), i.e. annual quotas that are measured at the final sinks of a waste management network, and represent the ratio between waste materials at sources and transformed materials with respect to the demanded quota. Herein, β represents an annual quota that must be met. In accordance, parameters β_{sm} represent the fraction of material m that is recycled at sink s.

$$\beta \sum_{q \in \mathcal{Q}} \sum_{m \in \mathcal{M}} N_{qmt} \leq \sum_{s \in \mathcal{S}} \sum_{m \in \mathcal{M}} \beta_{sm} \left(\sum_{q \in \mathcal{Q}} x_{qsmt} + \sum_{i \in \mathcal{I}} x_{ismt} + \sum_{j \in \mathcal{J}} x_{jsmt} \right) \qquad \forall t \in \mathcal{T} \quad (7)$$

Constraints 8 represent the decision variables' domains, which restrict the decision variables.

$$x_{qimt}, x_{qsmt}, x_{ijm\left(m'\right)t}, x_{ism(m')t}, x_{jsm(m')t} \geq 0; y_{it(t')}, y_{jt(t')} \in \mathbb{N}^{+}$$
$$\forall q \in \mathcal{Q}; i \in \mathcal{I}; j \in \mathcal{J}; s \in \mathcal{S}; m, (m^{'}) \in \mathcal{M}; t, (t^{'}) \in \mathcal{T} \quad (8)$$

Constraints 1-8 represent the feasible recycling and recovery infrastructures, i.e. recycling and recovery infrastructure that holds for all conservation of mass. Additional technical and political restrictions are feasible for the defined planning problem.

B.1.2. Objectives: Economic and Environmental Evaluation of Feasible Solutions

The choice of economic and environmentally optimized feasible recycling and recovery infrastructures is determined by the objectives of the bi-objective optimization model.

Objectives Obj 1 and Obj 2 represent the economic and environmental objective, respectively. For transparency, we separate the economic objective into revenues (Rev^{econ}), acceptance costs (AC^{econ}), transportation costs (TR^{econ}), operational costs (OP^{econ}) and investments (IN). We separate the environmental objective into sink related GWP (Rev^{env}) and final treatment GWP (AC^{env}), transportation GWP (TR^{env}) and operational GWP (OP^{env}). Also, we summarize the transportation arcs within set $\mathcal{A}$. Set $\mathcal{A}$ represents all transportation arcs between sources q ($q \in \mathcal{Q}$), first stage i ($i \in \mathcal{I}$), second stage j ($j \in \mathcal{J}$) and sinks s ($s \in \mathcal{S}$). Each arc is denominated by the sending vertex v_1 and the receiving vertex v_2, i.e. $(v_1, v_2) \in \mathcal{A}$. Also, the two processing stages, i.e. first stage i ($i \in \mathcal{I}$), second stage j ($J \in \mathcal{J}$), are represented by set $\mathcal{P}$. Each processing stage is denominated by p. The corresponding decision variables and parameters are adjusted accordingly.

$$C^{econ} = \sum_{t \in \mathcal{T}} \frac{1}{(1+z)^t} \left(Rev_t^{econ} - AC_t^{econ} - TR_t^{econ} - OP_t^{econ} - IN_t \right),$$

with

$$Rev_t^{econ} = \sum_{s \in \mathcal{S}} \sum_{m \in \mathcal{M}} r_m st^{econ} \left(\sum_{q \in \mathcal{Q}} x_{qsmt} + \sum_{i \in \mathcal{I}} x_{ismt} + \sum_{j \in \mathcal{J}} x_{jsmt} \right),$$

$$AC_t^{econ} = \sum_{s \in \mathcal{S}} \sum_{m \in \mathcal{M}} i_{mst}{}^{econ} \left(\sum_{q \in \mathcal{Q}} x_{qsmt} + \sum_{i \in \mathcal{I}} x_{ismt} + \sum_{j \in \mathcal{J}} x_{jsmt} \right),$$

$$TR_t^{econ} = \sum_{(v_1,v_2) \in \mathcal{A}} \sum_{m \in \mathcal{M}} c_{v_1 v_2 m}^{econ} x_{v_1 v_2 m},$$

$$OP_t^{econ} = \sum_{p \in \mathcal{P}} \sum_{t' \in \mathcal{T}[:t]} C_{pt}^{fix,econ} y_{pt'} + \sum_{m \in \mathcal{M}} \left(\sum_{i \in \mathcal{I}} \left(\sum_{q \in \mathcal{Q}} C_{it}^{var,econ} x_{qimt} + \sum_{j \in \mathcal{J}} C_{jt}^{var,econ} x_{ijmt} \right) \right)$$

$$IN_t = \sum_{p \in \mathcal{P}} C_{pt}^{IN} y_{pt}$$

$$, \text{ for all } t \in \mathcal{T} \quad \text{(Obj 1)}$$

$$C^{env} = \sum_{t \in \mathcal{T}} Rev_t^{env} - AC_t^{env} - TR_t^{env} - OP_t^{env},$$

with

$$Rev_t^{env} = \sum_{s \in \mathcal{S}} \sum_{m \in \mathcal{M}} r_{mst}{}^{env} \left(\sum_{q \in \mathcal{Q}} x_{qsmt} + \sum_{i \in \mathcal{I}} x_{ismt} + \sum_{j \in \mathcal{J}} x_{jsmt} \right),$$

$$AC_t^{env} = \sum_{s \in \mathcal{S}} \sum_{m \in \mathcal{M}} i_{mst}{}^{env} \left(\sum_{q \in \mathcal{Q}} x_{qsmt} + \sum_{i \in \mathcal{I}} x_{ismt} + \sum_{j \in \mathcal{J}} x_{jsmt} \right),$$

$$TR_t^{env} = \sum_{(v_1,v_2) \in \mathcal{A}} \sum_{m \in \mathcal{M}} c_{v_1 v_2 m}^{env} x_{v_1 v_2 m},$$

$$OP_t^{env} = \sum_{m \in \mathcal{M}} \left(\sum_{i \in \mathcal{I}} \left(\sum_{q \in \mathcal{Q}} C_{it}^{var,env} x_{qimt} + \sum_{j \in \mathcal{J}} C_{jt}^{var,env} x_{ijmt} \right) \right)$$

$$, \text{ for all } t \in \mathcal{T} \quad \text{(Obj 2)}$$

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Part III.

Conclusion

7. Contribution

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In this thesis, an analysis approach for the ex-ante planning of waste management of GFRP/CFRP was developed. The following chapter concludes the thesis by outlining the main findings, summarizing the contribution and the derived managerial insights, listing remaining limitations of the thesis, and presenting an outlook on future research.

Main Findings of the Thesis

This thesis contributes to the field of waste management and sustainable material management by developing an analysis approach to ex-ante plan the management of future GFRP/CFRP waste streams. Herein, all relevant decisions and interdependencies within recycling and recovery networks are considered, e.g. investments into treatment infrastructures, process and transportation costs, revenues and treatment costs as well as policy regulations and technological developments. In the following, the main findings of each chapter are summarized.

In Chapter 1, the challenges in achieving a circular economy are described. It is stated that waste management is the key to achieve a circular economy. The need for sophisticated analyses is motivated to support decision makers with relevant information before large quantities of novel waste masses occur.

In Chapter 2, a description of the waste management of GFRP/CFRP is given. GFRP/CFRP are introduced as high performance composite materials, which have advantages in the usage phase of products but provide challenges at the End-of-Life. The state-of-the-art waste treatment options are shortly introduced and characterized from an economic, environmental, regulatory and technical perspective. In this respect, it is highlighted that the choice of the optimal waste treatment option is challenging for both waste streams. While more advanced recycling technologies require high investments and incur high costs, they enable high-quality recycling at high revenues. However, the development of secondary markets for the resulting products is uncertain. In contrast, the less sophisticated waste treatment technologies require little investment and have low process costs, but in return do not allow for high-quality recycling. Against this background, six research questions were derived regarding the optimal treatment choice of GFRP/CFRP from an economic, environmental and regulatory perspective. The research questions are answered in Chapters 4, 5 and 6.

In Chapter 3, the planning problem is placed in the broader research context of Reverse Logistics. For three decades, the research field of Reverse Logistics has been concerned with the planning of strategic infrastructure networks for the recovery of various waste streams applying mathematical optimization models. It is highlighted that researchers increasingly focused on developing initially one-dimensional, deterministic optimization models further towards multi-objective, uncertain optimization models. The required model formulation to adequately represent the introduced planning problem from Chapter 2 is further classified into the literature of Reverse Logistics: a multi-product, multi-period, multi-objective, capacitated mathematical optimization model is required.

In Chapter 4, RQ1 is answered. To provide a foundation for the ex-ante planning of the waste management of GFRP/CFRP, the upcoming waste streams are estimated. An estimation approach is developed based on a simulation study, regression analyses and a stochastic distribution function. In comparison to the existing estimation approaches, the developed approach enables a detailed analysis of the spatial and temporal distribution of GFRP and CFRP waste individually. The results show that more than 500.000 [t] of GFRP/CFRP waste from the wind energy industry will occur in the EU between 2020 and 2030. For these waste streams, the optimal treatment paths are still unknown and the required waste treatment infrastructure is still missing.

In Chapter 5, RQ2-RQ4 are answered. A decision support system to plan recycling and recovery infrastructures for GFRP/CFRP waste is developed as an integrated mixed integer linear optimization model for location, technology and capacity selection. The impact of political regulations, such as recycling and recovery targets as well as the impact of secondary market development on the overall economic viability of recycling and recovery infrastructures is analyzed through scenario analyses. The application of the developed decision support system on the estimated GFRP/CFRP waste streams provides information for political decision makers and investors on the choice of technologies as well as the resulting economic burdens and benefits. From a purely economic perspective, the optimal waste treatment of GFRP is incineration, as low-value secondary materials (rGF) prevent the economic feasibility of recycling (RQ2). However, the optimal treatment for CFRP is chemical recycling, due to the high-value secondary materials (RQ2, RQ3). If secondary markets do not develop, co-processing of CFRP remains the only option (RQ3). Besides, it is shown that high circularity and recycling targets lead to high costs, as GFRP must be chemically recycled, which leads to a tremendous increase in costs at low additional revenues. The treatment of CFRP does not differ, i.e. CFRP is still chemically recycled (RQ4).

In Chapter 6, RQ5-RQ6 are answered. The decision support system to plan recycling and recovery infrastructures for GFRP/CFRP waste is extended to a multi-objective decision-making approach, i.e. the processes are additionally evaluated from an environmental perspective. Life Cycle Assessment is conducted to evaluate the environmental impact of each treatment option. The impact of political regulations on the overall economic and environmental benefit/ burden is analyzed by scenario analyses. The results show that regardless of political regulations, the optimal treatment for CFRP is chemical recycling through solvolysis due to large economic and environmental benefits (RQ5). In contrast, the optimal treatment for GFRP is either incineration (economically favored), mechanical recycling (environmentally favored at little additional costs) and chemical recycling through solvolysis (neither favored from an economic nor environmental perspective, but required in case of certain political regulations) (RQ5). Besides, it is shown that adequate recycling targets lead to good solutions from an environmental perspective at little additional costs. Also, it is shown that high recycling targets lead to a deterioration of the solutions not only from an economic but also from an environmental perspective (RQ6).

In summary, this thesis presents an analysis approach to ex-ante analyze the waste management of (innovative) waste streams. The approach is generic as is it transferable to other waste streams besides GFRP/CFRP. The advantages of using the approach for sophisticated ex-ante analyses of the future waste management of other products, materials or waste streams are shown in Chapters 5 and 6 of this work. By applying such analyses to more and more waste streams, political decision makers will be able to better steer sustainable material management.

Contribution of this thesis

This thesis provides an analysis approach to ex-ante plan the management of waste streams. Applying this approach generates relevant information for political decision makers and investors. Hence, it increases the effectiveness of potential political regulations and supports investors with relevant information concerning potential business models. The approach consists of various advanced methodologies that enable ex-ante planning. In line with this, one main contribution of this thesis is **the demonstration of the advantage of advanced methods** in the ex-ante planning of waste management. In addition, a second contribution is the specific **insights for stakeholders**.

Regarding **the demonstration of the advantages of advanced methods**, the approach consists of various methodologies. The waste mass estimation approach in the first paper (Chapter 4) consists of a simulation study, regression analyses and a stochastic distribution function. The simulation study allows the consideration of several uncertainties in the estimation parameters, e.g. in the lifetime of products or in the mass of products. In contrast, most estimation approaches use only deterministic values, e.g. average mass per application and deterministic lifetime of x years. The advanced method enables more detailed spatial and temporal planning. The decision support system developed in the second and third paper (Chapter 5 and 6) bases on mathematical optimization models, a multi-objective decision-making approach and Life Cycle Assessment. Mathematical optimization models endogenously solve the implemented real-world problem regarding complex interdependencies, which would otherwise be only possible on a highly aggregated level. The concept of Life Cycle Assessment integrated into such models enables to ex-ante map the environmental benefit/burden of the waste treatment options.

Regarding the **insights for stakeholders**, the presented approach provides useful information for improved decision making. The information on the quantity and quality of waste streams as well as the economic evaluation is useful for further business development. Additionally, the information on the economic and environmental evaluation regarding different political targets can serve political decision makers as an indicator on how to set up political regulations to achieve a circular economy. The approach can be transferred to other waste streams with similar challenges. The thesis clearly highlights the need for more sophisticated waste stream specific ex-ante analyses to support decision makers with relevant information.

Limitations of this Thesis

Although this thesis provides a comprehensive analysis approach for analyzing the waste management of innovative materials in general and for GFRP/CFRP in particular, five main limitations remain:

First, the representation of the processing of waste streams is based on fixed transformation coefficients. This is a reasonable assumption to decrease the complexity, if the treatment processes are run at stationary operating points. However, for real-world planning problems, parameterized distribution coefficients should be applied.

Second, the approach does not explicitly account for uncertainties in planning parameters. In particular, the quantity and quality of upcoming waste masses are highly uncertain. Also, the technological development, the transformation coefficients and the development of sales markets as well as the future revenues for recycled materials are uncertain. Furthermore, these uncertainties might be interdependent, e.g. a lower waste quality requires higher efforts during the transformation processes in order to achieve high revenues from secondary materials.

Third, although a multi-objective model is presented that analyzes the trade-off between economic and environmental performance, *i*) other environmental indicators besides the Global Warming Potential could be implemented, such as Eutrophication or Resource Equivalents and *ii*) additional social objectives could be considered, such as Provision of Labor Force in economically underdeveloped regions.

Fourth, the case study was limited to GFRP/CFRP from rotor blades of wind power plants. However, including GFRP/CFRP from other industries, e.g. aerospace or automotive industry, could provide additional managerial insights and point out cross-industrial effects, e.g. high quality waste streams from aerospace could be re-used in automotive industry. Again, this holds not only for the specific case but in general.

Fifth, the length of the planning horizon is crucial, in particular for recycling and recovery infrastructures that require large investments, and thus have large payback periods. In the applied case study, a planning horizon of eleven years has been considered due to the specific waste streams as well as due to the applied waste estimation approach. However, such recycling and recovery networks should rather be planned for at least 25 years. This underlines once more the importance of explicitly regarding uncertainties in planning parameters.

Regardless of the outlined limitations, the developed approach and the conducted analyses serve as a starting point for future research.

Outlook on future research

Based on the summary of the main findings and limitations of this thesis, two main directions for future research were identified. These directions include the implementation of solution methods and the integration of uncertain parameters.

One of the major reasons of aggregating data, e.g. focusing on national waste masses instead of region-specific waste masses, is to reduce computational effort. Larger instances cannot be solved to optimality using state-of-the-art commercial solvers. Herein, solution methods could be implemented that are explicitly designed for the given problem. If powerful solution methods were implemented, the number of time periods, the number of potential locations for technologies as well as the number of capacity classes could be increased. For waste stream planning problems with various waste treatment paths and various intermediate products, such solution approaches would be helpful for real-world ex-ante planning.

One of the main challenges in waste management is the many uncertainties, e.g. uncertain quality and quantity of waste masses, uncertain technological development, uncertainty or variation of transformation coefficients. Even if such information was available and each planning parameter could be characterized by either distribution functions or ranges, a methodological approach would be needed to fully exploit the given information. The underlying mathematical optimization models could be extended by stochastic and/or robust optimization approaches. If such approaches were implemented, more resilient statements could be derived. However, the integration of stochastic and/or robust formulations would likely require a sophisticated solution method due to the increase in the scope of the model.

In summary, additional opportunities for further research remain. Addressing these opportunities could generate additional value for practitioners, but also contribute to the scientific progress. Herein, the developed analyses approach presents a starting point.