



Full length article

## Regional rotor blade waste quantification in Germany until 2040

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## ABSTRACT

Worldwide, wind turbine stocks are ageing and questions of reuse and recycling particularly of rotor blades become urgent. Especially, rising rotor blade wastes face lacking good recycling options and exact quantification is difficult due to information gaps on the rotor blade size, mass and exact material composition. In a combined approach, the expected rotor blade waste is quantified and localized on a national level for Germany until 2040. Fibre-reinforced plastics (FRP) from rotor blades are in focus and differentiated into two material classes: glass-fibre reinforced plastics (GFRP) and glass- and carbon-fibre reinforced plastics (GFRP/CFRP). The quantification approach is based on a national power plant stock database (Marktstammdatenregister) and regression models, combined with a power class-based estimation for missing datasets. As a result, between 325,726 and 429,525 t of waste from the GFRP material class and between 76,927 t and 211,721 t of waste from the GFRP/CFRP material class arise from obsolete rotor blades in Germany until 2040. This corresponds to a share of between 11% and 32% of wind turbines with GFRP/CFRP rotor blade material in Germany. For GFRP, waste peaks in 2021, 2035 and 2037 are expected with around 40,000 t of waste per year. For GFRP/CFRP, waste peaks in 2036 and 2037 will induce more than 20,000 t/a. Mostly affected federal states are Lower Saxony, Brandenburg, North Rhine-Westphalia and Schleswig-Holstein. The methods are applicable and transferable to other countries, particularly with ageing wind turbines fleets.

## Notation

CFRP carbon-fibre reinforced plastics  
EO(S)L End-of-(service)life  
GFRP glass-fibre reinforced plastics  
FRP fibre reinforced plastics  
MaStR Marktstammdatenregister (German register for power plants)

## 1. Introduction

Many countries worldwide install wind turbines to increase the renewable energy share. However, as early commercial wind turbine installations now approach their end of life (EOL), the problem of rotor blade material recycling/recovery is emerging (Liu and Barlow 2017; Ortegon et al., 2013). Until today, recycling of rotor blades is not possible (Liu and Barlow 2017) or difficult. Amongst other reasons, this is based on uncertainties regarding the materials used in rotor blades, so that many studies describe potential rotor blade material compositions (Andersen et al., 2016; Zimmermann and Gößling-Reisemann 2012; Garret et al. 2011, 2013a,b; Eymann et al., 2015; Geuder 2004; Vestas

2006; D'Souza et al., 2011; Martinez et al., 2009; Ghenai 2012; Razdan and Garrett 2017). Industrial solutions for rotor blade material recovery is shredding and landfilling, incinerating, or energetically using it in cement plants (Larsen 2009; Beauson and Brøndsted 2016). Fibre-reinforced plastics (FRP) could be recycled as filler material in cement products (Larsen 2009; Cherrington et al., 2012), or in composites used for floor tiles or road barriers (Mamanpush et al., 2018). However, these recycling options for the main rotor blade materials glass-fibre reinforced plastics (GFRP) and carbon-fibre reinforced plastics (CFRP) are not established. Technically, glass and carbon fibers have different technical characteristics leading to different GFRP and CFRP recycling technologies that must be employed (Liu et al., 2019). As FRP contribute to 2–3% to the overall waste of an obsolete wind turbine (Janzing 2019), quantification and characterization of used rotor blades is crucial to develop waste management strategies, recycling technologies and business models. The variety of rotor blades, the publicly unavailable product and material information, and variations in designed and real service lifetime hamper an exact quantification of future waste streams and a planning of necessary recycling infrastructure (Sommer et al., 2020).

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In 2019, 205 GW of installed wind turbines generated 15% of Europe's electricity (WindEurope 2020a;b). In 2019, Germany had the highest share (31.7%; 54 GW) of installed onshore wind turbine capacity of all EU-28 (WindEurope 2020c). In 2018, 29,213 onshore wind turbines (on land) in Germany generated 53 GW (17%) of the total German electricity feed-in (Statista 2020). The number of onshore wind turbines more than tripled in the last 20 years. In addition to the rising numbers, the continuous increase in size and complexity of the material composition of the rotor blades is thrilling. Rotor diameters have increased dramatically from 15 m to 160 m to ensure a high and constant energy yield also in yet uneconomic, low-wind locations (Stoevesandt et al. 2019).

Due to the expected lifespan, the reduction and expiry of the German remuneration of early wind turbines,<sup>1</sup> an increasing decommissioning or repowering of wind turbines is observed and expected. The upcoming FRP waste from rotor blades demands for functioning recycling networks in Germany.

Literature quantifies expected rotor blade waste on national level (Ortegon et al., 2013 (US); Andersen et al., 2016 (SE); Arias 2016 (US); Pehlken et al., 2017 (GER); Sultan et al., 2018 (UK); Zotz et al., 2019<sup>2</sup> (GER, onshore only); Tota-Maharaj and McMahon 2020 (UK)), in Europe (Sommer et al., 2020; Lichtenegger et al., 2020) and worldwide (Lefevre et al., 2019; Liu and Barlow 2017; Larsen 2009). Various models estimate the rotor blades' masses depending on their properties. The methodological approaches differ, however.

The majority of the studies use installed nominal capacities and age (e.g. Liu and Barlow 2017; Pehlken et al., 2017; Albers et al., 2009), or clusters with similar construction (e.g. Andersen et al., 2016; Zotz et al., 2019), which are multiplied by material-specific factors to derive material quantities. However, Pehlken et al. (2017), Arias (2016) and Albers et al. (2009) do not distinguish FRP, metals and adhesives. This is limiting the informational value of the studies for designing recycling networks, as material-specific information is needed. They estimate the upcoming waste by a rule of thumb multiplying the rotor blade length with material factors. Marsh (2017) and Janzing (2019) extend this approach by introducing material-specific factors for FRP. However, this is also not sufficient, since rotor blades usually have a tapering structure and, therefore, require a functional relationship for material estimation. Tota-Maharaj and McMahon (2020) built regression functions for capacity and weight but the tapering structure of rotor blades is better displayed by regressions of rotor blade length and weight.

Thus, other studies introduced regression models to estimate the rotor blade waste (Andersen et al., 2016; Lichtenegger et al., 2020; Sommer et al., 2020). Lichtenegger et al. (2020) and Sommer et al. (2020) quantified the waste on European level and, developed regression models for the European wind turbine stock. Thereby, it is unclear which wind turbine models are used to derive the regression functions. However, the used material varies depending on the manufacturer and the region (Sommer et al., 2020). Therefore, country specific regression models that include locally specific wind turbines seem appropriate. Lichtenegger et al. (2020) allocate the waste streams to individual European countries, but do not distinguish materials. Sommer et al. (2020) differentiate between materials GFRP and CFRP, but only on an aggregated regional level (e.g. Northern Europe) and not on country level. Andersen et al. (2016) developed a country specific regression model for

Sweden and differentiate materials of the wind turbine but not of the rotor blades. However, the differentiation of fibre materials is needed to design recycling networks as they require different treatments.

Literature and research gaps persist in quantitative, country-specific studies on the rotor blade material composition by fibre-type and upcoming waste streams. Product data sheets and LCAs do not necessarily differentiate in that level of detail (except for Pereg and de la Hoz 2013). Therefore, this study estimates the GFRP and CFRP waste from dismantling rotor blades in a case study for Germany until 2040. The novelty of this study is the FRP blade waste material forecast for Germany based on a country-specific regression model, the differentiation between GFRP and CFRP rotor blades and consideration of regional differences in a detailed spatial analysis. The results can be used for recycling network design or decision-making on potential circular economy pathways in Germany.

## 2. Methodology

First, available data on wind turbine stock was collected, prepared, enhanced and cleaned (Fig. 1, Section 2.1). Then, the existing stock of wind turbines was analysed regarding the number, types, manufacturers, date of commissioning, size of rotor blades and wind turbine locations (A) (Section 3.2). Based on the enhanced data basis, additional research for rotor blades' composition was done (Section 2.2). Literature and product data sheets of wind turbine and rotor blade manufacturers were evaluated resulting in a second dataset with additional information, i.a. on rotor blade length and weight per wind turbine type (B).

Straightforward rotor blade waste quantifications multiply the rotor blade length with material factors. However, since these usually have a tapering structure, a functional relationship is preferable to simple multiplication factors (F) (Section 2.3). Thus, we performed and extended three regression approaches based on Sommer et al. (2020). These require length and main material of the rotor blades (GFRP or a mix of GFRP and CFRP) (D). If this information is not available, a simplified material estimation according to Liu and Barlow (2017) or Albers et al. (2009) based on power classes and commissioning date applies (E). Different assumptions for the rotor blade life time are made to forecast future GFRP and CFRP waste streams from rotor blades (C) (Section 2.2.4).

### 2.1. Data analysis, enhancement and clearance

The following methodology is applied to derive GFRP and CFRP material waste streams from wind power plant registers. To analyse the wind turbine stock, we used an extract of a national power plant database "Marktstammdatenregister" (MaStR) in Germany (see Section 3.2). However, also other national or worldwide databases<sup>3</sup> could be used, but might vary regarding availability and quality of relevant information.

To close data gaps (A), duplicates were removed and the database extraction was cross-checked with other databases and literature regarding the number of operating wind turbines in Germany. Then, the dataset was analysed regarding the completeness of the individual data sets. In a third step, 10,546 data gaps of manufacturer and type were

<sup>1</sup> Ca. 5,000-6,000 wind turbines will drop out of Renewable Energy Sources Act (Erneuerbare-Energiengesetz, EEG) remuneration in 2021 (Janzing 2019; IPH 2018; Wallasch et al. 2016), followed by 1,000-2,000 wind turbines annually in the following years (Janzing 2019; IPH 2018).

<sup>2</sup> Zotz et al. (2019) estimate and differentiate between GFRP and CFRP composites from German rotor blades until 2040. However, they do not differentiate between the materials CFRP and GFRP but only quantify a total amount of GFRP and GFRP/CFRP material class. Their clusters are technology-driven and power class-driven.

<sup>3</sup> Worldwide: <https://www.thewindpower.net/> (access: 29 Jan 2021), UK: <https://www.renewableuk.com/page/UKWEDSearch> (access: 29 Jan 2021), Sweden: <http://www.vindstat.nu/stat/index.htm> (accessed on 8 Feb 2021), Denmark: <https://ens.dk/en/our-services/statistics-data-key-figures-and-energy-maps/overview-energy-sector> (access: 29 Jan 2021), US: <https://eersmap.usgs.gov/uswtbd/> (access: 29 Jan 2021).

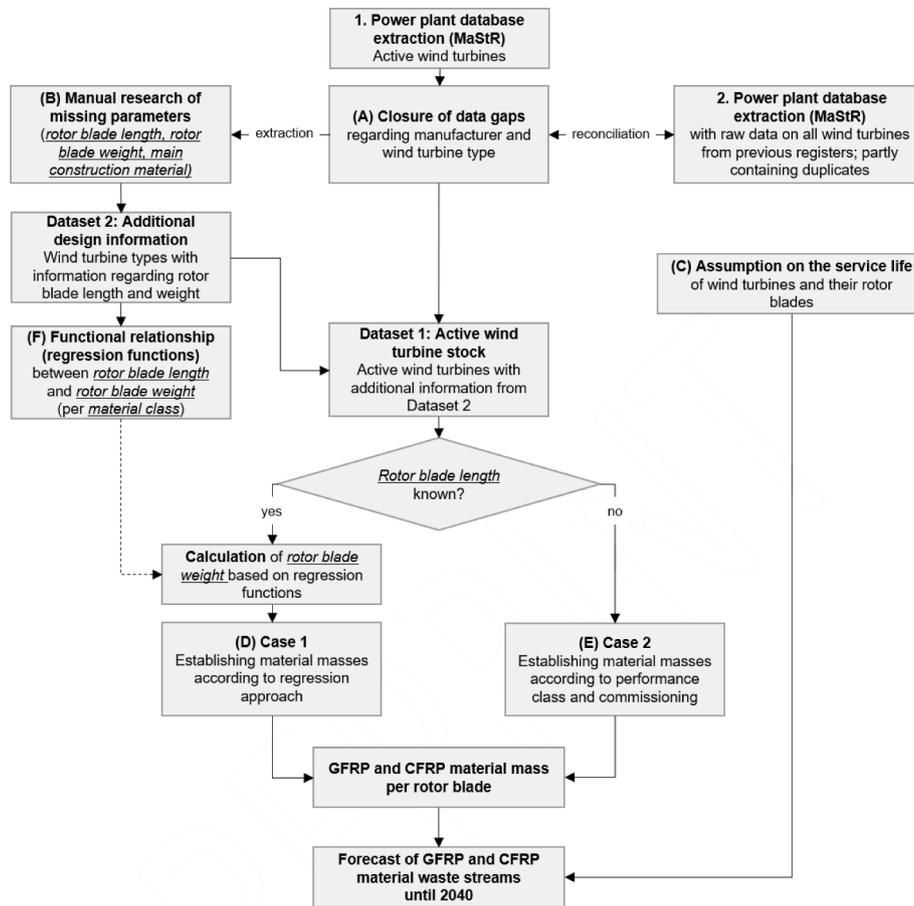


Fig. 1. Methodical approach to estimate waste streams of GFRP and CFRP until 2040. Relevant calculation parameters are underlined and in italics. The naming follows the order in which it is mentioned in the text.

closed by merging prior register<sup>4</sup> entries via other attribute combinations of the wind turbines (Section 3.2). Then, we identified wind parks (with  $\geq 10$  wind turbines at the same location) with missing information in MaStR and manually researched and added available information provided by the website of the operator. Thus, we added missing data for 1,654 wind turbines. Also, we reduced the data gap of the rotor diameter by plausible additions to the data set. If the rotor diameter for a wind turbine model was known we added this information to data entries where it was missing and also included information derived from the wind turbine model description. Finally, the dataset was cleaned from outliers and harmonized regarding the syntax of manufacturer names and wind turbine types resulting in (*Dataset 1: Active wind turbine stock*).

## 2.2. Parameters for waste assessment from rotor blades

The following sections describe the parameters needed to assess waste from rotor blade dismantling. As Sommer et al. (2020) do not provide the information basis of their regression functions, manual research (B) for rotor blades' compositions was carried out to identify the relevant parameter values for the active wind turbine stock (*Dataset 2: Additional design information*).<sup>5</sup>

<sup>4</sup> Since 2014, wind turbines are registered in Germany (Zotz et al. 2019). However, entries were only introduced at notifiable events (approval, commissioning, decommissioning) so that older wind turbines were not represented.

<sup>5</sup> Dataset 2 with additional design information is available upon request.

### 2.2.1. Rotor blade lengths

Since rotor blades usually have a tapering structure, we performed regressions based on *Dataset 2* to quantify the rotor blade wastes by a function of the rotor blade length. The length of rotor blades changed over time and with the blades' age, resulting in different waste amounts and compositions. Based on the MaStR data this development is visible: The average rotor diameter of the wind turbines installed in 1995 was less than 40 m. Between 2010/2011 and 2016 it had almost doubled to between 70 m and 88 m (see also Cherrington et al., 2012; Pehlken et al., 2017). In 2019, the average rotor diameter exceeded 133 m (Figure 8, Figure 9, supplementary information (SI)).

### 2.2.2. Rotor blade weights and main construction material

Also, rotor blade weights are influencing the waste quantification. There are several rules of thumbs to quantify the weight of a rotor blade: Albers et al. (2009) and Pehlken et al. (2017) calculate 10 tons (t)<sup>6</sup> of rotor blade material per megawatt (MW) of installed nominal capacity. Arias (2016) calculates with a factor of 9.57 tons/MW.

Additionally, some studies also estimate the share of fibre reinforced plastics (FRP) per rotor blade with 10–15 tons of FRP per MW nominal capacity (Marsh 2017; Janzing 2019) or with a share of 85% FRP within a rotor blade (Arias 2016). And, the weight is also influenced by the type of FRP as CFRP is lighter than GFRP. Therefore, these material classes should be considered separately.

The material class GFRP includes all rotor blades that use GFRP as

<sup>6</sup> Throughout the article tons refer to metric tons and are abbreviated with "t".

main construction material (besides metals, core, adhesive and painting), while the material class GFRP/CFRP includes all rotor blades that also contain CFRP. This distinction enables estimating material-specific waste streams to design a suitable recycling network as GFRP/CFRP material must be separated because CFRP is a disruptive factor in established GFRP recycling processes (Janzing 2019). Literature (BEW 2010; Christensen, 2009) and product data sheets of wind turbine and rotor blade manufacturers (Pereg and de la Holz 2013; Vestas 2016) were evaluated regarding the main rotor blade construction material. The rotor blade construction material for 349 of 460 occurring wind turbine types in MaStR could be identified, of which the blade weight of 110 models could also be identified. 266 were assigned to the material class GFRP, 42 to GFRP/CFRP and 41 to aluminium and steel. Within material class GFRP, for 37% of the wind turbine types the rotor blade weight was identified corresponding to 39% of installed wind turbines in Germany. Within GFRP/CFRP, for 31% the rotor blade weight was identified corresponding to 56% of the installed wind turbines in Germany.

### 2.2.3. Share of CFRP within rotor blades

Despite the importance to distinguish GFRP and CFRP waste streams, there is still a large knowledge gap regarding the CFRP share within rotor blades. So, even if a rotor blade is assigned to the GFRP/CFRP material class, then its CRFP content is still uncertain.

Literature values range between 2.5% (Albers et al., 2009), between 2.3% and 5.1% (Sommer et al., 2020), 6% (Lefevre et al., 2019), 15.81% (LCA study Gamesa G90 wind turbine) and between 10 and 20% (Zotz et al., 2019). See Table 4 (SI) for an overview. We address this uncertainty in different scenarios for the CFRP share within rotor blades (Section 4.3).

### 2.2.4. Rotor blade life time expectancy

The designed service life<sup>7</sup> of rotor blades depends on regulatory and legal aspects, technical aspects and economic aspects (Berkhout et al. 2013). Technical aspects include the wind load zone and turbulence at the site, the actual rotor blade condition and the availability<sup>8</sup> of the turbine (Berkhout et al. 2013). Repowering decisions due to expected revenues or subsidies may lead to shorter service lives.

The designed service life of a wind turbine is usually 20 years (Berkhout et al. 2013; DiBT 2012; Beuth, 2019; Pehlken et al., 2017; Dolan and Heath, 2012)). Life time extensions are possible if wind turbines and their rotor blades are proven to be safe and not harmful to the environment via analytic methods and monitoring/inspections (DiBT 2012). In addition, wind turbines must be profitable with electricity prices when dropping out of the remuneration after 20 years (EEG) despite additional costs for verification procedures, close monitoring and retrofitting measures (Wallasch et al., 2016). Below a permanent market price of 4 ct/kWh, plants with an average cost structure cannot continue to operate economically (Wallasch et al., 2016). As the electricity price on the spot market was below 3.785 ct/kWh in 2020 and even below 2 ct/kWh between February and May 2020 (Netztransparenz, 2020), it can be expected that in Germany turbines that will fall out of EEG remuneration will be increasingly decommissioned or repowered from 2021 onwards. Lichtenegger et al. (2020) mention a lifetime distribution but do not provide details. Therefore, this study assumes that wind turbines are dismantled after 20 years to forecast material waste streams until 2040 (C).

## 2.3. Regression approaches

Regression functions from Sommer et al. (2020) were applied to

MaStR data and they were adapted to Germany based on newly collected data (Section 2.2). The material quantity of the remaining wind turbines (with partly missing information) was estimated via their power class according to Liu and Barlow (2017).

Based on the operating German wind turbine stock (Dataset 1) and the additional design information (Dataset 2), first we applied the regression models (D) of Sommer et al. (2020) (regression I). Sommer et al. (2020) used regressions to quantify multiple materials (FRP, metals, core, adhesive and painting) from rotor blades in the EU. They distinguished between GFRP (eq. (1)) and CFRP (eq. (2)) in two regression functions depicting a functional relationship between rotor blade length and material mass.

$$Rotor\_blade\_weight_{GFRP} [t] = 0.00063 \left[ \frac{t}{m} \right] * Rotor\_blade\_length [m]^{2.5} \quad (1)$$

$$Rotor\_blade\_weight_{GFRP/CFRP} [t] = 0.00070 \left[ \frac{t}{m} \right] * Rotor\_blade\_length [m]^{2.4} \quad (2)$$

Sommer et al. (2020) also derived a functional relationship for the GFRP mass saved by using CFRP components (for details see there).

If rotor blade length and main construction material are unknown, its FRP are estimated based on the power class and its commissioning date (E) (Sommer et al., 2020; Liu and Barlow 2017; Albers et al., 2009). Thus, our Dataset 1 is divided into five power classes. The nominal capacity of the individual wind turbine is multiplied by the average rotor blade weight and a GFRP and CFRP material-specific parameter of the respective power class to determine its specific waste (Sommer et al., 2020). For each power class, there are two sets of material-specific parameters (before and after 2001), as from 2001 onwards some manufactures substituted GFRP parts with CFRP parts (Jamieson and Hassan 2011; TheWindPower 2020; WindTurbineModels 2021). However, as Sommer et al. (2020) consider wind turbine types and rotor blades installed all over the world for their regression model, a more precise analysis for Germany is necessary.

Thus, we adjusted the regression functions to the German wind turbine stock (regression II) (F) based on the researched additional design information (Dataset 2). The adjusted functions approximate the wind turbines and rotor blades installed in Germany more precisely. Then, the rotor blade weight with GFRP and GFRP/CFRP as main material is calculated according to eq. (3) and eq. (4) (Fig. 2).

$$Rotor\_blade\_weight_{GFRP} [t] = 0.0053 \left[ \frac{t}{m} \right] * Rotor\_blade\_length [m]^{1.9272} \quad (3)$$

$$Rotor\_blade\_weight_{GFRP/CFRP} [t] = 0.0045 \left[ \frac{t}{m} \right] * Rotor\_blade\_length [m]^{1.8996} \quad (4)$$

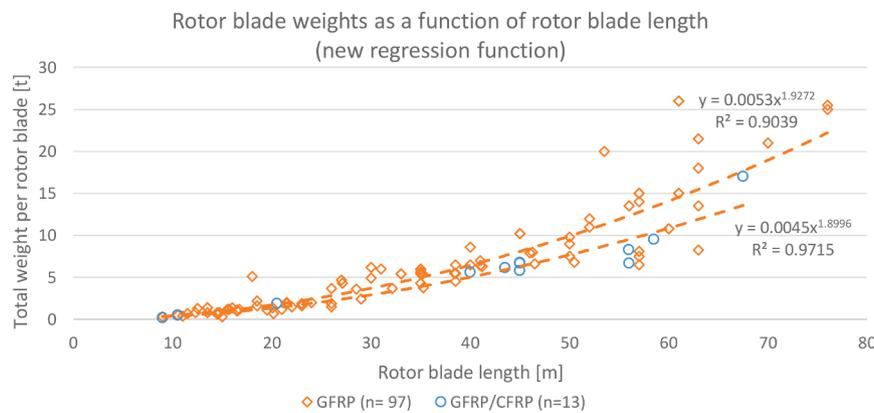
In the material estimation based on power classes and commissioning date, no adjustments were made. Within regression II, we also adjusted the share of wind turbines with CFRP. For this, we assigned rotor blades without main material information but with known length to the material class GFRP/CFRP. In addition, qualitative statements on the rotor blades' materials were also considered.<sup>9</sup> This leads to a share of 24% that it conforms with literature values (Table 4, SI).

Finally, because of uncertainties in CFRP shares within rotor blades (Section 2.2.3) we adjusted the share of CFRP per rotor blade in the GFRP/CFRP material class (regression III). We assessed three scenarios with a low, medium and high share of CFRP per rotor blade. For each scenario, we vary the factor of weight reduction for using CFRP instead of GFRP. This results in different material-specific waste streams per scenario.

<sup>7</sup> Synonyms: planned service life or minimum service life.

<sup>8</sup> Over 20 years, an availability of 95% instead of 100% can lead to an additional year of continued operation (Berkhout et al. 2013, p.81).

<sup>9</sup> Official manufacturer statements regarding CFRP use in rotor blades are rare, except for Vestas (Pehlken et al. 2017, p.252).



**Fig. 2.** New regression functions of rotor blade weight and length for GFRP and GFRP/CFRP material classes. The coefficient of determination  $R^2$  indicates the quality of the regression function; values close to 1 indicate a high quality.

Via these different ways, we quantified the expected FRP waste from rotor blades for Germany until 2040 (Section 4). This was done by combining the material masses per rotor blade<sup>10</sup> with their expected service life and their date of commissioning of the respective wind turbine. The forecast of material-specific waste per year cumulates all rotor blades' materials that are expected to be dismantled in that year. Then, the results are compared with literature (Section 5.1) and shortcomings of the approach are discussed (Section 5.2). The results can be used to feed decommissioning decision making, recycling technology development and simulations on industrial recycling networks (e.g. regarding logistics, location problems) (e.g. Westbomke et al., 2018; Rentizelas et al., 2019).

### 3. Case study

#### 3.1. General information and assumptions

The system boundaries of the case study are installed and operating wind turbines and their rotor blades in Germany. The used database on wind turbines (Section 3.2) does not contain any information on the rotor blades, neither type, age nor replacements of defective or more powerful rotor blades (repowering). Therefore, we assume that each wind turbine is equipped with a set of three equal rotor blades. And, we assume that the rotor blades are as old as the wind turbines they are attached to. However, they might have been repaired, reconditioned or replaced by new ones. We assume a rotor blade life time of 20 years (Section 2.2.4) starting from the commissioning date of the associated wind turbine. Also, we assume that all wind turbines older than 20 years are dismantled in 2021.

Due to the limited data available, we neither consider resale and continued use (reuse, second hand) of wind turbines or rotor blades nor import and export of rotor blades. Furthermore, the second-hand market is about to saturate due to an ageing fleet, a decreasing demand for used rotor blades and spare parts due to obsolescence (increasing repair) or repowering (declining revenues) and technical limits (Zotz et al., 2019). Eventually, the reuse of rotor blades will not reduce the waste amount, but only postpone it to the future (Zotz et al., 2019).

#### 3.2. The German Marktstammdatenregister (MaStR)

Since 2019, the Marktstammdatenregister (MaStR) is the official and publicly available register for electricity and gas generation plants in Germany. Among others, it was established to merge information on

German power plants and to coordinate enhancement and extension of the power grid. The obligation to provide data<sup>11</sup> for new and existing systems lies with their operators, who are also responsible for keeping the data up to date. In the register, all onshore and offshore wind turbines are listed with their current status. Due to the original purpose of the register, only energy-related information is obligatory. Information on the installed rotor blades and their material mass or composition is missing completely. Information to derive the expected waste (e.g. age, wind turbine type, rotor blade length and used rotor blade materials) are only partly available. Particularly for older wind turbines, only few information is available. Comparable databases such as Ramboll or WindPower are confidential or less comprehensive (Table 2, SI).

For the further analysis, a database subset of 30,161<sup>12</sup> onshore wind turbines with the status "in operation" (status: 16th July 2020) was extracted. The total number was compared with other databases and literature (Table 2, SI) and seems reasonable. A specific European database on the installed wind turbine stock including number, manufacturer, type, nominal capacity, rotor diameter, location and further detailed information is not available, even though global databases like WindPower provide regional reports. As WindPower focuses on wind turbines worldwide, a comparison does not seem reasonable.

In particular, the attributes of the wind turbine type, rotor blade length, rotor diameter and weight, nominal capacity, age and location are relevant for the rotor blade waste estimation. Since the data is entered in the MaStR by the wind turbine operator, the data quality of the individual datasets fluctuates. Thus, the data quality was checked in a first step. Mainly, manufacturer, type and rotor diameter information is missing (Table 3, SI). This makes it particularly difficult to estimate the market shares of the installed systems and rotor blades in the stock.

We closed some data gaps by merging prior register entries via seven other attributes' combinations per wind turbine (Table 5, SI). By combining attributes, 10,546 data records could be supplemented with manufacturer and type information. With the subsequent manual research, further 1,654 wind turbine datasets could be expanded, so that the manufacturer and the type could be stored for additional 12,200 wind turbines. This reduced the associated data gap in the attributes of manufacturer and type from the previous 64–65% to 24%. The data gap of the rotor diameter was reduced from 64% to 25% by plausible additions to the data set (e.g. wind turbines of the same manufacturer and type have the same rotor diameter). Furthermore, the MaStR dataset was cleaned by outliers and harmonized, e.g. with respect to varying syntax of wind turbine types (see Table 7, SI for a data quality comparison).

<sup>10</sup> In the calculation, the hub diameter was subtracted from the rotor diameter given in MaStR. The remaining rotor blade length is then applied to three rotor blades.

<sup>11</sup> Obligatory data of the registered systems includes names, addresses, locations, technologies and nominal capacity (MaStR 2020a).

<sup>12</sup> Due to prior registers and data migration, a statistical filter of the Bundesnetzagentur was used to avoid double counting (MaStR 2020b).

The wind turbine types differ in particular with regard to the nominal capacity, the hub height and the rotor diameter. It turns out that 64% of the wind turbines have no information on the hub height. The data gap for rotor diameters could be reduced to 25%. The wind turbines with data for both attributes (hub height and rotor diameter) have comparatively high hub heights (>90 m) and comparatively large rotor diameters of >70 m. In contrast to older wind turbines, more information was provided in the MaStR for newer (larger) wind turbines.

## 4. Results

### 4.1. Installed wind turbines in Germany

The general method described above has been applied to Germany, using the most relevant publicly available data. Based on the enhanced database extract (Section 3.2), most wind turbines (72%) in Germany were installed by Enercon, Vestas, Nordex, Senvion, GE Renewable Energy and Siemens Gamesa (incl. merges and acquisitions) (Figure 11, SI). The actual proportion can be even higher, since the manufacturers of over 7,000 wind turbines could not be determined via the described methodology. A comparable study showed that the market shares of these six manufacturers could be as high as 94% (Table 8, SI) (Fraunhofer IEE 2018). And, except for NEG Micon Deutschland GmbH they also dominate the older wind turbine stock. Smaller manufacturers such as REpower Systems SE, DE Wind GmbH and Tacke GmbH & Co. KG have around 150 older wind turbines each. 415 manufacturers are classified as "dissolved". Around half of the wind turbines (6,707) older than 15 years have no manufacturer information. Analyses show no clear correlation between the age and a specific manufacturer of a wind turbine.

527 different wind turbine types could be identified in MaStR. The previously described adjustments and harmonization reduce this number to 492 different types. The five largest manufacturers installed 236 different wind turbine types. Age and frequency analyses show the ageing wind turbine fleet and the most frequently installed types in existing stock (Figure 9, Figure 10 and Table 6, SI). Rotor diameters vary between 1 m and 180 m in the database. An accumulation of rotor diameters between 71 and 90 m (7,731 wind turbines) and 111–130 m (5,596 wind turbines), followed by 51–70 m (3,819 wind turbines) is visible (Figure 9 and Table 6, SI).

The age distribution of wind turbines in operation (Figure 7, SI) based on the attribute "date of commissioning" shows that 4,994 operating wind turbines (17%) are older than 19 years and thus already beyond the designed service life time (Section 2.2.4). They dropped out of EEG funding at the end of 2020 and their dismantling can be expected. Further 7,749 wind turbines (26%) are between 15 and 20 years old and will therefore reach the end of design life and of EEG remuneration in the next few years. In total, more than a third (39%) of the wind turbines are older than 15 years and, it can be assumed that their rotors will soon reach their end of life. Another third of the wind turbines (36%) are between 6 and 15 years old. Their rotor blades will also soon be due for repair and/or replacement (i.e. dismantling and disposal). As the MaStR does not contain any information on the rotor blade age, we assume that they are as old as the wind turbines.

### 4.2. Forecast of waste streams from dismantled rotor blades until 2040

The total amount of waste from rotor blades in Germany is expected to be between 664,230 t (regressions II and III) and 724,670 t (regression I) between 2021 and 2040 (Figure 12, SI). If wind turbines older than 20 years are shut down and dismantled after their EEG funding, around 65,868 tons (58,660 tons according to regression II/III) of rotor blade waste must be handled in 2021. In the following years, quantities are expected to be significantly lower (below 35,000 tons). From 2034 onwards, a waste increase is expected with a maximum of 86,453 tons in 2037. In the two following years, the amount of waste will decrease due

to less new installations in 2018 and 2019.

### 4.3. Expected fibre reinforced plastic waste from rotor blades in Germany

In the following, regression models of Sommer et al. (2020) (regression I) and the more specific regression model for Germany (regressions II and III) are applied to forecast the regional waste of FRP to be expected from the dismantling of rotor blades. Therefore, wind turbines and their rotor blades (*Dataset 1*) are assigned to either GFRP or GFRP/CFRP material class and the respective regression functions are used for the waste quantification. If required information (rotor blade length and main construction material) is missing, the built-in material is estimated based on power classes and commissioning date. In all regressions, it was assumed that the life expectancy of a rotor blade is 20 years and that currently operating rotor blades older than 20 years will be dismantled in 2021 (Table 1, SI).

Main uncertainties are the share of rotor blades with CFRP and the share of CFRP material within a CFRP-containing rotor blade. We consider these uncertainties in regression II. Within regression III, we vary the share of CFRP per rotor blade in two additional scenarios: the first scenario results in a lower average CFRP share (5%) per rotor blade compared to the average share of 7% in regressions I and II. The second scenario results in an average CFRP share of 17%. These results are in line with literature (Table 4, SI).

#### 4.3.1. Regression I

For 22,050 wind turbines (73%) in Germany, main rotor blade material and the rotor blade length could be identified and expected waste could be quantified via two regression functions from Sommer et al. (2020). The material quantity of the remaining 8,117 wind turbines (27%) was estimated by their power class according to Liu and Barlow (2017). The results are summarized in Table 10 and Table 11 (SI). Rotor blades that can be clearly assigned to the material class GFRP, induce 392,914 t of GFRP until 2040 (Fig. 3). Rotor blades clearly assigned to the material class GFRP/CFRP comprise 76,927 t of FRP over the next 20 years. The methodology of Sommer et al. (2020) allows the differentiation of the total amount into the individual fibre wastes. Accordingly, the total amount includes 7,188 t of CFRP and 69,739 t of GFRP. The majority of the wind turbines' rotor blades in MaStR are made of GFRP; only 11% of the rotor blades contain CFRP.

Within the material class GFRP, the waste amount increases by 37,400 t to a total of 429,525 t<sup>13</sup> adding material from rotor blades considered by power class. The waste estimate of the GFRP/CFRP material class increases by 93,945 t to a total of 170,872 t<sup>14</sup> It includes 10,816 t CFRP and 160,056 t GFRP (Fig. 3). The share of rotor blades with built-in CFRP increases to 21%.

The strong increase in the GFRP/CFRP results from the methodology chosen to close the data gap. Per power class, the total waste amount is divided into individual waste fractions by material-specific allocation parameters. Compared to GFRP and the respective fibers' proportions in the regression model, the allocation parameters for CFRP are significantly lower. This explains the strong increase in GFRP compared to CFRP. The strong absolute increase results from additional 90% high-performance wind turbines and their GFRP/CFRP rotor blades that were built after 2001 with correspondingly high allocation parameters. So, the increase by 130% seems plausible.

#### 4.3.2. Regression II

The regression II results (Fig. 3; Table 12 and Table 13, SI) are calculated with regression functions tailored to the case of Germany

<sup>13</sup> Only rotor blades were included that did not contain any CFRP according to their power class and age.

<sup>14</sup> Only rotor blades were included that can contain CFRP according to their power class and age.

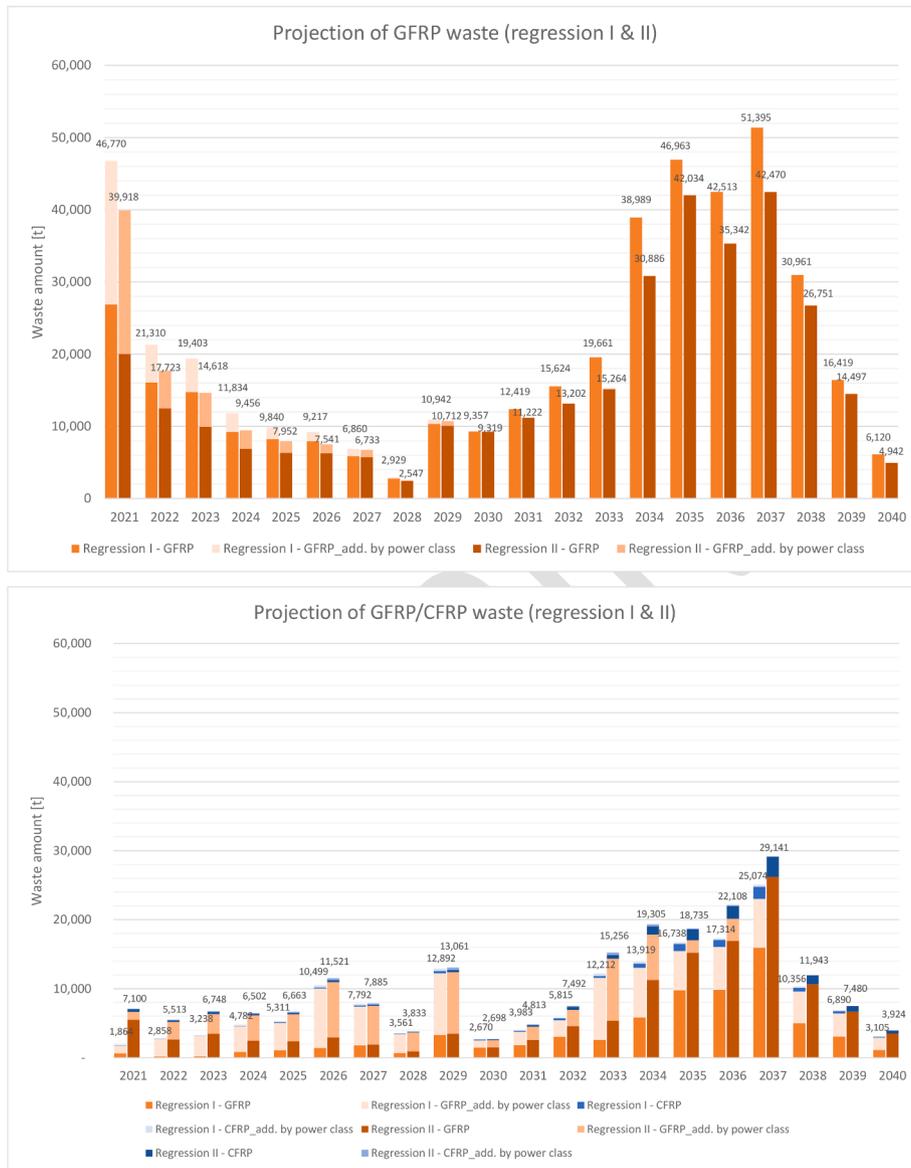


Fig. 3. Regressions I & II for GFRP (top) and CFRP/GFP (bottom) waste projection until 2040.

(Section 2.3) and additionally addresses the uncertainty of the share of rotor blades with CFRP. Through extended research and additional assumptions, data gaps on rotor blade material could be reduced. As a result, a larger part of the rotor blades' material could be calculated by regressions, and the power class approach is less important.

In the dataset, rotor blades with definitive CFRP use (11%) are underrepresented compared to *Zotz et al. (2019)* (23%). Thus, rotor blades without main material information but whose length is known, were assigned to the material class GFRP/CFRP. In addition, qualitative statements regarding rotor blades' materials were considered, whereby all rotor blades on Vestas wind turbines were also assigned to the GFRP/CFRP material class (acc. to *Lefeuve et al., 2019*). In this modified data set, 7,195 (24%) wind turbines and their rotor blades belong to the GFRP/CFRP material class. 15,426 wind turbines (51%) and their rotor blades fall into the GFRP material class. The remaining 25% are accounted via the power class approach.

In regression II, rotor blades clearly assigned to the material class GFRP induce 325,726 t waste until 2040 in Germany. Compared to regression I, the amount decreases mainly because of the assignment of Vestas' rotor blades to the GFRP/CFRP material class. Rotor blades that could be clearly assigned to the material class GFRP/CFRP will

accumulate to 143,832 t until 2040. This is almost twice as much as in regression I, because the number of considered rotor blades in this material class almost doubled. The total amount includes 13,620 t of CFRP and 130,211 t of GFRP, respectively.

Adding the materials from the power class approach,<sup>15</sup> the GFRP increase by 37,400 t to a total of 363,127 t. This corresponds to the same increase as in regression I. The forecast of GFRP/CFRP materials increases by 67,889 t to a total of 211,721 t, including 16,190 t of CFRP and 195,531 t of GFRP, respectively. This raises the share of wind turbines with CFRP rotor blades to 32%. The strong increase in material volumes of the GFRP/CFRP material class can be explained by additional 2,425 wind turbines (33%) that are assigned to this material class via power class approach. The material-specific allocation is higher compared to *Sommer et al. (2020)*, which is why GFRP increases more than CFRP. In total, 558,675 t of GFRP and 16,190 t of CFRP are generated in Germany until 2040.

The modification of the dataset in regression II leads to a significant

<sup>15</sup> Only rotor blades were included that contain CFRP according to their power class and age.

increase of the GFRP/CFRP material class. Uncertainty regarding the share of rotor blades containing built-in CFRP ranges between 24% and 32% and fits to literature values (Section 2.2).

4.3.3. Regression III

For regressions II and III, the same dataset is used. However, regression III considers the second uncertainty: the mass fraction of the built-in CFRP components. Since the results for the material class GFRP do not change compared to regression II, results are only shown for the material class GFRP/CFRP. Regressions I and II lead to an average CFRP-share of 7% in GFRP/CFRP rotor blades that is comparable to Lefeuvre et al. (2019). However, literature values vary between 2% and 20% (Table 4, SI). Therefore, we calculated three scenarios with a low, medium and high CFRP-share per rotor blade by using the adapted regression formulas for Germany (Fig. 4). For the scenario *lowCFRPshare* per rotor blade, a factor of weight reduction was set to the maximum value of 8.5, meaning that CFRP components are 8.5 times lighter than structural identical GFRP parts within a rotor blade (Sommer et al., 2020; Jamieson and Hassan 2011). When calculating material masses per power class, the lower limit of the CFRP material interval was used (Table 9, SI). This leads to an average CFRP content of 5% within a CFRP-containing rotor blade. The scenario *mediumCFRPshare* equals regression II. Thus, it is not described in more detail. For the *highCFRPshare* scenario, the factor of weight reduction was set to the minimum value and the upper limit of the material intervals within the power classes were used. This results in an average CFRP share of 17.22% within a CFRP-containing rotor blade.

In the *lowCFRPshare* scenario, a total of 9,872 t of CFRP waste will be generated by 2040. The amount is 39% lower than in regression II (16,190 t). The *highCFRPshare* scenario results in a total of 35,657 t of CFRP waste by 2040. Compared to regression II, this is an increase of 120%. With a total waste amount of 211,721 t GFRP/CFRP, the GFRP amount adapts accordingly.

4.4. Regionality of expected rotor blade waste

Only Lichtenegger et al. (2020) located and forecasted rotor blade waste at a regional NUTS 2 level for Europe until 2050. This study provides a spatial analysis (Fig. 5) of the upcoming rotor blade waste on a more detailed spatial level (postal codes) in Germany. In the material class GFRP, in five postal code areas (Rostock: 3,531 t, Prenzlau: 3,400 t, Lichtenau: 3,133 tons, Jüterbog: 2,710 t, Bredstedt: 2,190 t) more than

2,000 t of GFRP will accrue until 2040. At the federal state level, most GFRP waste will arise in Lower Saxony (81,288 t), North Rhine-Westphalia (42,571 t) and Schleswig-Holstein (41,360 t). Waste volumes in Lower Saxony and North Rhine-Westphalia are constantly on a high level, while waste volumes in Schleswig-Holstein will not increase before 2033 (Table 14 and Figure 13, SI).

The spatial analysis for the GFRP/CFRP material class show that only two postal code areas (Prenzlau: 2,504 t; Bredstedt: 2,469 t) exceed 2,000 t of waste until 2040. At federal state level, most waste of the GFRP/CFRP material class will arise in Brandenburg (34,159 t), Lower Saxony (30,017 t) and Schleswig-Holstein (18,252 t). Waste peaks of the GFRP/CFRP material class are expected for 2026, 2029, 2034, 2036 and 2037. In Brandenburg, waste is generated constantly, while in Lower Saxony waste peaks in 2029. In Schleswig-Holstein, waste does not reach a relevant level before 2033 (Table 15 and Figure 14, SI). In 2036 and 2037, the peaks accumulate to more than 20,000 t FRP.

Prenzlau (Brandenburg) and Bredstedt (Schleswig-Holstein) are local centers, where most FRP waste from both material classes will arise. And, the spatial analysis shows, that wind turbines with GFRP rotor blades are more widespread than such with GFRP/CFRP. This is reasonable, as CFRP use was only started in 2001 (Sommer et al., 2020). Furthermore, no functional relationships are visible between waste amount and average age of rotor blades on postal code area level (Figure 15, Figure 16 in SI). The analysis does not show a regional trend of material usage (Fig. 5). However, more wind turbines are located in Northern Germany and therefore more FRP waste from rotor blades will arise there.

5. Discussion

5.1. Comparison with existing studies

Our projection leads to 589,581 t of GFRP and to 10,816 t of CFRP wastes from rotor blades in Germany until 2040 (regression I). The adapted methodology to Germany leads to 664,230 t of total waste with 558,657 t of GFRP and 16,190 t of CFRP wastes (regression II). Between 2021 and 2034, Pehlken et al. (2017) forecast total waste from rotor blades in Germany to around 252,500 t with a maximum of more than 30,000 t/a in 2034. They do not differentiate between material such as FRP, metals or adhesive. Their estimate is significantly lower than the results from this study with 413,905 t (regression I) and 379,315 t (regressions II & III) for this time period. Pehlken et al. (2017) estimated

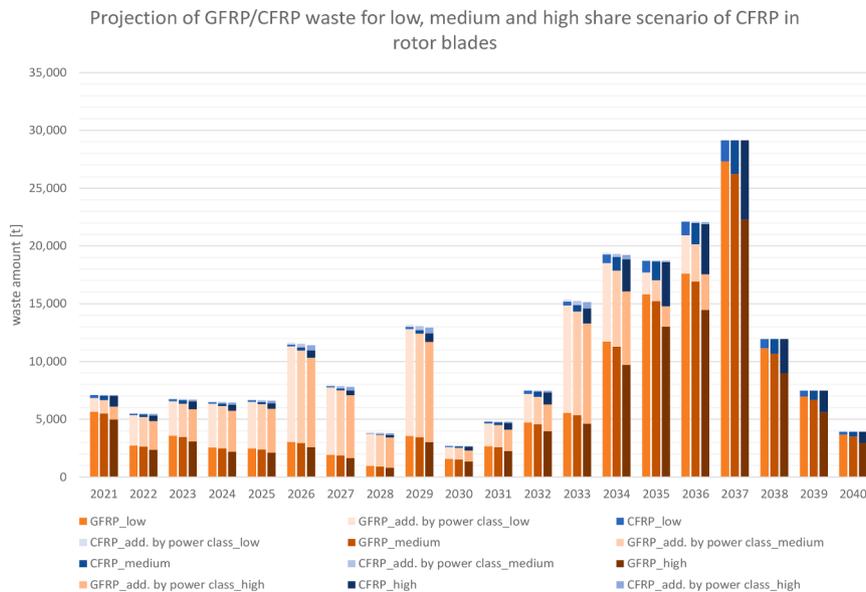


Fig. 4. Regression III with low, medium and high CFRP-share scenario in rotor blades. Projection of waste of material class GFRP/CFRP until 2040.

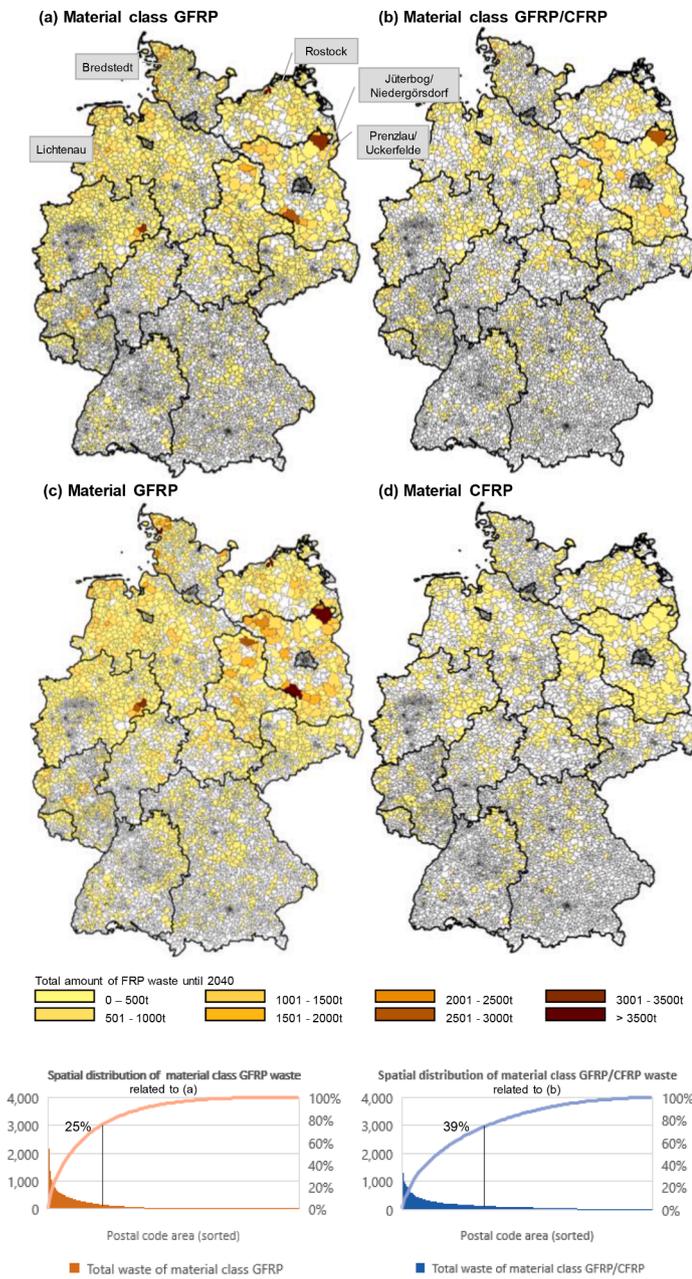


Fig. 5. Expected cumulated FRP waste [t] from rotor blades between 2021 and 2040 and its spatial distribution on postal code level in Germany (regression II) for the material class GFRP (a) and GFRP/CFRP (b) as well as the cumulative material waste for GFRP (c) and CFRP (d). A darker colouring of the map displays a higher amount of waste. Below, the spatial distribution of the expected waste per material class is displayed. For material class GFRP (left), 25% of the postal code areas are responsible for 80% of the waste and for material class GFR/CFRP (right) 39% respectively.

the upcoming waste by a rule of thumb assuming 10 t/MW of nominal capacity. Our results lead on average to 12 t/MW (regression I) and to 10 t/MW (regression II). However, also the expected dismantled capacity within that time period differs. This study estimates the dismantling of 35,175 MW and 22,706 wind turbines between 2021 and 2034 while Pehlken et al. (2017) estimates the dismantling of 25,250 MW in the same period. Albers et al. (2009) expect rotor blade waste peaks in Germany of 32,000 t/a in 2022 and 51,000 t/a in 2042, a lowering to around 15,000 t/a in 2027 and an intermediate level between 20,000 t/a and 30,000 t/a between 2030 and 2050. They estimate around half of the masses to be fibres and half of it to be resin and coating; core materials and others seem neglectable. However, they do not distinguish GFRP and CFRP.

By using the rule of thumb with 10 t/MW (Albers et al., 2009; Pehlken et al., 2017) and 9.57 t/MW (Arias 2016), 616,047 t resp. 589,557 t of total rotor blade waste will accumulate until 2040 due to the dismantling of 61,605 MW of wind power capacity in Germany (Figure 12, SI and Section 4.2). Here, the total rotor blades waste is

estimated to 724,670 t (regression I) and 664,230t (regressions II & III) (Section 4.2). Regression I (based on Sommer et al., 2020) is up to 23% higher than the results based on rules of thumb. Regression II with adapted regression functions leads to deviations between 8% and 13%.

Some studies assume between 10 and 15 t FRP per MW of nominal capacity (Marsh 2017; Janzing 2019), which results in 616,047 t (10 t/MW), 770,059 t (12.5 t/MW) and 924,071 t (15 t/MW) of FRP waste. This study estimates 600,396 t (regression I) and 574,848 t (regression II) of FRP waste which is below the results based on rule of thumb. The high deviations up to 61% demonstrate the uncertainties regarding FRP within rotor blades. A comparison to German production or waste statistics of prior years<sup>16</sup> is not possible since there are neither categories for produced nor spent rotor blades; only general GFRP production and

<sup>16</sup> E.g. via AVV/EWC (European Waste Catalogue) categories 170203 (plastics), 170904 (mixed construction and demolition waste), 101103 (glass-fibre waste) and production codes 2314 11 100ff.

waste are summarized.

Compared to [Zotz et al. \(2019\)](#), regressions I and II project a considerably lower GFRP waste by material class (429,525 t and 363,127 t) by 2040 than them (700,045 t). Reasons are the inclusion of the nacelle housing and a high assumed installation rate of wind turbines between 2018 and 2020, which did not occur. [Zotz et al. \(2019\)](#) expect GFRP/CFRP waste of 59,349 t by 2040 based on 23% of wind turbines with CFRP-containing rotor blades and an assumed CFRP-share of 10–20% per rotor blade. Compared to regression I without (76,927 t) and with (170,872 t) power class estimate and regression II without (143,832 t) and with (211,721 t) power class, the order of magnitude ranges from similar to 3.5 times higher. However, the material-wise comparison with [Zotz et al. \(2019\)](#) is difficult, because they do not explicitly differentiate between the materials GFRP and CFRP in their total waste amount.

For Germany, [Lichtenegger et al. \(2020\)](#) expect between 30,000 t (2020) and almost 40,000 t (2040) of onshore rotor blade waste from decommissioning (EOL) (42% of the European value) with a decrease between 2022 and 2035 and a peak around 2045 (52,000 t). This is consistent with our results. For Germany, we estimate the total rotor blade waste between 20,000 t/a and 30,000 t/a between 2024 and 2034 (Figure 12, SI). From 2034 onwards, it steeply increases to 55,000 t/a and to a maximum of more than 80,000 t/a in 2037. Afterwards, the expected waste amount drops to 10,000 t/a in 2040. However, [Lichtenegger's et al. \(2020\)](#) numbers are less volatile and development over time differs. We identified individual years with high waste generation, which are reached earlier compared to them.

In Europe, EOL rotor blade materials are projected between 50,000 t/a and 150,000 t/a in Europe in 2024 and 2034 ([Larsen 2009](#); [Marsh 2017](#); [Liu and Barlow 2017](#); [Lichtenegger et al., 2020](#)). Between 2020 and 2040, Europe will generate 2,527,500 t of rotor blade waste ([Liu and Barlow 2017](#)). Between 2021 and 2030, [Sommer et al. \(2020\)](#) estimate 517,817 t of GFRP waste and 16,974 t of CFRP waste from rotor blades in the EU.

Our study leads to between 26% and 30% of the European waste and is therefore comparable to the German share (30%) of installed wind power capacity in Europe ([WindEurope 2020b](#)).

## 5.2. Shortcomings

In contrast to high-level studies (e.g. [Lichtenegger et al., 2020](#); [Sommer et al., 2020](#)), general methods for national rotor blade waste quantification are complicated since data availability and quality is varying. The proposed method is adapted to the German case and shows that projections are possible even if data is scarce.

Main uncertainties persist in the share of rotor blades containing CFRP and the share of CFRP per rotor blade. To face the first, we enhanced the underlying database MaStR and adapted regression functions. To study the latter, we considered three scenarios varying the CFRP-share per rotor blade (regression III).

Like in other national studies ([Andersen et al., 2016](#)), considerable data gaps persist in the best available database on the national wind turbine stock in Germany (MaStR). They could be partially closed by manual research for the attributes wind turbine manufacturer, type and rotor diameter. Nevertheless, these entries are still missing in 24–25% of the datasets. Only 588 (2%) location entries are missing; these gaps can be neglected in the spatial analysis. Possibly, rotor blades especially on older turbines have been repaired, reconditioned or replaced. Unfortunately, MaStR does not contain any information on the rotor blade age, configuration or replacements of defective or more powerful rotors. Thus, rotor blade wastes from production/manufacturing, replacement and service are neglected. For Germany, [Lichtenegger et al. \(2020\)](#) quantify replacement waste on a quite constant level of around 10,000–15,000 t/a (onshore) and 2,500–5,000 t/a (offshore). Estimates on waste from rotor blade manufacturing are lacking for Germany. Also, offshore wind turbines and their rotor blades are neglected in this study.

[Lichtenegger et al. \(2020\)](#) quantify offshore EOL rotor blade waste up to 10,000 t/a for Germany. A further improvement of the MaStR data quality should be sought, but can only be achieved through mandatory manufacturer/operator information or through manual follow-up research.

Furthermore, a possible mismatch of “key pairs” in our database enhancements might have led to wrong data transfers from former registers and have affected results on manufacturer, type and rotor diameter.

Previous studies differentiate between main materials such as FRP, metals, core materials, adhesives and colour. [Liu and Barlow \(2016, 2017\)](#) as well as [Tota-Maharaj and McMahon \(2020\)](#) highlight the importance of composite material in EOL rotor blades (~93–95%) compared to balsa (~2%), metal (~3.3%), paint and putty (~3%). The majority of the studies does not differentiate FRP between glass or carbon fibers reinforcements ([Sommer et al., 2020](#)). Also, data gaps regarding the main rotor blade material class persist, e.g. due to bankruptcies of manufacturers/operators and unavailable manufacturers' data ([Pehlken et al., 2017](#)). To close the gap, our combined methods approach may have introduced uncertainties into the results.

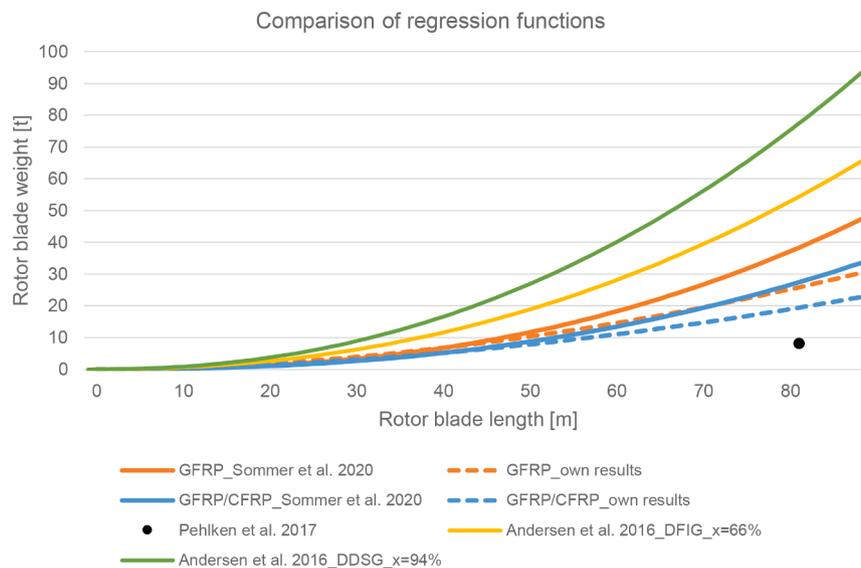
Furthermore, the new CFRP regression function is only based on 13 wind turbine types for which secured data was available. Data on further types would increase the quality of this regression function. A comparison with [Sommer et al. \(2010\)](#) shows ([Fig. 6](#)) a higher variability for rotor blade lengths of more than 50 m. The estimate of [Pehlken et al. \(2017\)](#) is significantly below the other regression functions. Based on [Caduff et al. \(2012\)](#), [Andersen et al. \(2016\)](#) estimate much higher regression functions and differentiate between direct drive synchronous generators (DDSG) and doubly-fed induction generator (DFIG). Other materials than GFRP and CFRP were not estimated due to existing recycling processes.

This study considers wind turbine and rotor blade lifetimes of 20 years (Table). Others assume 20–25 years ([Beauson et al., 2016](#); [Marsh 2017](#); [Mamanpush et al., 2018](#)) or up to 20–40 years ([Ortegon et al., 2013](#)) or show respective age distributions for wind turbine stocks in Europe (WindEurope 2020d). Life time extensions are possible with individual tests and authorities' approvals, but require much effort. Future research could analyse varying lifetimes of rotor blades; [Lichtenegger et al. \(2020\)](#) consider stochastic lifetimes already, but do not provide respective data. A shift of the predicted lifetime would offset the waste several years in either direction. [Liu and Barlow \(2017\)](#) expect a waste reduction up to 21% if rotor blades can serve for as much as 25 years and a waste increase by up to 10% if the blade lifetime falls below the design lifetime. Replaced rotor blades are not considered as they range between 2% and 2.4% per year and wind turbine ([Andersen et al., 2016](#)).

Used rotor blades are available on worldwide operating platforms.<sup>17</sup> But, in relation to the 345,000 operating wind turbines worldwide ([Marsh 2017](#)), this market is currently quite small. Like [Zotz et al. \(2019\)](#) or [Andersen et al. \(2016\)](#), we neglect the resale and continued use (e.g. at a new location) of entire wind turbines or rotor blades as the second-hand market is about to saturate and due to technical limits. Including continued (re)use into the analysis will not necessarily reduce but only postpone the waste amount into the future ([Zotz et al., 2019](#)). However, more extensive research on service life extension, market mechanisms, environmental impact and associated costs is needed.

Also, the analysis is restricted to onshore wind turbines as data gaps hamper analyses on offshore wind turbines.

<sup>17</sup> On such platforms e.g. Wind Turbines (<https://wind-turbines.com/marktplatz/komponenten/rotorblaetter>), BayWa renewable energy GmbH (<https://www.baywa-re.de/de/wind/weitere-themen/gebsrauchte-anlagen/>), or Wind Nielsen GmbH (<https://www.wind-nielsen.de/produkt-kategorie/rotor/rotorblaetter>), between 30 and 500 used rotor blades were for sale (Status: 04 Dec 2020).



**Fig. 6.** Comparison of the used regression functions (dashed lines) with literature (Sommer et al., 2020 (Europe), Pehlken et al., 2017 (Germany), Andersen et al., 2016 (Sweden) based on Caduff et al., 2012). Andersen et al. (2016) only provide the rotor diameter instead of the rotor blade lengths; thus, we halved the diameter which might lead to inconsistencies ignoring the hub.

## 6. Conclusion and outlook

This study estimates the regional waste generation from rotor blades from the German wind turbines stock between 2020 and 2040. The method is transferable to other countries and results were compared with literature. Until 2040, rotor blade waste will accumulate to between 325,726 t and 429,525 t (material class GFRP) and to between 76,927 t and 211,721 t (material class GFRP/CFRP). Mostly affected federal states are Lower Saxony, Brandenburg, North Rhine-Westphalia and Schleswig-Holstein. For the GFRP material class, waste volumes in Lower Saxony, North Rhine-Westphalia and Brandenburg are constantly high, while waste volumes in Schleswig-Holstein will not increase before 2033. For the GFRP/CFRP material class, waste is generated constantly in Brandenburg, while Schleswig-Holstein sees no significant amounts before 2033. Prenzlau (Brandenburg) and Bredstedt (Schleswig-Holstein) are local centers, where most FRP waste will arise.

Today, recycling solutions are required given the fast installation rate and the aimed material and value recovery (Ortego et al. 2013; Andersen et al., 2016). Currently, the cement industry is the only demander of GFRP from rotor blades for thermal recovery and thus dictates volumes and prices (Janzing 2019). Particularly, the high spatial and timely resolution of our study results allow decision makers in industry and research to establish the required recycling technologies, networks and capacities for spent GFRP and CFRP parts from rotor blades.

In the future, a further differentiation between the used plastics (epoxy resin, thermoplastics) and their recycling is conceivable and relationships between age and used materials could be established. Also, wind load zones and wind turbine locations could be blended to estimate a potential service life extension of underused rotor blades.

The methods are applicable and transferable to other countries, particularly with ageing wind turbine stock.

## Author contributions

Magnus Herbst and Christoph Stallkamp performed the original research where Rebekka Volk provided guidance, literature review and valuable comments. The paper was initiated by Rebekka Volk and mainly written by Rebekka Volk and Christoph Stallkamp. All authors participated in the peer-review process.

## CRedit authorship contribution statement

**Rebekka Volk:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Christoph Stallkamp:** Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Magnus Herbst:** Methodology, Formal analysis, Investigation, Resources, Data curation. **Frank Schultmann:** Supervision, Writing – review & editing.

## 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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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.resconrec.2021.105667](https://doi.org/10.1016/j.resconrec.2021.105667).

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