Estimation of glass and carbon fiber reinforced plastic waste from end- of-life rotor blades of wind power plants within India

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Abstract:

India, as a developing country is focusing on 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 rein-forced 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 in India. Based on the considered dataset, it is estimated that 570 [Mt] of fiber reinforced plastic waste will occur between 2020 and 2030 in the country of which18 [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 India aims at increasing resource efficiency and establishing a circular economy to cope with limited natural resources and to decouple economic growth from resource consumption. In line with this, regulations have been developed that define the 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 plastics. 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. In 2018, an amendment on waste was published, which focus on the 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. It is stressed that ‘‘the targets laid down in the directive on waste for preparing for re-use and re-cycling of waste should be increased to make them better reflect the objective to move to a circular economy”. 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 considered 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 target oriented 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 in various states of India. Installed power production capacities have increased from 5 GW in 2000 to 145 GW in 2024 (Wind power in India, 2024). With an average power production capacity per wind power plant of 2 MW (Lefeuvreetal., 2019), an estimated amount of 85,000 wind power plants were operated in India by 2024. Taking into account an average service life of 16–25 years (Albersetal.,2018; Lefeuvreet al., 2019; Lichtenegger et al., 2020), the annual amount of waste masses from wind power plants is expected to increase considerably. Accordingly, the government address the problem of increasing waste streams from wind power plants (Liuand Barlow, 2017; Zotzetal., 2019). A recent study of the German Environmental Protection Agency (UBA), for instance, emphasizes the importance of an exante 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 reuse, as preferred waste prevention, is limited for wind power plants. Reuse 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 Wind SystemsA/S, 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 MW (Albers et al., 2018). Other general lifetime extension measures are usually already considered in the calculation of the life times of wind turbines, i.e. expected waste masses are postponed (cf. Lichtenegger et al., 2020). As reuse 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 rein-forced plastics (GFRP) and carbon fiber reinforced plastics (CFRP) (Albers et al., 2018; Kaiser and Seitz, 2014), for which treatment options are still being researched (e.g.Karuppannan 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 India. 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). A typical composite blade used in wind turine is as shown in figure 1.

As motivated, this publication concentrates on the estimation of future FRP waste and therefore denominate the non-critical materials as other materials. In particular, aggregated FRP is not considered, 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).

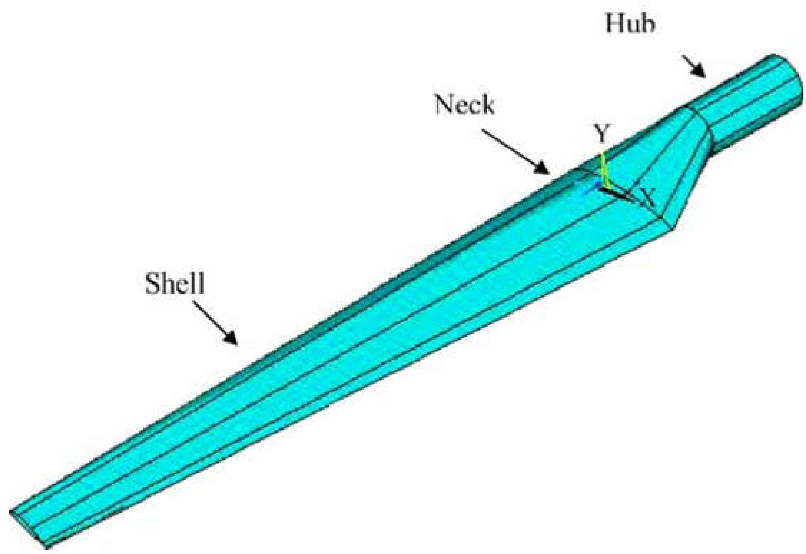


Figure 1: Wind Turbine Blade

Wind turbines are characterized by their power production capacity [MW] and the diameter of its rotor [m] (Wind turbine denominations e.g. Vestas Wind Systems A/S, 2019a). 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 (Liuetal.,2019). Some manufacturers use only GFRP, others a mixture of GFRP and CFRP (Data sheets of wind turbines e.g. Siemens Gamesa Renewable Energy, S.A, 2019; Vestas Wind Systems A/S,2019b) as main construction materials. A photographi view of damaged EoL of Wind turbine blade is shown in Figure 2.

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, Siemens Gamesa and Vestas manufacture wind turbines for the same wind zone, but applying different material compositions. While Siemens Gamesa 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 (Siemens Gamesa Renewable Energy, S.A, 2019; Vestas Wind Systems A/S,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.

Figure 2: Failed Composite Wind Turbine Blades

Second, due to different technical characteristics of the specific fibers, e.g. the electric conductivity and high resistance against thermo-chemical 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 (e.g.Ehrenstein,2006; The Society of Fiber Science and Technology, 2016). Extensive literature exists concerning the treatment of GFRP as well as CFRP waste (e.g. Karuppannan Gopalraj and Kärki, 2020;Liuet 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 (Liuetal.(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 (Liuet al., 2019), secondary markets for the low value glass fibers are unlikely (e.g. 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 (e.g. Schmidl, 2010; Walter, 2017). 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., 2019, 2018). 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 life time of rotor blades.

In the following section, an estimation approach has been developed 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, existing approaches based on the power production capacity is also extended by applying material specific shares to the total rotor blade weight. Further-more, a simulation study is developed 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 life time is applied.

First, existing approaches were reviewed for the forecasting of FRP and total blade waste from rotor blades of wind turbines in Section 3.1. In Section 3.2, an estimation approach was developed that contributes to the existing literature by providing the required level of detail. In Section 3.3, the results of the applied approach is presented on a dataset representing 75 % of the installed power production capacity. In Section 3.4, the findings are elaborated and present the contributions of the estimation approach. The Appendices A–C provides the supporting information for Section 3.2.

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 life-time must be considered to forecast waste streams. With this consideration, existing publications with regard to these characteristics are categorized.

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), Liu and Barlow (2017) 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 based on newly installed power production capacity per year in MW multiplied by several factors 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 life time of a wind turbine instead of the rough estimation of the average life time of other existing approaches.

Table 1: Waste mass estimations from wind energy industry – Literature survey outcome

Publishing Author	Step 1: Mass Determination					Step 2: Projecting masses	
	Method	Total blade waste			Weight Difference Estimate	Method	Life Time estimate (years)
		FRP	GFRP	CFRP			
Albersetal.,2009	average	Yes	--	--	--	deterministic	20
Larsen,2009	average	Yes	--	--	--	deterministic	20
Papadakisetal.,2010	average	Yes	--	--	--	deterministic	20
Liuand Barlow,2015	average	Yes	--	--	Yes	deterministic	20
Bankand Franco R.Arias,2016	average	Yes	--	--	--	deterministic	20
Andersenetal.,2016	regression	Yes	--	--	Yes	deterministic	20
Liuand Barlow,2017	average	Yes	--	--	Yes	deterministic	20
Pehlkenetal.,2017	average	Yes	--	--	--	deterministic	20
Sultanetal.,2018	average	Yes	--	--	--	deterministic	20
Lefeuvreetal.,2019	average	--	--	Yes		deterministic	20
Lichtenegger etal.,2020	regression	Yes	--	--	Yes	deterministic	16 - 18
This paper	Constitutive law	Yes	Yes	Yes	Yes	stochastic	$\mu = 17.08$ & $\sigma^2 = 12.67$

As a Summary, 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. With this literature background, an estimation approach is being developed that fills this literature gap.

3.2 Methodological approach:

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

In the first step, the GFRP and CFRP masses that are currently installed in operating wind parks throughout the country are calculated. Since the available information on wind parks is diverse, the calculation of the installed GFRP and CFRP masses depends on the information given. The following four different data availability cases are developed that dictate the necessary calculation steps with decreasing necessary data availability (Section 3.2.2.).

(a) Straight forward

(b) Main construction materials

(c) Liu's case

(d) Albers' case

Depending on the case, uncertainties in the distribution of GFRP and CFRP masses exist. Therefore, parameters that influence the installed GFRP and CFRP masses are varied to account for these uncertainties in a simulation study.

In the second step, the calculated installed GFRP and CFRP masses are projected into the future (Section 3.2.3.). To do so, deterministic lifetime estimation as done in most publications so far is not considered in this work, but generate an operating time of each wind park individually based on a stochastic distribution function. To account for the uncertainty, the individual lifetimes are varied in the simulation study. The data that is used to derive the stochastic distribution function represents several influencing factors, such as life time 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 Datasets

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 ($p \in P$). The installed wind turbine type$\left(w_p\right)$, the number of installed wind power plants$\left(n_p\right)$, the year of commissioning$\left(t_p\right)$, the total power production capacity$\left(c_p\right)$, and the wind parks' specific location. The simulation study is applied on dataset1.

The second dataset (dataset 2) contains general data on wind turbine types $\left({}^{w}/_{w_p} \in W\right)$ respectively $\left(w_p\right)$ with regard to wind park p of dataset1 (Wind Turbine Models, 2017; manufacturer data): the wind turbine specific power production capacity $\left({}^{c_w}/_{c_{w_p}}\right)$, its rotor blades' material specific masses $\left({}^{m_{aw}}/_{m_{aw_p}}\right)$,$\vee\ a \in A$, {GFRP, CFRP}), 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 dataset 1 and dataset 2. From dataset 1, usable wind park data can be understand, and from data set 2, material specific weight functions can be developed. (Appendix A).

The third dataset contains data on German wind parks (Bundesnetzagentur, 2019): their date of commissioning and date of operation end. The generated stochastic distribution function based on dataset 3.

3.2.2 Step1: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, there are four different cases.

Case (a): Straight forward:

In this case, e_{pa} is calculated straight forward by equations (1) matching dataset 1 and dataset 2. 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.

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

The incompleteness of dataset 1 and dataset 2 in terms of specific wind turbine type w_p, material specific waste masses m_{aw_p} and 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:

This case is similar to earlier, but the installed material specific masses m_{aw_p} are determined before-hand. 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. Dataset 2 contains information on the specific wind turbine type w_p, its main construction materials $cm_{w_p}$and rotor blades' length r_{w_p}, but lacks information on the corresponding GFRP and CFRP masses m_{aw_p}. In this case, m_{aw_p} is determined by material specific weight functions of the installed rotor blades' length r_{w_p} 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, the uncertainties in the amount of CFRP are represented by the term α.

Case (c): Liu's and Case (d): Albers':

These cases 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 Albersetal (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, a material specific allocation parameter γ_{pa} is needed for each of the power production classes introduced by Liu and Barlow (2017) and Albers et al. (2009). In Appendix B, the derived material specific weight functions is used and the extensive dataset 1 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, uncertainties arises 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 γ_{pa} values are generated in dependence of specified ranges (Appendix B).

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

The required and used information concerning the cases (a), (b), (c) and (d) are summarized in Table 2.

Table 2: Differences between the four calculation cases in terms of provided data.

Cases	w_p	n_p	c_p	cm_{w_p}	r_{w_p}	e_{pa}	Additional information
(a) Straight forward	Yes	Yes	--	--	--	Eqn. (1)	m_{aw_p} from dataset 2
(b) Main construction materials	Yes	Yes	--	Yes	Yes	Eqn. (1)	m_{aw_p} from Appendix A
(c) Liu's case	--	Yes	Yes	--	--	Eqn. (2)	μ_p, γ_{pa} from Appendix B
(d) Albers' case	--	--	Yes	--	--	Eqn. (2)	μ_p, γ_{pa} from Appendix B

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 life time of 16–25 years (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, a probability function based on empirical data is determined as presented in Appendix C and further use the distribution function within the estimation, respectively vary life times 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 life time (lt_p). Subsequently, knowing the annual waste masses of each wind park p, equations (4) can be applied to calculate annual waste masses per region (e_{sat})., where P_s states the set of wind parks p within a certain regions $(s \in S)$, e.g. within India, within the states of India.

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

$$e_{sat} = \sum_{p \in P_s} e_{pat} \qquad \forall\, s \in S, a \in A, t \in T \tag{4}$$

In the following section, the simulation study is described that allows coping with relevant uncertainties within step 1 and stepping 2.

3.2.4 Simulation study

In step 1 and step 2, uncertainties encountered with regard to the impact on the reduction of the total blade weight if applying CFRP as well as with regard to the life time of rotor blades. To account for these uncertain parameters, a simulation study is developed that repeatedly execute step1 and step 2 for individual scenarios (Number Scenarios). In line with this, within each scenario (Current

Scenario), scenario specific waste streams are generated.

In step1, parameters α and c_{pa} are varied (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, parameter lt_p is varied in equations (3), which affects the temporal projection of the installed GFRP and CFRP masses. The simulation procedure is summarized in the following pseudo code:

Start
0: Current Scenario = 0
1: while Current Scenario < Number Scenarios:
  2: for each data point (wind park):
    3: Get Case, Construction Method, Life time
    4: if Case = straight forward:
      5: Calculate e_{pa} following eq.(1), next p
    6: if Case = construction method:
      7: if Construction Method = GFRP:
        8: mGFRP, w_p = eq.(GFRP1)
        9: mCFRP, w_p = 0
        10: Calculate e_{pa} following eq.(1), next p
      11: else:
        12: Get Alpha
        13: mGFRP, w_p = eq. (GFRP/CFRP3)
        14: mCFRP, w_p = eq.(GFRP/CFRP4)
        15: Calculate e_{pa} following eq.(1), next p
    16: if Case = Liu's or Albers:
      17: Get γ, μ
      18: Calculate e_{pa} following eq.(2), next p
  19: Calculate e_{pat} or e_{sat} following eq.(3) or (4) applying Life time and save
  20: Current Scenario = Current Scenario + 1
End

Current Scenario is the running index of the number of scenarios to be generated. Number Scenarios represents the total number of scenarios. Each run results in a scenario of future waste streams that differ due to variation of individual Lifetime, α and γ values. The function Case gets the specific case depending on the available data (Table 2). The function Construction Method 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 (Appendix C). The function α 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 (Appendix A). The function γ 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) (Appendix B, in particular Table 3). The function μ 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/CFRP3 and 4) can be found in Appendix A.

Table 3: Material specific allocation parameter

$C_{Liu} \bigcup C_{Albers}$	C_c $[MW]$	μ_c $[t/MW]$	L_c $[m]$	$\gamma(ca\|tp < 2001)$		$\gamma(ca\|tp \geq 2001)$	
				GFRP	CFRP	GFRP	CFRP
1	(0.0, 1.0)	8.43	[10, 22]	0.89	0	0.89	0
2	(1.0, 1.5)	12.37	[26, 37]	0.87	0	0.87	0
3	(1.5, 2.0)	13.34	[34, 45]	0.86	0	[0.79, 0.83]	[0.015, 0.04]
4	(2.0, 5.0)	13.41	[41, 58]	0.84	0	[0.76, 0.81]	[0.016, 0.044]
5	(5.0, ∞)	12.37	[62, 80]	0.82	0	[0.72, 0.77]	[0.018, 0.05]
φ	--	10.00	--	0.83	0	0.81	0.025

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.

4. Results and Discussion:

The simulation study is applied on dataset 1 that consists of about 14,000 operating wind parks (61,000 wind power plants) installed between 1995 and 2020 in India. 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 2020. According to C-WET (2020), the total power production capacity of wind power is estimated to be 141 GW (2020). Figure 3 shows a comparison between the considered dataset and C-WET (2020) in terms of installed power production capacity per year and total power production capacity in India 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 C-WET (2020).

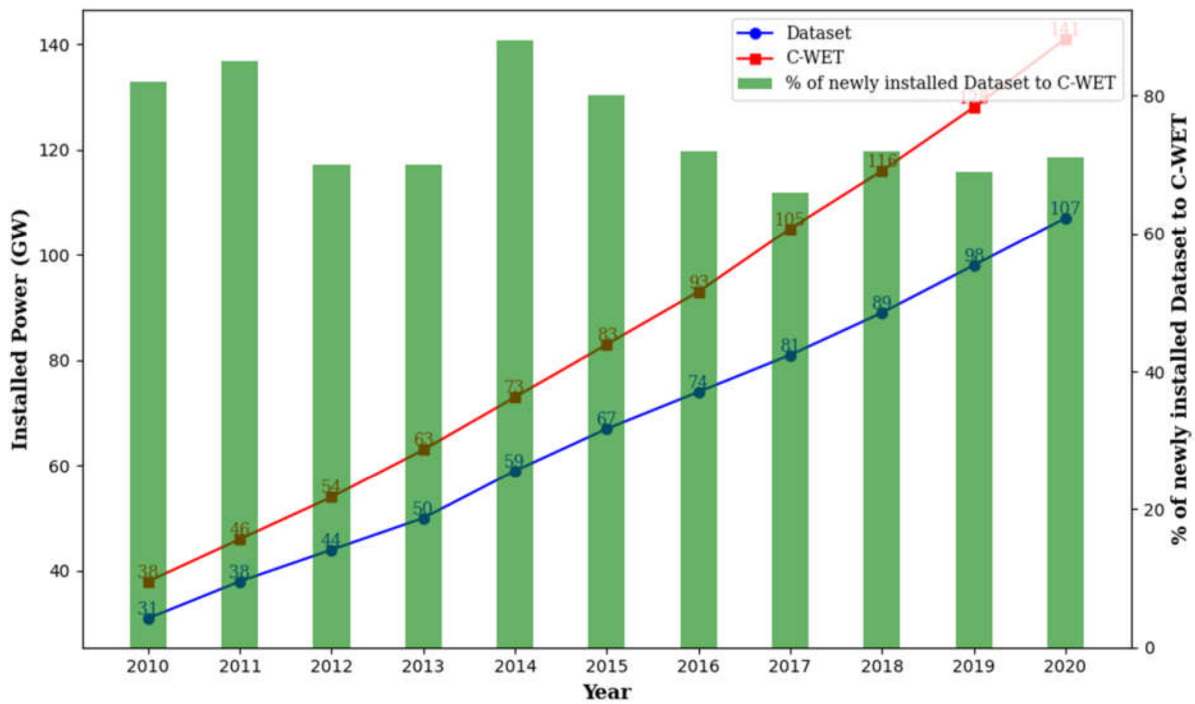
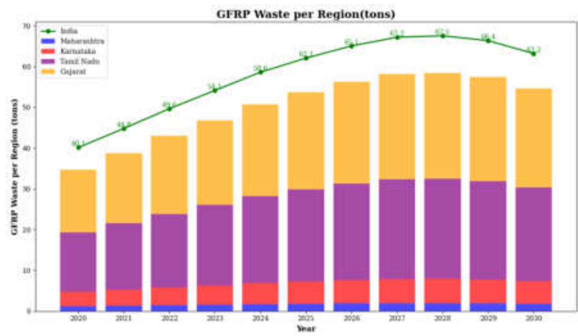
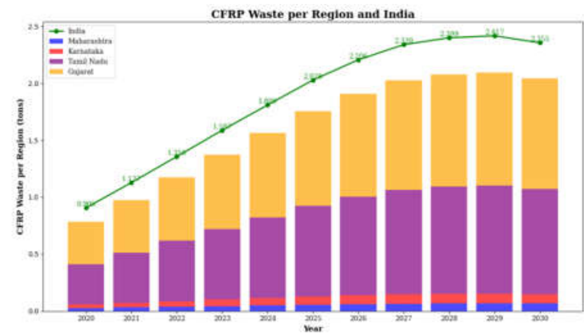


Figure 3:Details of Installed power and new installation in various years

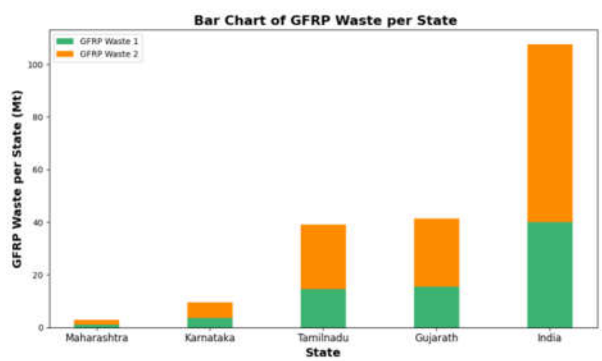
Also simulation study is employed for the estimation of possible future waste streams. To do so, 1000 simulation runs are conducted following the pseudo code discussed in Section 3.2.4. The resulting annual waste masses in India and within four major potential states of wind energy harvesting namely Gujarat, Tamil Nadu, Karnataka, and Maharashtra are determined for each simulation run. In total, 1000 possible future waste streams are determined. Figure 4a) and b) show the average of the annual GFRP and CFRP waste streams for the 1000 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 shows a stronger increase. The slight drop at the end of the time horizon can be explained by the underlying dataset (Figure 3, Figure 4c) and d) show two box plot diagrams that describe the variation of the occurring GFRP and CFRP waste masses over the time horizon and over the 1000 simulation runs for each geographical region, i.e. the annual variation of waste masses within the 1000 possible future scenarios. Exemplarily, in Figure 4c) the first box-plot represents the set of estimated annual occurring GFRP in India. Herein, on average 50 Mt are expected, which is in line with the results depicted in Figure 4a).



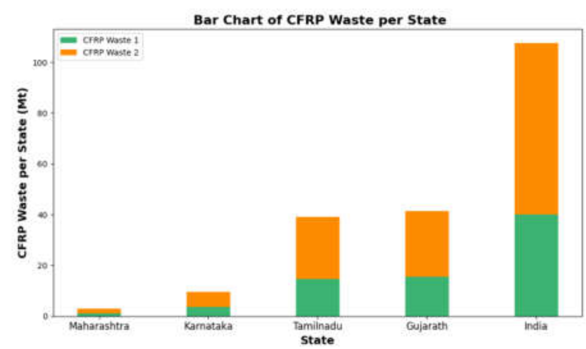
(a) Distribution of GFRP waste over years



(b) Distribution of CFRP waste over years



(c) Distribution of GFRP waste over region



(d) Distribution of CFRP waste over region

Figure 4: Simulation study results

However, the maximum annual GFRP in India is 87 Mt in one specific year within one of the 1000 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. 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, the average tonnage per installed power [tons/MW] of this approach can be compared to the tonnage per installed power estimated by other approaches. Hence, the average tonnage per power is used as a key performance indicator (KPI) to show that the estimation approach leads to robust results. Moreover, the ranges of CFRP ratios for GFRP/CFRP rotor blades are listed and the results are compared with the average ratio of CFRP used by Lefeuvre et al. (2019).

Applying the developed estimation approach on dataset 1, the average tonnage of waste per power production capacity between 2010 and 2020 results in 9.7 tons/MW, which is almost equal to the value of 10 tons/MW assumed by other publications (Alberset 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 dataset 1 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 (Appendix A for coefficients of determination R^2). Regarding the presented results, the estimated impact of the share of CFRP on the total amount of waste is rather small 9.7 vs. 10 tons/MW. However, this is because the corresponding KPI 9.7 tons/MW is calculated for the whole data from India, 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 or to smaller regions with more CFRP/GFRP wind power plants.

4 Conclusion:

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 life time 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 reuse, i.e. a certain number of wind turbines that might be re-used, e.g. by repositioning of wind turbines or as play ground 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 dataset 3 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 (Albersetal.,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 (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 (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.

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 etal.,2017). Since2001, 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; The Wind Power, 2017; Wind Turbine Models, 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. Figure 5 shows two scatter plots describing the total weights of 248 GFRP and 48 GFRP / CFRP rotor blades from 296 different wind turbine types independence of their respective lengths (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 independence 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, Δr can be expressed as stated (cf. Jamieson and Hassan, 2011).

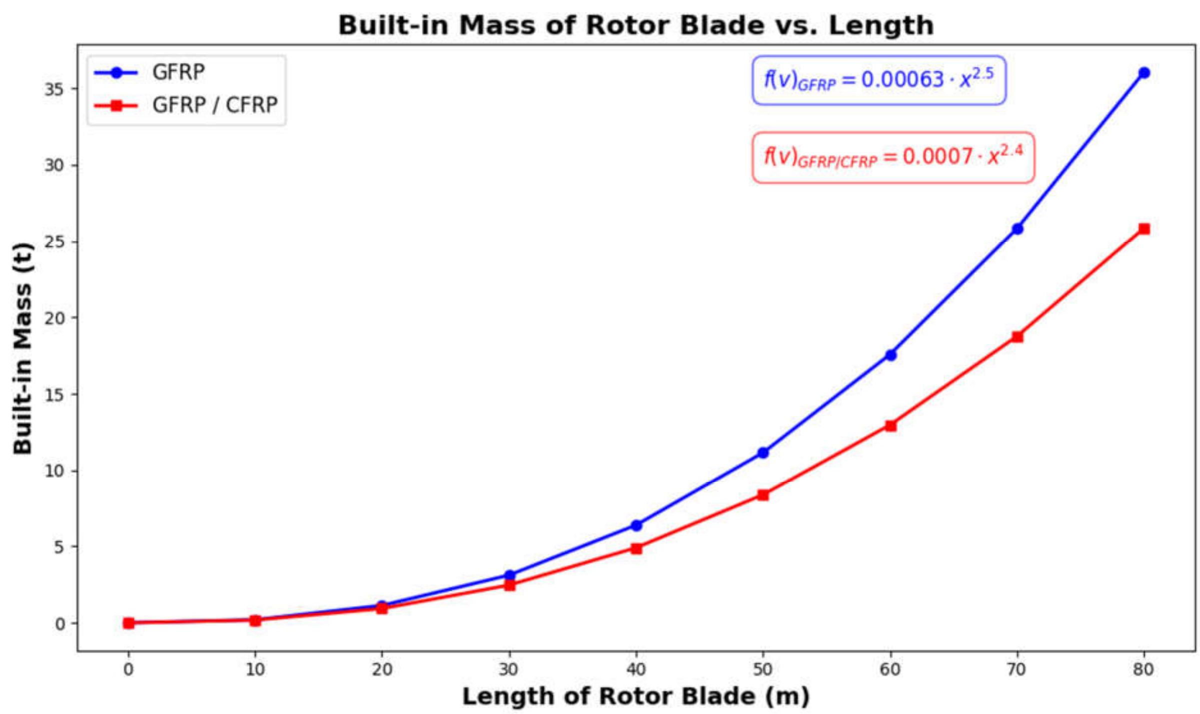


Figure 5: Dependence of Blade weight with material

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 Wind Turbine Models (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 $R^2_{GFRP} = 0.92$ and $R^2_{GFRP/CFRP} = 0.91$ respectively (Fig.3). The mass of the rotor blades is divided into GFRP and CFRP and other materials.

$$f(r)_{GFRP} = 0.00063r^{2.5} = f(r)_{(GFRP|GFRP)} + f(r)_{(GFRP|CFRP)} + others\ (r) \qquad (GFRP)$$

$$f(r)_{GFRP/CFRP} = 0.00070r^{2.4}$$
$$= f(r)_{(GFRP/CFRP|GFRP)} + f(r)_{(GFRP/CFRP|GFRP)}$$
$$+ others\ (r) \qquad (GFRP/CFRP)$$

The following section describes the amount of GFRP and CFRP masses in dependence of construction method.

GFRP Rotor blade:

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

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

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

For the remaining materials $others\ (r)$, regression function based on datasets are as under:

$metal\ (r) = 0.0007r^{3.38}$; $core\ (r) = 0.0023r^{3.25}$; $adhesive\ (r) = 0.0713r^{2.12}$; $painting\ (r) = 0.0168r^{2.51}$.

GFRP / CFRP rotor blades:

For GFRP / CFRP rotor blades, the weight reduction Δr 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 $m_{GFRP}^{out}(r)$ less the amount of CFRP inserted $m_{CFRP}^{in}(r)$.

$$\Delta r = m_{GFRP}^{out}(r) - m_{CFRP}^{in}(r) \qquad (GFRP/CFRP\ 1)$$

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.

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

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

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

$$f(r)_{(GFRP/CFRP|GFRP)} = \mathrm{m}_{\mathrm{CFRP}}^{\mathrm{in}}(\mathrm{r}) \qquad (GFRP/CFRP\ 4)$$

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) (equations Material Specific). As mentioned in Section3.2.2., at first the total blade waste (tw_p) is calculated following the approaches developed by Liu and Barlow (2017) and Alberts etal. (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 per installed power in tons/MW. Herein the publication differs, 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, ∞) MW. For each power production class c ($c \in C_{Liu}$) the authors determine a power production class specific tonnage per power (μ_c). In contrast, Alberts etal. (2009), consider only one average power production class φ ($\varphi \in C_{Alberts}$) with a specific tonnage per power (μ_φ) (Table 3). Applying these two approaches on wind parks p in data set 1, 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 μ_φ following the approach of Albers et al.(2009).

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 determining material specific tonnages per installed power. Within the following, material specific weight ratios per power production capacity class c ($c \in C_{Liu} \cup C_{Alberts}$) of Liu and Barlow (2017) and Alberts etal. (2009) are determined γ_{ca} using the material specific functions in equations GFRP 1 and 2) as well as (GFRP/CFRP 3 and 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) Alberts.

$$e_{pa} = \mu_p c_p \gamma_{pa} \qquad \vee\, p \in P, a \in A \qquad\qquad (Material\ specific)$$

Case c) Liu's:

At first, a set of representative number of rotor blades' length (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 ($c \in C_{Liu}$) (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 ($r \in L_c$). 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.

$$\gamma_{cr}^{(GFRP/CFRP|GFRP)} = \frac{f(r)^{(GFRP/CFRP|GFRP)}}{f(r)_{GFRP/CFRP}} \qquad \vee\, c \in C_{Liu}, r \in L_c \qquad (Liu\ 1)$$

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 > 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 $dataset_1$ and $dataset_2$.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 Lefeuvreetal.(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 0.36 in average, which is less than the 0.66 of Lefeuvreet 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 (Lefeuvreetal.,2019), the estimated ratio by Lefeuvre etal.(2019) is somehow biased and cannot be applied to the EU-28. Moreover, Siemens Gamesa and Nordex that do not use *GFRP/CFRP* rotor blades are widely represented in Europe (Lefeuvreet al., 2019). Equations Liu 2 shows the calculation.

$$\gamma_{cra} = (1 - \beta_c)\gamma_{cr}^{(GFRP|a)} + \beta_c \gamma_{cr}^{(GFRP|a)} \quad \forall\, a = A, c \in C_{Liu}, r \in L_c \qquad (Liu\ 2)$$

By averaging γ_{cra} over the power production class specific integer rotor blade lengths (L_c), material specific weight ratios are determined for the five power production classes of Liu andBarlow (2017) (equation Liu 3). Results are shown in Table 3. The depicted ranges result due to maximum and minimum α values (equations GFRP/CFRP 2). Values were calculated for wind turbines installed before and after 2001, since the extensive dataset 1 and dataset 2 showed that the first GFRP and CFRP rotor blades were installed in 2001 (e.g. Vestas 2000–90, Vestas Nearshore2000–80, Enercon 2000–66).

$$\gamma_{ca} = \frac{1}{|L_c|} \sum_{r \in L_c} \gamma_{cra} \qquad \forall\, a = A, c \in C_{Liu} \qquad (Liu\ 3)$$

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 c_{ca} (Table 3), the mean value is chosen. Results are shown in Table 3.

$$\gamma_{\varphi a} = \frac{1}{|C_{Liu}|} \sum_{c \in C_{Liu}} \gamma_{ca} \qquad \forall\, a = A \qquad (Albers\ 1)$$

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, μ_φ and $\gamma_{\varphi a}$ 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. Life time of rotor blades:

Instead of assuming a deterministic lifetime of 20 years as most publications (Table 1), Zimmermann etal. (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 life times or machine failures (e.g.Abernethy, 1996; 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 and standard deviation of the function seem to be 16–18 and 3–4 respectively.

Dataset3 on German wind power plants with known dates of commissioning and demolition allows us to derive a stochastic distribution function (Bundesnetzagentur, 2019). Herein, 1314 wind turbines with power production capacities of up to 5.0 MW show an average life time of 17.08 years with a standard deviation of 3.56. Figure 6 shows the density function of N (17.08, 12.67) and the discrete distribution of the wind turbine lifetimes based on the dataset3.

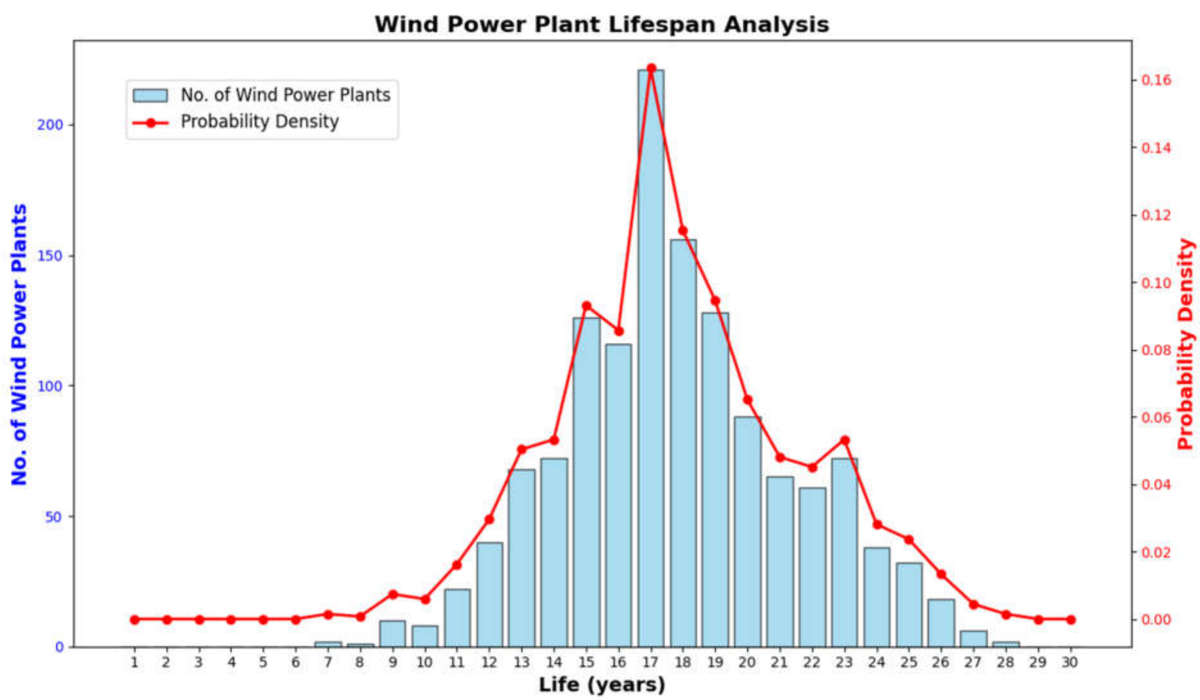


Figure 6: Probability function of Life of Wind Power Installations

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 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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