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RESEARCH ARTICLE

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Method for estimating the future annual mass of decommissioned wind turbine blade material in Denmark

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Abstract

A model of the evolution of the onshore wind turbine blade mass installed in Denmark is proposed described by a Weibull distribution, and the age of the blades is estimated from decommissioning data to $t_{50\%,onshore} = 29$ years when half of the blade mass of an installation year has been decommissioned. This is considerably longer than the 20 year design lifetime of onshore turbines, which is often assumed to be an estimate of the End-of-Life of turbine blades. Thus, blade waste predictions using the simple assumption may predict that installed blade masses are entering recycling processes about 9 years sooner that what is observed in Denmark. The blade mass for decommissioning in Denmark is estimated to peak at 2000 and 5000 ton/year in 2028 and 2045 using the Weibull model.

KEYWORDS
blade recycling, decommissioning, design life time, operation life time, wind turbine blade mass

1 | INTRODUCTION

Wind turbine blades are mainly made of glass fiber reinforced polymer composite with a thermoset resin, such as epoxy or polyester. These composite materials with directional optimized mechanical properties provide sufficient stiffness at a relatively low weight and cost. The superior properties of glass fiber composite do however turn into a challenge when the turbine reaches End-of-Life and needs to be taken apart in a recycling process. As reported in multiple research publications, recycling wind turbine blades is challenging, due to various factors such as the material composition of blades, the diversity in blades in terms of geometry, dimension and material content, or the difficulty to transform blades into valuable recycled materials.[1–5] To find solutions, part of the research has been dedicated to the development of recycling processes, such as repurposing blades into new structural applications, and recycling using mechanical, thermal, or chemical processes.[6–10] However, in recent years, it has become clear that along recycling processes, estimating the amount of blade waste available is essential to establish feasible recycling solutions. A number of publications have suggested methods to determine future amounts of waste and their location.[11–18] These predictions are generally based on a combination of available information such as the wind turbine capacity installed in a given region and assumptions, as, for example, the time, at which blades will be recycled. One central assumption used across the literature is to consider wind turbines available for recycling immediately after decommissioning. This assumption does not take into consideration the cases where wind turbines are sold and reused in new locations or when wind turbine blades are kept as spare parts. Assuming that wind turbine blades enter the waste stream

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Abbreviations: EOL, End-Of-Life; ABA, Scoping work, data analysis and model formulation; JB and JPJ, Scoping work, literature review and paper review; KWL, ESM and DPR, Literature review and paper review.

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immediately after decommissioning might overestimate predictions of the amount of blade material available for blade recycling processed in the next 10 years. Thus, business plans for recycling companies might turn out to be too optimistic in terms of blade mass volumes to process. To predict the future amount of wind turbine blade waste, it is therefore necessary to establish clear definitions for the End-of-Life of wind turbines. Bank et al. (2021)[19] suggest several definitions to clarify and differentiate the different stages during the End-of-Life of wind turbines. The life cycle stages of a turbine or component can be described by the following events: installation at operation site 1, decommissioning from operation site 1 (end-of-location-life), reselling/refurbishing, installation at operation site 2, decommissioning at operation site 2 (end-of-functional-life) and recycling (End-of-Life). In this paper, the definition of a wind turbine or a component End-of-Life age is the time at which the turbine or component can no longer be reused and must be scrapped in a process recycling the materials. As mentioned above, in general, the time of end-of-location-life has been used as the time at which wind turbines are entering the waste stream. However, this is not considering that turbines or components might still hold second-hand value and can be installed in a different country for site 2.

Another central assumption when predicting future amount of wind turbine blade waste is to estimate the time at which decommissioning takes place. In the literature, it is sometimes assumed to be the design life time t_{DLT} or the design life time plus or minus a few year. The time of decommissioning is governed by several parameters including regulations, technical aspect, and economic consideration. Determining the time of decommissioning is therefore complex. Wind turbines are designed to have a design life time $t_{DLT,onshore} = 20$ year for onshore turbines and $t_{DLT,offshore} = 25$ year as required by IEC 61400 standards.[20,21] The meaning of the design life time $t_{DLT,onshore}$ is that the probability of major failures of the turbines is limited by the manufacturer to $5 \cdot 10^{-4}$ when exposing the turbine to the loads of the environment (ex. wind and waves) and faulty operation (ex. yaw errors and controller issues) in the duration of the design life time.[22] This condition is put in place to guarantee that if the investment payback time of the turbine is assumed shorter than the design life time, then there is a high probability of returning the investment of the asset. When the age of the turbine exceeds the investment payback time, then the turbine owner only has expenses for the operation and maintenance (O&M) and eventually the decommissioning. As long as the O&M expenses are lower than the income of selling the produced electricity, then the owner is likely to keep operating the turbine. Thus, when the age of a turbine is exceeding the design life time, the owner of the turbine may continue the operation, if it is still a possibility to generate a profit. There are, however, different rules regarding continued operation beyond the design life time in different countries ranging from a demand for annual inspections of the structural parts (Denmark) and to third party estimation if the structural integrity of the turbine allows further operation (Germany).[23] The relation between the time of decommissioning and the design life time is that the chance of decommissioning is increasing as the turbine age is increasing beyond the design life time. Therefore, to assume that turbines are decommissioned on the date, where the turbine age is reaching the design life time is a simplification. Finally, political incentives such as support for repowering in a specific country can change the pace of decommissioning.

The objective for this paper is to predict the yearly amount of decommissioned wind turbine blade materials available in Denmark until 2060. The prediction is therefore not taking into consideration that blades might be resold after the decommissioning and used as spare parts or installed in other countries. The decommissioning of the Danish wind turbine fleet is described mathematically by the depletion of a wind turbine fleet as function of time as given by a Weibull function. This is similar to the framework used in several other studies in the literature.[11,14] The input parameters for the model are obtained by characterizing the evolution of the Danish onshore wind turbine fleet from 1977 to 2021. The model is then fitted to describe the onshore wind turbine decommissioning from 1977 to 2021. By assuming a similar depletion of all types of onshore turbines and all years, a prediction of the expected decommissioning rate for the onshore fleet in the period from 2022 to 2060 is obtained. The decommissioning of the offshore fleet in Denmark has only started in 2017, where the Vindeby offshore wind farm was decommissioned. This wind farm consisted of 11 turbines of a power rating of 450 kW and contained 32 tons of blades. Since the total installed Danish offshore blade mass is of about 29,000 tons, this means that only 0.1 % of the offshore fleet has been decommissioned so far. There is therefore not enough data for fitting a depletion model for the offshore turbines. A proposal on adjusting the onshore model to provide an initial guess of the offshore fleet depletion is presented and used to predict the amount of decommissioned blade mass of Denmark if the current onshore and offshore fleet are depleted without any installation of new turbines. The amount of decommissioned blade material is compared with the actual decommissioning rates observes in Denmark and also compared with the literature.

2 | LITERATURE ON MODELS TO PREDICT END-OF-LIFE BLADE MASS

A literature review has been performed to provide an overview of the previous predictions of blade mass waste for different parts of world. The list of articles is presented in Table 1. The articles are categorized by their modeling approach for estimating the time of decommissioning and the geographical dispersion considered in the studies. There are two main methods used in the literature to set the time of decommissioning. The first one is named in the following simple methods and assumes that the decommissioning time t_{Decom} is fixed. The second method describes the decommissioning time t_{Decom} by a distribution function $f(t, t_0, \delta t)$ with a certain time t_0 for the largest decommissioning activity and a spread in time of the decommissioning activity δt, where t is the time. Throughout the literature, different tools are used to predict future amount of wind turbine blade waste such as material flow analysis (Tazi et al., 2019,[13] Lefeuvre et al., 2019,[24] and Chen et al., 2021[15]), mathematical regression

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TABLE 1 Overview of the literature dedicated to the prediction of End-of-Life wind turbine blade material.

Authors	Method for time of decommissioning	Geographical dispersion
Andersen et al. (2016)[25]	Simple t_{Decom}=20 years	Sweden and Denmark (onshore)
Liu and Barlow (2017)[11]	Simple t_{Decom}=18, 21, and 26 years	Europe + world (onshore)
Sultan et al. (2018)[12]	Distribution $t_0 = 25$ years	Great Britain (onshore and offshore)
Tazi et al. (2019)[13]	Simple t_{Decom}=15 years	France (onshore)
Lichtenegger et al. (2020)[14]	Distribution $t_0 = 18$ years	Europe (onshore and offshore)
Tota-Maharaj et al. (2021)[27]	Simple t_{Decom}=20 years	Great Britain (onshore and offshore)
Chen et al. (2021)[15]	Distribution $t_0 = 14$, 18, and 21 years	China (onshore and offshore)
Cooperman et al. (2021)[16]	Simple t_{Decom}=20 years	United States (onshore)
Heng et al. (2021)[18]	Simple t_{Decom}=20, 25, and 30 years	Canada (onshore and offshore)
Delaney et. al. (2021)[17]	Distribution $t_0 = 20$ years	Ireland (onshore)
Sommer et al. (2020)[26]	Distribution $t_0 = 15$ years	Europe (onshore and offshore)
Lefeuvre et al. (2019)[24]	Simple t_{Decom}=25 years	World (onshore and offshore)

Note: The simple method has a fixed age for decommissioning t_{decom}, and if a distribution $f(t, t_0, \delta t)$ is used, then the time of the largest decommissioning activity is indicated by the time t_0.

models (Andersen et al. 2016,[25] Lichtenegger et al., 2020,[14] Liu and Barlow, 2017[11]), stochastic modeling (Sommer et al., 2020[26]), and life cycle assessment (Heng et al. (2021)[18]).

2.1 | Time of decommissioning

As mentioned in Section 1, the time of decommissioning of wind turbine is one of the key assumptions in predicting future amount of wind turbine blade waste. In the reviewed studies, the time of decommissioning ranges from 14 years at the lowest (Chen et al., 2021[15]) and up to 30 years at the highest (Heng et al., 2021[18]). Some studies use the design life time from the manufacturer to estimate the time of decommissioning (Cooperman et al., 2021,[16] Lefeuvre et al., 2019[24]), while other studies analyze historical data on wind turbine park commissioning and decommissioning dates (Chen et al., 2021,[15] Lichtenegger et al., 2020,[14] Sommer et al., 2020[26]). Andersen et al. (2016)[25] adopt the 20-year design life but complement with a comparison between actual and expected decommissioning in early adopting countries (Denmark, Germany, and Sweden) resulting in a validation of 20 years as the expected life. Yet, the data included were from 2015 and prior. For instance, Andersen et al. (2016)[25] state that "As the wind power technology is still relatively young, few countries have markets that have been well-developed for more than 20 years, and hence, there is not yet much empirical data on turbine life time". This argument is supported by Cooperman et al. (2021)[16] who addresses the issue by assuming a 20-year life time and introducing a sensitivity analysis of this assumption using a Weibull distribution. Sommer et al. (2020)[26] present a lifetime for wind turbines of 17 years by applying a stochastic distribution function on two datasets covering Europe and Germany until 2016. This is close to the results of Lichtenegger et al. (2020)[14] of 18 years. Even though Chen et al. (2021)[15] study the geographical area of Guangdong province of China, they apply a Weibull distribution fitted to the data from the Danish wind energy database to model the average life time of wind turbines in the province of Guangdong. This results in an expected lifetime and time of decommissioning of 18 years, similar to the expected lifetime estimate by Sommer et al. (2020)[26] and Lichtenegger et al. (2020).[14] Common for these approaches is that only parks that are already decommissioned are included in the analysis, leaving out parks that are yet to be decommissioned. Delaney et al. (2021)[17] utilize a 20-year design life in their modeling. Their results show that wind farms that should have been decommissioned by the expected lifetime in 2020 were still in operations, because these wind turbines were still profitable to operate. The lifetime and time of decommissioning varies significantly depending on the modeling approach, assumptions, and data input. These differences results in large variances in the waste flow peaks predicted, thus affecting the business case of possible recycling facilities. Thus, there is a need to address the matter of assumed lifetime and time of decommissioning.

2.2 | Geographical dispersion

The largest geographical area of analysis, being worldwide, is studied by Liu and Barlow (2017)[11] and by Lefeuvre et al. (2019).[24] Lichtenegger et al. (2020)[14] and Sommer et al. (2020)[26] study the geographical area of Europe and several studies concentrate on a single country, that is, the United States (Cooperman et al., 2021[16]), Canada (Heng et al., 2021[18]), Ireland (Delaney et al., 2021[17]), Sweden (Andersen et al., 2016[25]), and United Kingdom (Sultan et al., 2018[12]). Liu and Barlow (2017)[11] find that until year 2050, 43 million tons of blades waste must be handled worldwide. About 25% of this quantity will be in Europe. Also modeling the global waste stream, Sommer et al. (2020)[26] find that 570.000 tons of glass

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fiber reinforced composite and 18.000 tons of carbon fiber reinforced composite material must be handled between 2020 and 2030. By focusing on Europe, Lichtenegger et al. (2020)[14] concludes that by 2050, 325.000 tons of material must be handled yearly, with a mix of 24% from offshore and 76% from onshore turbines. The aforementioned studies are all targeting the waste streams on a multinational level, but Delaney et al. (2021)[17] argue that to develop sustainable solutions at national levels, more national studies must be conducted. As emphasized by Lichtenegger et al. (2020),[14] Denmark is a pioneering country in wind energy where approximately 40% of the country's electricity is covered by wind energy. This makes Denmark a very interesting case to study since the early adoption of wind energy also include several parks and single turbines to be decommissioned.

3 | METHODOLOGY

The methodology of this paper is to investigate the decommissioning history of the Danish wind turbine fleet and to describe the decommissioning as a depletion process of the different installation years with one general distribution as function of time. A general relation between the length of the turbine blades and the mass of the blades is established using literature data and additional information about the blade mass of smaller blades. The blade mass relation is applied to the public available data of decommissioned and operating turbines in Denmark. The depletion of the fleet is determined as the ratio between the decommissioned turbine blade mass by 2021 and the installed blade mass of a certain installation year. The depletion distribution is determined only for the onshore fleet, since the decommissioning of the offshore fleet has only started and too little data is available to determine an offshore distribution. A transfer of the onshore to a guess of the offshore distribution is provided, and finally, an estimate of future decommissioning blade mass of the Danish onshore and offshore fleet is provided. This is compared with the prediction for Denmark provided by Lichtenegger et. al.[14] and the differences are discussed.

3.1 | Master data register for wind turbines in Denmark

Since 1977, there has been a registration of all the Danish wind turbines with power rating larger than about 6 kW in the database called “Master data register for wind turbines” or “Stamdataregister for vindkraftanlæg” (Danish name).[28] This database is holding a unique turbine ID number, installation date, the type of turbine, and the main properties such as rotor diameter, hub height, and power rating. The owner and the position in Denmark are also registered, and finally, the annual energy production during the different years of operation is noted. A second sheet of the database is holding similar information about the wind turbines decommissioned in Denmark. Interactive maps of the position of the turbines in Denmark are provided by the Danish Energy Agency,[28] and Figure 1 is showing the current operational turbines with different power ratings.

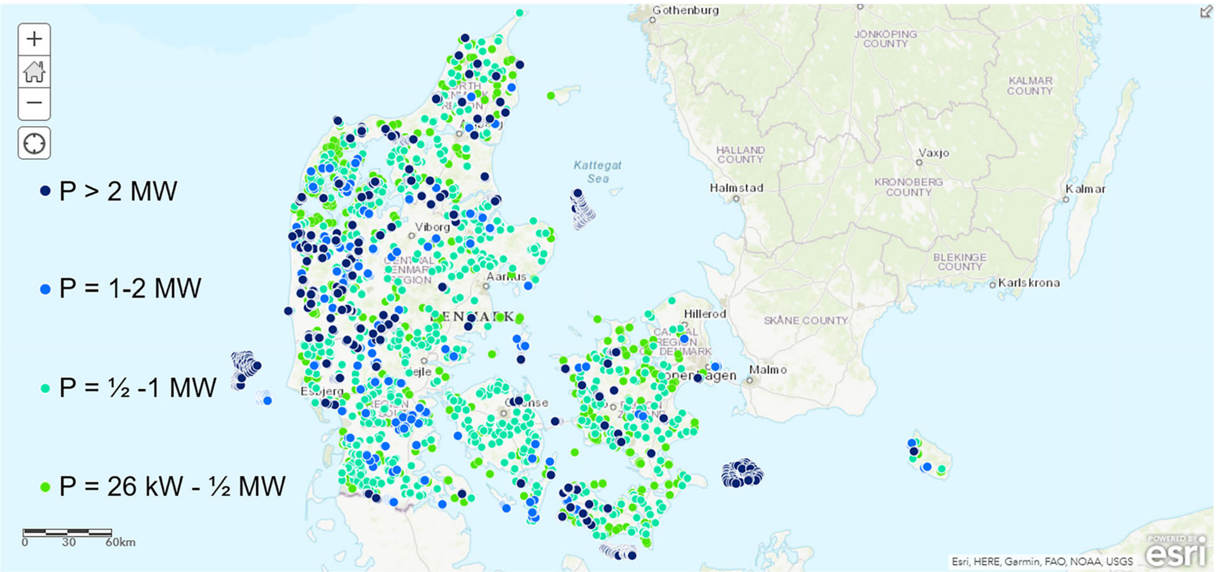

FIGURE 1 Illustration of the position of the Danish wind turbines as registered in the Master data register of wind turbines of the Danish Energy Agency.[28] The figure has been produced using the ArcGIS web-tool provided by the Danish Energy Agency and the legends to indicate the power range of the turbines. Green: $P = 26 - 500$ kW, dark green: $P = 501–1000$ kW, light blue: $P = 1001–2000$ kW, and blue: $P > 2000$ kW.

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3.1.1 | (1) Depletion model of installed turbine blade mass

The basic model used for the prediction of the future decommissioned blade mass is to describe that the time to decommissioning of a number of turbines installed at the same time is given by a cumulative Weibull distribution[29]. The fraction of the turbine fleet or the blade mass that has been decommissioned as function of time is therefore given as

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

where t is the time variable, λ is the time constant of the depletion of the turbine fleet characterized by the scale parameter of the cumulative Weibull distribution F, and the exponent k is called the shape parameter.

The corresponding Weibull distribution function specifying the amount of blade material decommissioned per year is then given as

$$f(t,\lambda,k) = \frac{k}{\lambda}\left(\frac{t}{\lambda}\right)^{k-1} \cdot \exp\left(-\left(\frac{t}{\lambda}\right)^k\right) \tag{2}$$

with similar parameters as given for Equation (1).

If the depletion of all turbines are assumed to follow an universal cumulative Weibull distribution F as characterized by the λ scale and k shape parameters, then one can write the expected amount of decommissioned blade material for a specific year j as given as a sum of contributions from the installations years i

$$m_{decom}(t_j) = \sum_{i=0}^{j} m_i \cdot f(t_j - t_i, \lambda, k) \tag{3}$$

where m_i is the total installed blade mass in year $i, f(t,\lambda,k)$ is the Weibull distribution function given by Equation (2), t_i is the year of the installation of the blade mass m_i, and t_j is the year where the decommissioning blade mass is determined by collecting the contributions from the different installation years.

Once the Weibull distribution has been determined, one can ask the questions of how long time t_p it will take before a certain fraction p of the fleet has been depleted.

$$F(t_p,\lambda,k) = 1 - \exp\left(-\left(\frac{t_p}{\lambda}\right)^k\right) = p \rightarrow t_p = \lambda\left(\ln(1-p)^{-1}\right)^{1/k} \tag{4}$$

This can be used to define median of the distribution corresponding to the time $t_{50\%}$ it will take before half of the fleet has been decommissioned as well as the $t_{10\%}$ and $t_{90\%}$ corresponding to 10 % and 90 % have been decommissioned.

$$t_{10\%} = \lambda\left(\ln(1-0.1)^{-1}\right)^{1/k} = \lambda(0.1054)^{1/k} \tag{5}$$

$$t_{50\%} = \lambda(\ln 2)^{1/k} = \lambda(0.6931)^{1/k} \tag{6}$$

$$t_{90\%} = \lambda\left(\ln(1-0.9)^{-1}\right)^{1/k} = \lambda(2.303)^{1/k} \tag{7}$$

where λ and κ are the Weibull scale and shape parameters.

From the definition of $t_{50\%}$, one observes that $t_{50\%}$ is scaling directly with the scale parameter λ and if the shape parameter k is larger than 5, then the $t_{50\%} \approx \lambda$ with less than 10 % error.

In order to understand how the Weibull parameters will describe the decommissioning, one can also define the duration Δt of the main depletion corresponding to removing 10 % to 90 % of the fleet by using [5].

$$\Delta t = t_{90\%} - t_{10\%} = \lambda\left(2.303^{1/k} - 0.1054^{1/k}\right) \Rightarrow \tag{8}$$

$$\frac{\Delta t}{\lambda} = 2.303^{1/k} - 0.1054^{1/k} \tag{9}$$

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It is seen that the transition duration time scaled by the scale parameter $\frac{\Delta t}{\lambda}$ only depends on the shape parameter k and that a slow transition results from a small shape parameter k, whereas a fast transition is seen for a large shape parameter k.

In the case where the Weibull distribution cannot be considered universal for all the turbines of the fleet, then one might need a more general formulation, where an individual Weibull distribution is assigned to each installation year. An argument for using individual Weibull distributions is that the turbine size of the Danish turbines has changed as shown in Figure 5 and that the marked conditions over time have also changed.

$$m_{decomadvanced}(t_j)=\sum_{i=0}^{j} m_i\cdot f\left(t_j-t_i,\lambda_{ij},k_{ij}\right) \tag{10}$$

where λ_{ij} and k_{ij} specify a different Weibull distribution for each installation year i and also a possible change with time t_j. This advanced model will call for a method for reliable estimating individual distribution parameters and will not be applied in this paper.

3.1.2 | (2) Determination of the mass of wind turbine blade material currently installed in Denmark

In this article, the mass of wind turbine blade material as function of the blade length as proposed by Liu and Barlow (2017)[11] is used for determining the blade mass of the turbines registered in the Master data register of Danish turbines. The data from Liu and Barlow are presented in Figure 2, where the blade mass is shown as a function of the blade length. Additional blade masses on the blades LM37.3 P2 of LM Wind Power,[30] V-47 of Vestas,[31] and B45 of Siemens Gamesa Renewable Energy[32] as provided by the Blade Material Passports of the DecomBlades project have been added to the dataset.[33] Secondly, some blade masses from small rotor diameter turbines have been added as found in old turbine specification data sheets (Vestas V-17 and V-27 as well as the LM-17 HHT blade used for the decommissioned Vindeby offshore wind farm in Denmark). The smaller blades were added in order to determine a scaling function extending down to blade lengths of about 10 m, since these are present in the Master data register of Danish turbines.

A blade mass scaling relation was fitted to the blade masses shown in Figure 2 using a power law function

$$m=a\cdot\left(\frac{L}{L_0}\right)^b \tag{11}$$

where L is the blade length in the unit of [m], $L_0=1$ m, the prefactor is $a=1.29\cdot10^{-3}\pm2\cdot10^{-4}$ metric ton, and the exponent is $b=2.32\pm0.03$.

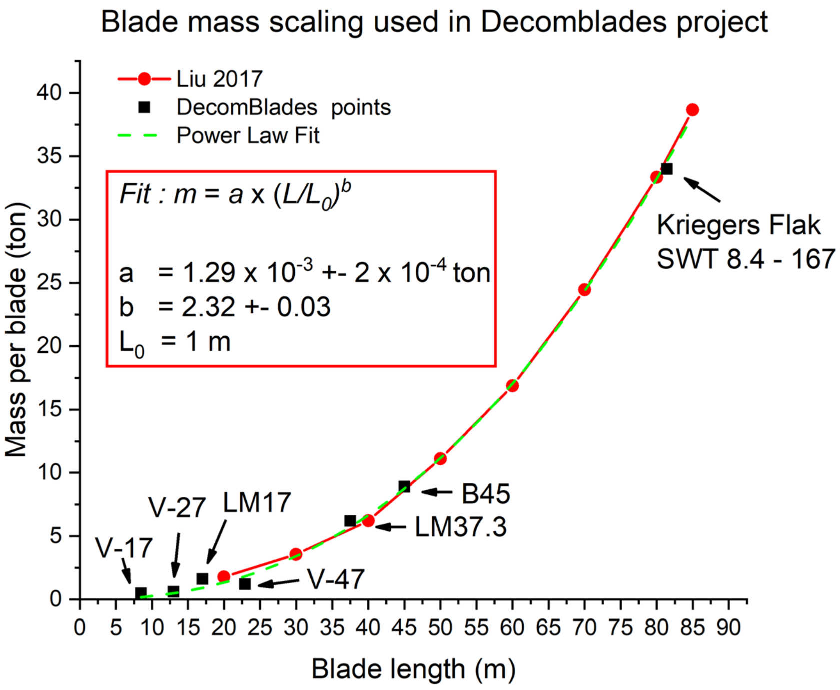

FIGURE 2 Wind turbine blade mass as a function of the blade length as reproduced from Liu and Barlow[11] and by adding additional blade masses.[30–32] The fitting of a power law function result in the parameters $a=1.29\cdot10^{-3}\pm2\cdot10^{-4}$ metric ton, the exponent is $b=2.32\pm0.03$, and $L_0=1$ m.

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3.1.3 | (3) Determination of the time of decommissioning

In order to obtain a model for the decommissioning age of the Danish turbines, then the age of the turbines in the Master database of the decommissioned turbines was calculated as the difference between the installation date and the decommissioning date. Figure 3 is showing the distribution of age of decommissioned turbines in the period from 1977–2021 in Denmark. It is observed that most turbines were decommissioned at an operation age of 18 years, which is about 2 years before reaching the design life time of 20 years for onshore turbines. This could be explained by a wish to resell the decommissioned turbine, because the reselling price is probably higher if the turbine has not yet reached the design life time. Figure 3 is showing the histogram of the turbine age as used by Lichtenegger et al[14] to describe the stochastic process of decommissioning the Danish fleet. The two curves are seen to be quite similar. The age of the operating turbine of Denmark was determined, and Figure 4 is showing the age distribution of the operating fleet by January 2022. It should be mentioned that all turbines in the Master turbine database are included in Figure 4. Thus, both small-scale farmer turbines with a size < 25 kW, all regular onshore, as well as all offshore turbines are shown. There has been no attempt to clean the Master database of turbines for the not so well-specified turbines, which is sometimes seen where the rotor diameter seems very small or even zero compared with the power rating. This inconsistency is only observed for very old turbines and is not considered as a source of large differences in determining the blade mass of the Danish turbine fleet. Figure 4 is showing that more than 2000 of the Danish turbines have an age higher than the design life time, which illustrates that decommissioning is not taking place immediately after the design life time is exceeded. Figure 5 is showing the observed rotor diameter of the operating fleet as function of the turbine age with respect to 2022. Thus, by comparing Figures 4 and 5, it is observed that the turbines with an operation age in 2022 above the design life time of 20 years will have rotor diameters below 80 m, and turbines with operation age in 2022 higher than 30 years will have rotor diameters below 40 m.

In order to obtain an overview of the in-operation and decommissioned blade mass of Denmark, one can sort the Master turbine database by either the installation year of the blades or by the year that the blades were decommissioned. In the first case, then the decommissioned turbines were sorted by the installation year and the total amount of blade mass decommissioned for a specific installation year was summed up until the end of the data registration period which is January 1, 2022 and as given as $m_{\text{decommissioned from year } i \text{ by } 2022}$ in Equation (12). This blade mass then represents all the blades decommissioned over time from the installation year of example 1985 and until 2022. This blade mass is important to determine, since this must be added to the blade mass in operation of a specific years $m_{\text{in-operation from year } i}$ in order to determine the installed blade mass of the different years as given in Equation (12). The depletion of an installation year can then be defined as the ratio between the decommissioned and installed blade mass as given by Equation (13)

$$m_{\text{installed in year } i} = m_{\text{in-operation from year } i} + m_{\text{decommissioned from year } i \text{ by } 2022} \tag{12}$$

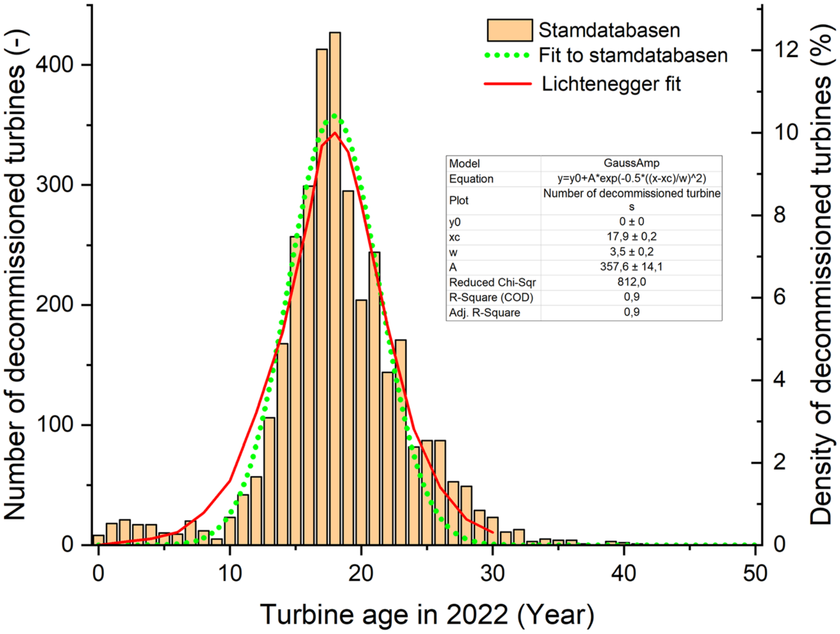

FIGURE 3 Age distribution of decommissioned wind turbines in Denmark by 2022 obtained from the Stamdatabase.[28] A Gauss function has been fitted to the density of decommissioned turbines and it is seen that a majority of the turbines were decommissioned at an age of 18 years with a spread of 3 years. The age distribution of Denmark reported by Lichtenegger et al. has been reproduced and shows a high similarity to the Gauss fit.

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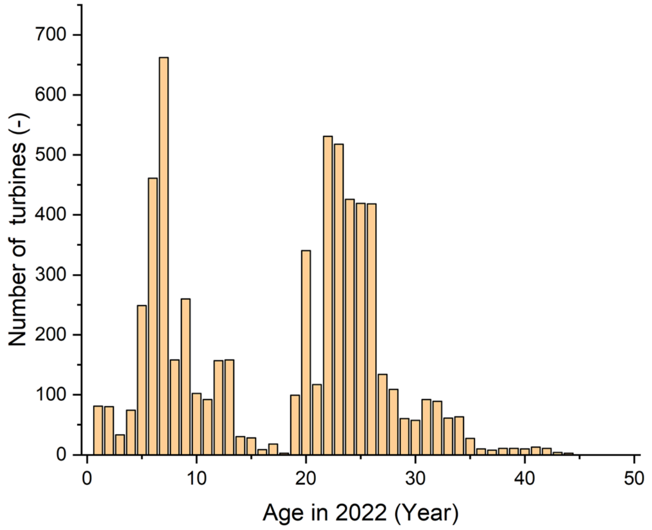

FIGURE 4 Age of the turbines in operation in Denmark by 2022.

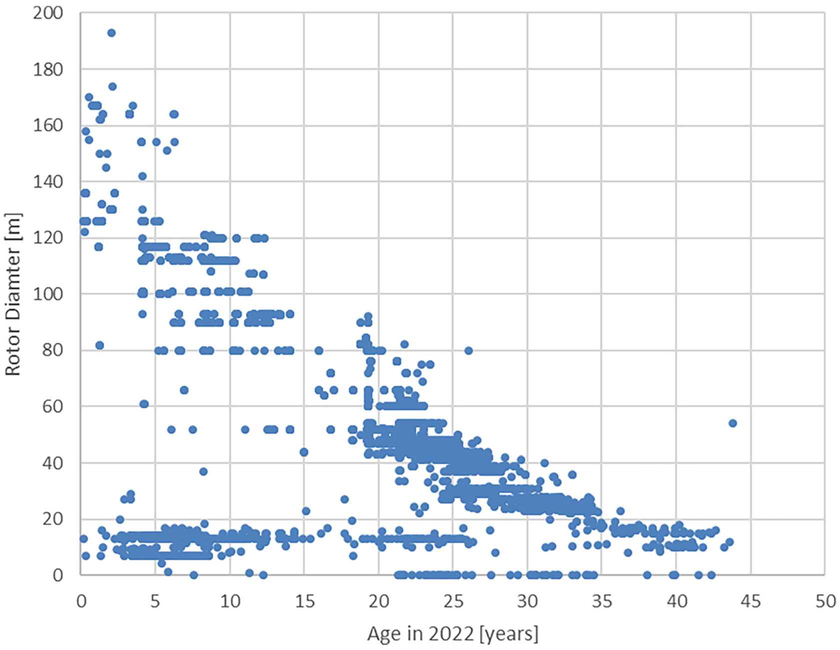

FIGURE 5 Rotor diameter of the turbines in operation in Denmark by 2022 shown as function of turbine age with respect to 2022.

$$Depletion_{year\ i} = \frac{m_{decommissioned\ from\ year\ i\ by\ 2022}}{m_{installed\ in\ year\ i}} \quad (13)$$

Figure 6 shows the installed blade mass of the onshore and offshore turbine blades in operation from 1978, which is the installation year of the first turbine registered in the Master turbine database. The onshore curve is showing that three main peaks of capacity were added in 1990, 2000, and 2015 as well as the pause of installation between 2003 and 2007. The decommissioned onshore blade mass is seen to reach the installed blade mass for turbines installed before 1988 reflecting that for these years, then all the installed capacity has been decommissioned. For the turbines installed later than 1988, then one can see that the installed blade mass is much higher than the decommissioned blade mass showing that most of the turbines are still operating. The actual decommissioning mass shows that the decommissioning of onshore turbines in Denmark first started in 1999, peaked in 2017 with about 1000 tons of blades handled and that the amount of blade mass removed in 2021 was about 200 tons.

Similarly, the offshore curve in Figure 6 is showing peaks corresponding to offshore wind farms being added to the Danish fleet. The decommissioning of the offshore wind farms first started in 2017 with the removal of the Vindeby offshore wind farm holding about 32 tons of blade material. However, this is the only farm removed and a reliable dataset for investigating the distribution of offshore wind decommissioning does not exist yet.

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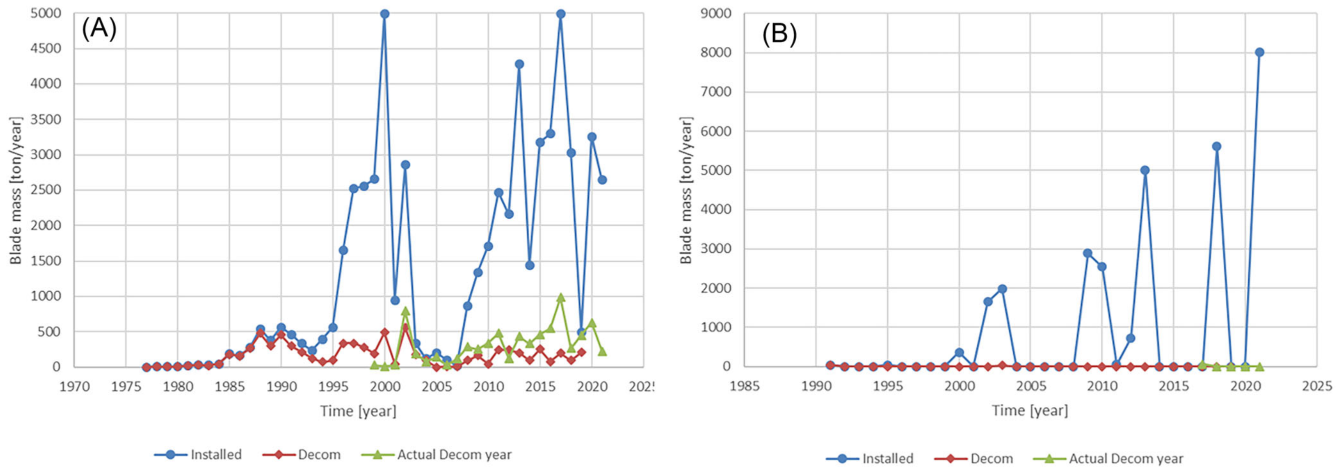

FIGURE 6 Installed and decommissioned blade mass of a) onshore and b) offshore wind turbine of Denmark as function of time from 1978 and until January 2022. The decommissioned blade mass has been sorted either by the installation year (red) or by the actual year of the decommissioning (green). Thus, the decommissioned blade mass (red) for the year 1985 is the sum of all blades decommissioned between 1985 and January 2022 but all installed in 1985. The green curve shows the blade mass decommissioned in a specific year but from turbines installed in different years.

4 | RESULTS

The results are organized into three sections. First, the depletion of the onshore wind turbine fleet installed in Denmark is quantified and characterized. It is then suggested how the onshore distribution can be transferred to a guess of how the offshore distribution will look like. Finally, the obtained distributions are used to estimate the future decommissioning blade masses of Denmark.

4.1 | Analyzing the Danish wind turbine fleet

From Figure 6, one can see that the decommissioned blade mass is reaching the installed blade mass for turbines installed before 1995. Figure 7 shows the ratio between the decommissioned blade mass for the different installation years and the total installed blade mass of those years in order to quantify the depletion of the onshore fleet as defined by Equation (13). By assuming that all the wind turbines of Denmark obey the same decommissioning probability function as given by the Weibull distribution of Equation (1), then one can roughly fit the Weibull depletion function to Figure 7 as shown by the red line. The obtained Weibull parameters are a scale of $\lambda = 30$ years and a shape of $k = 10$. This means that it takes $t_{50\%} = \lambda(ln2)^{1/k} = 28.9$ years before half of the onshore fleet is decommissioned and, respectively, $t_{10\%} = 24.0$ years and $t_{90\%} = 32.6$ years before 10% and 90% of the fleet is decommissioned by using Equation (5). Secondly, the time span of the depletion is $\Delta t = t_{90\%} - t_{10\%} = 8.6$ years using Equation (8). This onshore depletion must be compared with the design life time of onshore turbines being 20 years. In Figure 7, the design life time of onshore turbines is illustrated by a Weibull distribution having $\lambda = 20$ years and $k = 70$ resulting in a $\Delta t = 0.9$ year. This design life time depletion is representing a scenario, where the entire fleet would be decommissioned when the age of the turbines is reaching the design life time and then removed within a year. It is seen that the observed depletion is much slower and more widely distributed in time. There is a large peak in the depletion curve in Figure 7 for blades ages of 17–19 years, which is deviating from the Weibull distribution. This peak is caused by a very low installation volume in the years 2003–2007 as seen in Figure 6 and also by the fact that the national test center for large turbine Høvsøre was starting to decommission demonstration turbines, which are only tested for a few years. Thus, the peak is considered an artifact not representing the main turbine fleet. It is however interesting to note that there seems to be an initial depletion level of about 5 % for all blade years, and this is believed to be caused by the increasing testing of demonstration turbines in Denmark as performed at the Høvsøre and Østerild national test sites. A more advanced Weibull distribution function can be constructed by adding this initial decommissioning

$$F(t,\lambda,k) = 1 - c_1 \exp\left(-\left(\frac{t}{\lambda_1}\right)^{k_1}\right) - c_2 \exp\left(-\left(\frac{t}{\lambda_2}\right)^{k_2}\right) \tag{14}$$

where the constants c_1 and c_2 represent that fraction of the fleet being removed as demonstration and production turbines with corresponding Weibull parameters λ_1, k_1, and λ_2, k_2.

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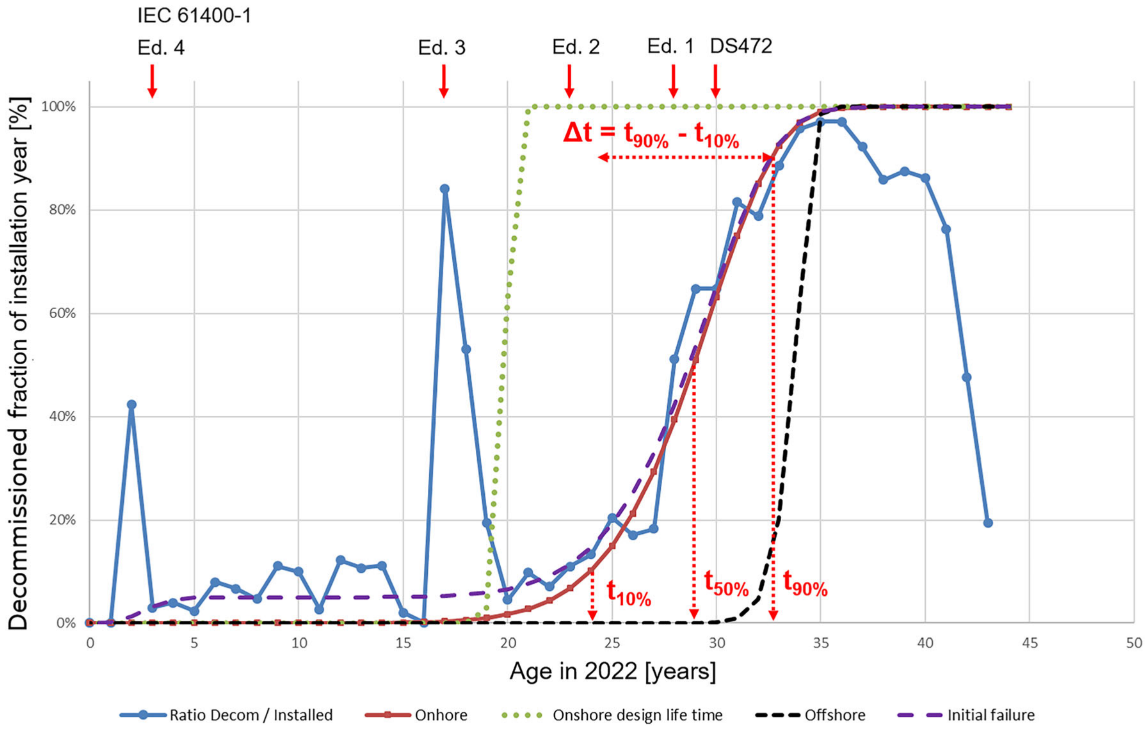

FIGURE 7 Depletion of the Danish onshore wind turbine fleet shown by the ratio between decommissioned blade mass and installed blade mass for the different installation years as by January 1, 2022. A Weibull depletion function as given by Equation (1) is shown by the red line and the resulting Weibull parameters are as follows: scale $\lambda = 30$ years and shape $k = 10$. The corresponding time when 10%, 50%, and 90 % of the fleet that has been depleted is shown as $t_{10\%}, t_{50\%}$, and $t_{90\%}$. The duration of the depletion is characterized by the time spam Δt. The peak of depletion from year 17–19 with a depletion value of 85 % is an artifact of the very low installation rate in the period from year 15 to 18 shown in Figure 4 corresponding to the year 2003–2007 in Figure 6. Thus, these points are neglected in the analysis. The turbine older than 35 years are also neglected, since they were constructed before wind turbine design standards were introduced as marked for the IEC 61400-1 standard[20] with different editions (Ed.1-4) as well as the Danish standard DS472 introduced in 1992[34] (marked at top of the figure). Finally, the depletion curve seems to have an offset of about 5 % even for the new turbines (purple), and this is believed to be caused by the relative high number of demonstration turbines tested in Denmark, which are decommissioned after a few years of initial testing.

In Figure 7, the advanced Weibull distribution is shown for the fractions $c_1 = 0.05$ and $c_2 = 0.95$ and the Weibull parameters given as $\lambda_1 =$ 3 years, $k_1 = 3$, and $\lambda_2 = 30$ years, $k_2 = 10$. The latter distribution is similar to the red model curve in the figure.

4.2 | Proposal on depletion distribution for offshore turbine fleet

Since the decommissioning distribution of the offshore turbines is basically unknown as shown in Figure 6, then one will need a qualified guess on the distribution in order to estimate the future decommissioned blade mass of the offshore turbines. In this paper, it is proposed to use the same shift of the $t_{50\%}$ with respect to the design life time as observed for the onshore turbine onto the offshore turbines as well.

$$t_{50\%,offshore} = t_{DLT,offshore} + (t_{50\%,onshore} - t_{DLT,onshore}) \tag{15}$$

$$= 25 years + (28.9 years - 20 years) = 33.9 years \tag{16}$$

The time spread of the decommissioning of the offshore wind farms is however not believed to be as smeared out as for onshore, because decommissioning of the offshore farms will most likely be entire farms and not individual turbines. Thus, the time spread $\Delta t = 2$ years is assumed limited for offshore reflecting that a decommissioning campaign might span two summers of good weather conditions. This result in Weibull parameters of $\lambda_{offshore} = 33.9$ years and $k_{offshore} = 50$. The proposed offshore Weibull distribution is shown in Figure 7 for comparison with the onshore distributions.

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4.3 | Predicting decommissioned blade mass as function of time

By using the Weibull distribution parameters obtained from the fit to the depletion plot in Figure 7 and combining that with the installed blade masses of the different installation years as shown in Figure 6, one can apply the model for predicting the decommissioned onshore and offshore blade mass as given by Equation (3). The result is shown in Figure 8 for the period between 1978 and 2022 and also for the future until 2065, where the current installed wind turbine fleet of Denmark is expected to be completely depleted. The inset of Figure 8 illustrates how the installed blade mass of installation year 2000 is expected decommissioned over time using the Weibull function in Equation (2) and the onshore Weibull parameters $\lambda = 30$ years and shape $k = 10$ obtained from Figure 7. All onshore blade masses of the different installation years are treated with the same onshore Weibull parameters, whereas the offshore decommissioned blade masses are determined with the offshore Weibull parameter $\lambda_{offshore} = 33.9$ years and $k_{offshore} = 50$ from Equation (15).

5 | DISCUSSION

The assumption that two universal Weibull distribution functions can describe the decommissioning processes of all the onshore and offshore wind turbine of Denmark from 1978 to 2022 may look as an oversimplification that might lead to inaccurate conclusions. This is indeed true, since

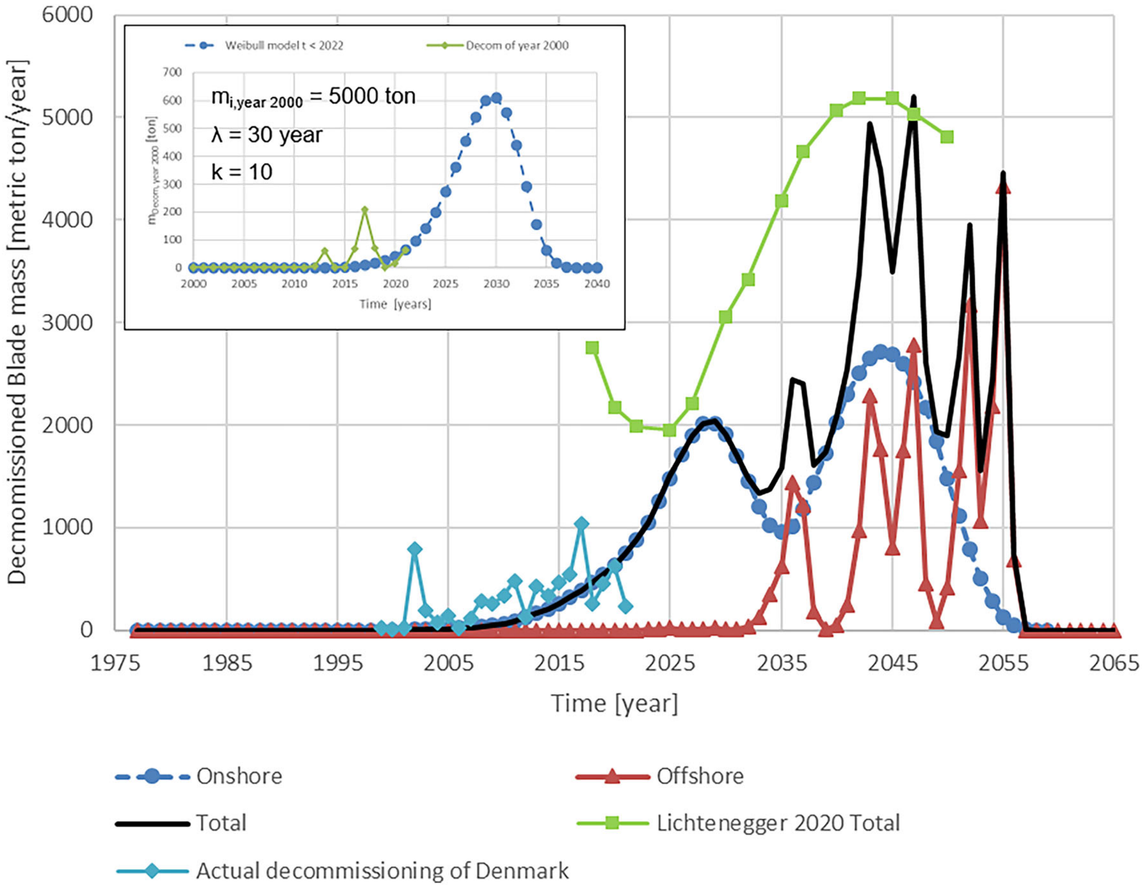

FIGURE 8 Predicted wind turbine decommissioned blade mass per year as function of time from 1978 when the first wind turbine was installed in Denmark. The model contribution from the onshore turbines (blue) is added to the offshore contribution (red), whereby the total blade mass is obtained (black). For comparison then the actual decommissioning blade mass of Denmark is shown (light blue) as well as the decommissioning blade mass prediction for Denmark of Lightenegger et al. 2020[14] (green). The predicted decommissioned blade mass of this paper is reaching about 2000 tons/year in 2028 and then it is increasing to about 5000 tons/year in 2045, when contributions from the offshore turbines are expected to increase. **Inset**: Illustration of the Weibull model prediction of the decommissioning blade mass as function of time of all the blades installed in the year 2000. The total installed blade mass in year 2000 is $m_{i,year2000} = 5000 ton$ as seen from Figure 6 and the decommissioned mass is $m_{decom,year2000}(t) = m_{i,year2000} \cdot f(t - t_{year2000}, \lambda, k)$ from Equation (3) using $\lambda = 30 year$ and $k = 10$. Since the Weibull distribution is normalized, then the sum of the decommissioned blade masses is equal to the 5000 tons installed. The green curve shows the actual decommissioning of the blade mass installed in year 2000, and this is only summing up to about 10 % of $m_{i,year2000}$. The same Weibull parameters of $\lambda = 30 year$ and $k = 10$ are applied to all the different onshore installation years in Figure 6 and added up to the resulting onshore decommissioned blade mass, whereas $\lambda_{offshore} = 33.9 year$ and $k_{offshore} = 50$ are used for the installed offshore blade masses.

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the turbine size and technology have evolved dramatically in the period and because the market conditions have changed from a period of subsidies for erecting wind turbines and then to the current situation, where onshore turbines must compete on market terms.

On the other hand, most of the turbines have been designed according to the International Electrotechnical Commission (IEC) standard for onshore turbines IEC 61400-1 specifying a design life time of 20 years[20] and the offshore standard IEC 61400-3 specifying a design life time of 25 years.[21] Since the demand of the IEC standard is a probability of major failures of $5 \cdot 10^{-4}$, then one would expect most of the turbines to function even after the age of the turbines has surpassed the design life time. This is indeed that case for the Danish onshore turbines, and one can determine the decommissioning fraction when the age is equal to the design life time as Equation (17) below

$$F(t_{design},\lambda,k) = 1 - \exp\left(-\left(\frac{t_{design}}{\lambda}\right)^{k}\right) = 1 - \exp\left(-\left(\frac{20years}{30years}\right)^{10}\right) = 0.017 \tag{17}$$

This is indicating that based on the Weibull distribution describing the Danish onshore wind turbine fleet depletion, then one should only expect about 1.7% of the installed turbine blade mass has been decommissioned when the turbines reach their design life time as specified in the IEC 61400-1 standard.[20] Thus, half of the wind turbine blade mass of an installation year is expected to operate about 9 years longer than their design life time and the time where 90% of the blade mass of an installation year is decommissioned is expected to happen about 13 years later than the design life time.

The Weibull distribution function found in this paper is also in reasonable agreement with an analysis of the evolution of the numbers of onshore turbine in Denmark as provided by the Danish Energy Agency in 2020[35] and Nielsen.[36] The analysis of the Danish Energy Agency predicts that all current onshore turbines in Denmark will be decommissioned by 2043–2048 depending on the electricity price and the cost of maintenance. Secondly, the Danish onshore wind turbine life time is stated to be 28 years by the Danish Energy Agency, which is also in reasonable agreement with the $t_{50}\% = 29$ years found in this paper.

The analysis of this paper is suggesting that there is a substantial delay between the wind turbine design lifetime and the decommissioning time of almost 9–13 years, and this is in large contrast to several of the previous End-of-Life blade mass predictions outlined in the literature review. The paper of Liu and Barlow[11] is using a fixed decommissioning time of 18, 21, and 26 years in their prediction of the blade waste amount for the world. If the Danish conditions can be transferred to the rest of the world, then one would only expect 21% of the fleet to be decommissioned after the 26 years using Equation (17). This is indicating that the predicted blade waste amount of Liu and Barlow[11] is about five times higher in 2020 than the decommissioned blade mass determined using the model of this paper. The paper of Lichtenegger 2020[14] is using a distribution function to describe the decommissioning of turbines in Denmark and Germany as illustrated in Figure 3. This function is seen to peak at a turbine age of about 18 year and if this is applied as the expected decommissioning age for all the onshore turbines of Denmark, then one will most likely estimate the amount of blade mass for decommissioning to happen about 10–15 earlier compared with the model of this paper. The prediction of the Danish decommissioning blade mass from the paper of Lichtenegger[14] has been included in Figure 8, and it is seen that the estimate around 2020 is about 10 times higher that the model prediction of this paper as well as the observed decommissioning masses of Denmark. A reason for the discrepancy is that only the decommissioning turbine data from the Danish master database have been used for fitting a distribution function as shown in Figure 3, whereby the turbines still in operation are neglected in the description of the depletion of the fleet.

In 2015, Danish owners of older turbines experienced an electricity payment as low as 22 €/MWh, which was approaching the cost of maintenance of the turbines at 17 €/MWh,[23] but this situation has changed with the current situation of shortage of natural gas in the European marked and very high electricity prices. Thus, revenue from old turbines is expected to be positive and large enough to pay for the maintenance and also repairs needed to keep the turbines operating. Based on this, one can argue that the old turbines will keep operating as long as the electricity prices remain high and that the Weibull distribution shown in Figure 7 will have to be shifted to the right toward longer depletion times. On the other hand, one can argue that if the revenue of the old turbines get high enough, then it might become feasible to remove the old turbine blades and upgrade the turbine with a new and longer set of blades in order to ensure another 20 years of operation and a higher revenue. The latter argument is suggesting an adjustment of the Weibull distribution of Figure 7 to the left toward faster depletion. It is suggested that further changes to the turbine fleet depletion rate must be investigated, but both a slow down as well as a speed up of the depletion are possible depending on the energy policies implemented in Denmark in the next decade. Thus, the decommissioned estimate presented by the simple model is seen as a compromise between these two considerations.

Finally, it should be mentioned that the development of wind turbine blade recycling value chains will need a certain amount of blade material to process in order to make a profitable business case. As explained in Section 1, then one cannot claim that decommissioning is guaranteeing that the blade is sent for End-of-Life processing. This paper will therefore only report on the predicted decommissioning blade mass and not the expected amount of blade waste. One can, however, claim that the predicted decommissioned blade mass of this paper is providing an upper limit on the blade mass that should be expected for recycling facilities in Denmark. Additionally, it will be interesting to apply the fleet depletion analysis of this paper to other European markets, like the German, to determine if a similar trend is observed and to create a joint estimate of the decommissioned blade mass in north Europe.

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6 | CONCLUSION

The decommissioning of the onshore wind turbines in Denmark has been described by a Weibull distribution function and the time when half of the fleet is decommissioned has been found to be $t_{50\%} = 29$ years, which is considerable longer than the 20 year design lifetime of onshore wind turbines. Many previous studies have used the design lifetime as an estimate of the End-of-Life of wind turbine blades, but this will result in an underestimation of the real End-of-Life time for wind turbine blades, and secondly, it is not known how large a fraction of the decommissioned turbines that are resold for a second operation period before End-of-Life is reached. Thus, the amount of wind turbine blade material than can be expected for recycling in Denmark will be shifted about 9 years further into the future compared with previous estimates. This is beneficial for lowering the environmental footprint of the turbines, but on the other hand, it is a challenge for the recycling industry, because the large inflow of wind turbine blade material for recycling is most likely delayed by 9 years.

By assuming an onshore and offshore distribution that can be applied to all turbines of Denmark, then an estimate of the blade decommissioning rate of 2000 tons/year is predicted for 2028 and a maximum of 5000 tons/year is predicted at 2045. Further studies are suggested to investigate if turbine fleet depletion will be slowed down by increasing electricity prices or if it will be accelerated due to replacement of blades as part of turbine upgrades.

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PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1002/we.2882.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available at the Danish Energy Agency at https://ens.dk/en, reference "Stamdataregister for vindkraftanlæg". These data were derived from the following excel file available in the public domain: https://ens.dk/sites/ens.dk/files/Statistik/anlaeg.xlsx.

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