DECOMMISSIONING INVENTORY FOR WIND TURBINE BLADES INSTALLED UNTIL 2022 IN EUROPE

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ABSTRACT

Wind turbines (WT) components have established recycling routes. However, wind turbines blades (WTBs) composite materials present unique challenges for recycling. This study aims to develop a comprehensive decommissioning inventory of wind turbines installed in Europe up to the year 2022, with a focus on accounting for the end-of-life (EoL) mass of WTBs composite materials. The inventory provides an estimate of the total amount of WTB composite material that will need to be decommissioned in the coming decades, in terms of mass, mass rates and volume. This estimate is further broken down by country, predicted decommissioning year, and blade architecture technology. To construct the inventory, data were collected on the total number of wind farms in operation, as well as those that are planned or under construction phase until the year 2022. The resulting inventory projects that over 7.6 million tons of EoL WTBs composite mass will need to be decommissioned in Europe by the year 2050.

1 INTRODUCTION

The primary wind turbine component materials are steel, aluminium, copper, permanent magnets rare-earths, concrete, and reinforced plastics (composites). Most of these materials have established recycling routes and are recyclable at the end of the wind turbine's operational life [1]–[3]. However, the environmental management of composite materials at the end-of-life (EoL) of wind turbine blades (WTBs) is still controversial given the different environmental regulations.

Several European countries (Austria, Finland, Germany and the Netherlands) have ban intact WTBs landfilling [4]–[6]. WindEurope called for a Europe-wide landfill ban on decommissioned wind turbine blades by 2025, actively committing to re-use, recycle, or recover 100 percent of decommissioned WTBs. At the same time, the industry undertakes not to send decommissioned WTBs from Europe to other countries outside of Europe for landfilling.

Landfilling ban accelerates the development of sustainable recycling technologies for composite materials. In this regard, WTBs recycling supply chains require accurate data to dimension and select adequate WTBs recycling technologies routes and recycling facilities for the coming years. In Beauson [6] and Walzberg [7] reviews on the EoL of WTBs in the European and US contexts point to the need for reliable estimates of WTBs EoL mass quantities and locations that feed into business models. There exist several studies in the literature where the EoL WTBs mass is forecasted. Cooperman [8] predicted a cumulative EoL WTBs mass in 2050 of approximately 2.2 million tons in the United States. And Liu [9] predict around 43 million tonnes of EoL WTBs mass worldwide by 2050.

This work describes the amounts of EoL WTBs decommissioning materials foreseeable for the next 30 years (until year 2050) in the European context. The inventory includes WTBs commissioned, planned or in the construction phase until 2022 in Europe. This work breaks down the primary materials technologies used in WTBs manufacturing sector. And forecast the pace of EoL material amounts that will face the recycling supply chain logistics and the different circular technologies routes.

The decommissioning inventory is based on different data sources [3], [10], [11]. By combining these data sources, an inventory was created describing European wind farms that are in the planning phase, in construction, already producing electricity, or that have been dismantled by 2022. Each wind farm record set includes the total wind farm power, the number of turbines, the commissioning year, the wind turbine model, and rotor weight. The wind farm information can be related to the wind turbine models, including WTBs characteristics regarding the rotor weight, technology, and manufacturer. In this regard, several assumptions were taken for the missing data, which are one of the sources of uncertainty for this study. The level of this uncertainty is evaluated by a sensitivity analysis which provides confidence ranges. Assuming an operational life of 20 to 30 [12], [13] years for a WTB until replacement or re-powering, the decommissioning year and amount of disposal material can be forecasted.

2 METHODOLOGY

The decommissioning inventory described in this study has been built using a variety of data sources [3], [10], [11]. The dataset includes all wind farms installed in Europe as of 2022, including both offshore and onshore facilities. This inventory comprises wind farms that are currently in production, under construction, or planned for construction in the near future. The collective total of these wind farms represents the estimated number of WTBs that will require decommissioning in the years following their operational lifetimes. For the wind farms that are planned but not yet in production, the study assumes that they will become operational within a range of one to seven years, based on a randomly square distributed timeline.

Each wind farm is considered as an inventory recordset. The recordset data fields included in this inventory are the wind farm location, the wind turbine manufacturer and model, the number of wind turbines, number of blades per WT, the nominal power and specifics about the windfarm and WTBs. Including rotor weight, composites materials, main resin family, and reinforcement types.

The composite EoL WTB mass materials resin types are divided into two main classes: epoxy and polyester/vinyl-ester resins. The fibre reinforcements classes are divided between glass fibre and carbon fibre. Where blades can be based only on glass fibre or based on a hybrid layup architecture combining glass and carbon reinforcements. Based on the WTB and blade model, the type of resin and fibres were assigned to each inventory recordset. The materials weight segmentation was carried out considering 55-70% reinforcing fibres and 30-40% resin by weight [14]–[16]. The weight of the core material was considered negligible accounting for values below 3 to 9% [9], [17]. In the case of hybrid blades with carbon fibre, the fibres reinforcement weight was divided considering between a 10-40% of carbon for the total weight reinforcements depending on the wind turbine.

The operational life of a WTB is accounted in a range of 20 to 30 years according to a normal distribution. It was considered that between 5 to 35% of the WTBs requires replacement due to lightning strikes or other operational damages. This variability on WTBs replacements was considered using a normal distribution. The variability in blade weights and reinforcements contents were considered with a coefficient of variation (COV) between 2 to 9%. The weight of root joint inserts, lightning protection cables or other metallic components present in a WTB were considered negligible in comparison with the composite weight. These metal parts can represent up to a 8% [17] for WTBs where the root joint is based on inserts. According to these variabilities a sensitivity analysis was carried out.

2.1 Sensitivity analysis

Based on the uncertainties described in the methodology section, a sensitivity analysis was performed for the EoL WTB inventory. For this purpose, the inventory was parametrised as a Python model with the main known uncertainties as variables. With the help of a sensitivity analysis tool [18], [19] multiple scenarios were generated and the overall scenarios population were evaluated to obtain the coefficient of variation.

According to the sensitivity analysis the main factor influencing the mass inventory results is the uncertainty on blade replacements and the uncertainty on the blade weight model. In this sense blade replacements varies largely from site to site and are dependent on operation and maintenance schemas. Overall, accounting with all the mentioned uncertainties, the scenarios mass calculations present a coefficient of variance of 7.5%. The relevance of this variation is visible in the error bars from Fig. 4.

On regards of the temporal forecasting. The main uncertainties are related to the commissioning date of the planned wind farms. And the operational life of a WTB. These two uncertainties impact on the generation rate of EoL WTB mass shifting the decommissioning date. This shifting can be observed in the Fig. 3 where the upper and lower confidence bands of the EoL WTB accumulated mass forecast are shown.

3 RESULTS AND DISCUSSION

According to this study Europe is projected to generate approximately 7.6 million tons of composite end of life (EoL) wind turbine blade (WTB) mass by 2050, because of actual wind farms which are in production, construction or planned phase until 2022. Fig. 1 illustrates the distribution of this composite disposal by wind farm phase. It's worth noting that the planned wind farms accounts for the 56% of the total figure, which adds some uncertainty to the study in terms of predicting the EoL year for the planned wind farms.

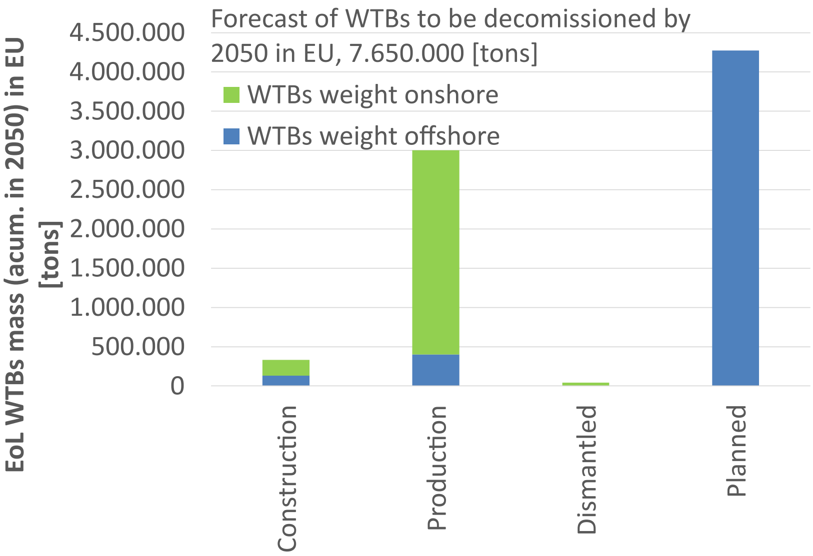

Fig. 1. Forecast of EoL WTBs mass to be decommissioned by 2050 in Europe.

In comparison, the United States is expected to generate 2.2 million tons of decommissioned onshore EoL WTB mass by 2050, according to Cooperman [8]. The decommissioning yearly rates predicted for Europe in 2040 are expected to be around 600 kilotons/year due to commissioned wind farms [5], [6]. This study predicts a rate 620 kilotons/year in 2040, which is align to the predicted figure but differs due to the variability on the estimates. Moreover, this figures are in the forecasted range provided by Liu and Barlow [9] for Europe between 5.35 to 10.85 million tons.

The amount of composite EoL WTB mass is expected to reach 7.6 million tons by 2050. This EoL WTB mass is categorized into on-shore and off-shore WTBs, with 2.8 million tons and 4.8 million tons respectively, that will be decommissioned by 2050. It is worth noting that a significant portion of the offshore composite waste is the result of recent planned wind farms developments along the European coast, many of which are expected to be commissioned before 2030. This is shown in Fig. 1, where the distribution of this composite EoL WTB mass is segmented by wind farm phase and offshore or onshore source.

It is important to consider that decommissioning offshore WTBs can be significantly more costly than onshore decommissioning. The cost of decommissioning offshore WTBs can range from 5 to 10 times higher [20], [21] than onshore decommissioning costs, depending on the distance from the coast and the power rating of the WTBs. Given this difference, the amount of offshore waste generated is an increasing concern for the industry and underscores the importance of developing more sustainable EoL solutions for offshore WTBs.

The cumulative distribution of the EoL WTB mass segmented by European country and onshore or offshore source is shown in Fig. 2. The largest amount of offshore EoL WTB mass is located in the United Kingdom, Sweden and Ireland, where a large amount of this EoL WTB mass belongs to planned offshore wind farms for the coming years. The largest amount of EoL WTB mass is expected to source from continental countries like Germany, Spain and France.

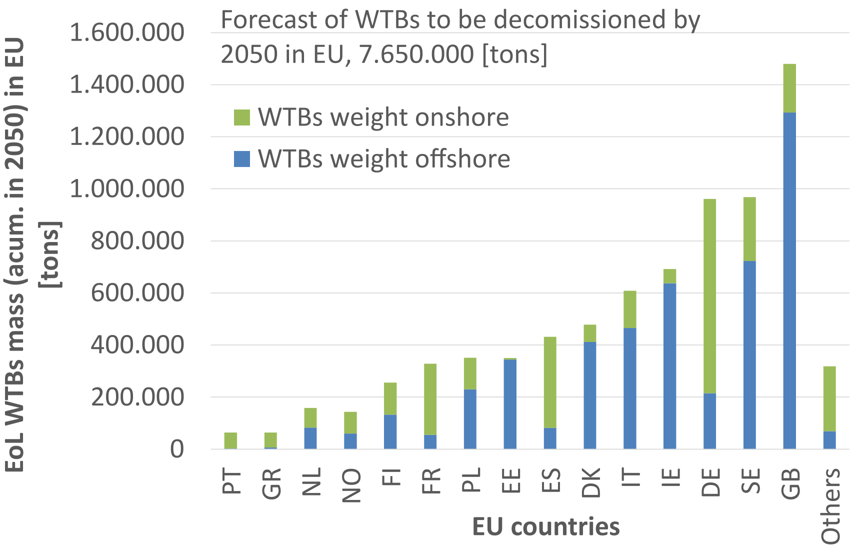

Fig. 2. Forecast of EoL WTBs mass to be decommissioned by 2050 in Europe, aggregated by countries.

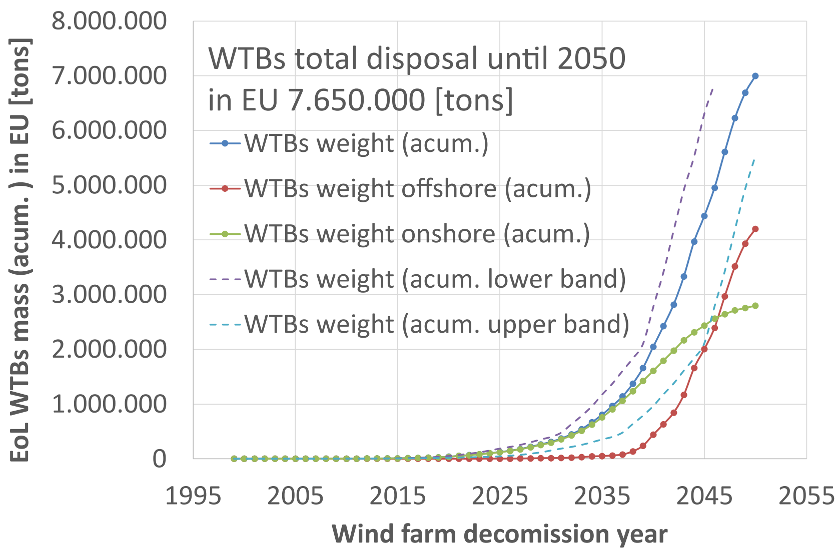

Fig. 3. Forecast of EoL WTBs mass to be decommissioned by 2050 in Europe. Accumulated by year, divided by on-shore and off-shore wind farms.

Based on the commissioning date and the expected decommissioning date, which is projected on a service life of 20 to 30 years, it is possible to anticipate how the cumulative distribution of the EoL WTB mass will evolve during the coming years. Fig. 3 shows the time evolution of the cumulative distribution of the EoL WTB mass segmented by onshore or offshore source. Due to the wind farms in production and the decommission of the same, a point of inflection is expected by 2030, followed by a rapid increase in the EoL WTB. This increase will be primarily related to onshore wind farms. By 2040, the mass rate of EoL WTB is projected to further increase due to the additional input of offshore EoL WTB mass.

The cumulative distribution of the EoL WTB mass allows to compute the mass rates of EoL WTBs that will be managed yearly by the different WTBs circular routes technologies. Fig. 4 shows that the EoL WTBs mass rates expected before 2030 are below 100.000 tons in the European context. Later, the EoL WTBs mass yearly rates will increase up to rates of 600 kilotons/year in 2040 and 950 kilotons/year in 2045.

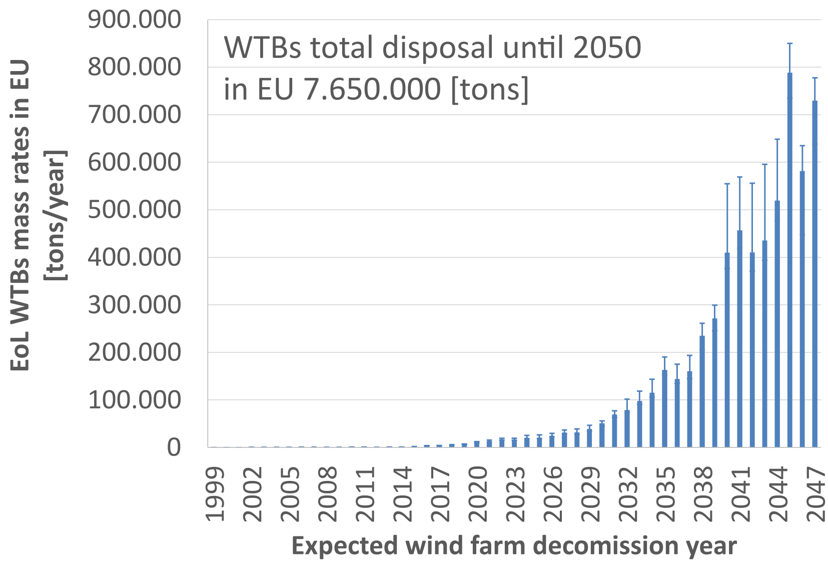

Fig. 4. Forecast of EoL WTBs yearly mass rates to be managed by 2050 in Europe.

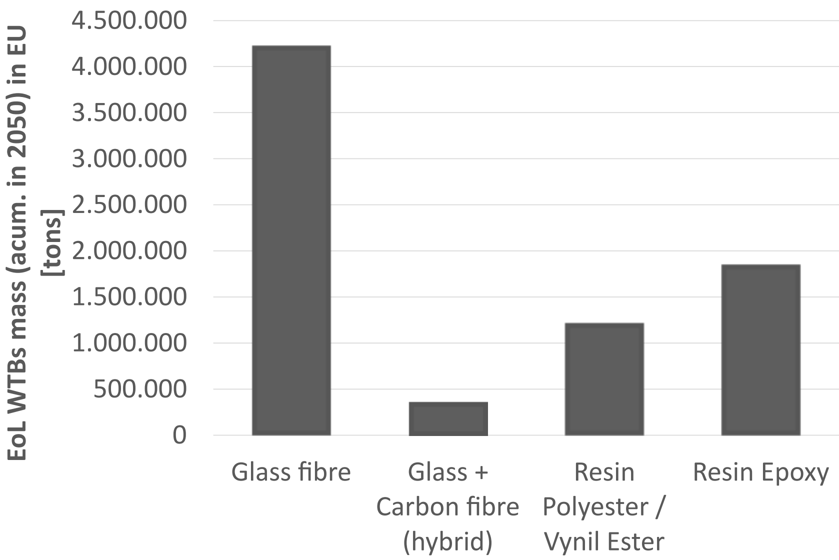

Fig. 5. Forecast of WTBs to be decommissioned by 2050 in Europe. Accumulated by raw material.

Due to the technical bottleneck in locations and grid capacity, the onshore EoL WTB mass is expected to achieve a certain plateau by 2050, which will increase at a slower rate and will be maintained due to the replacements or repowering of the wind farms and the EoL of the WTBs in production. In contrast, the growth of available sites appears to be more stable in the case of offshore wind farms, helping to stabilize the overall increase in the EoL WTB mass rate.

Attending to the composition of the EoL WTBs mass, Fig. 5 shows the main distribution of material which will compose this EoL WTBs mass. Since there are WTBs architectures based on glass fibre and hybrid layup architectures based on glass fibre and carbon reinforcements, the distribution of reinforcement materials is divided in both. In the case of the resin, in most cases the division can be made into blades architectures based on epoxy resins and others based on polyester/vinyl ester resins. This materials distribution of the EoL WTBs mass is of particular interest in the computation of the lifecycle analysis, the circular routes logistics dimension and costs analysis. For instance circular routes based on the incineration or the cement co-processing [3], [22], [23] will output higher heat flows on hybrid architectures than on glass fibre WTBs architectures [24]. Chemical circular routes might not perform equally on epoxy or polyester/vinyl ester resins matrixes [25]. Moreover, the mechanical circular routes powder from epoxy and polyester/vinyl ester matrixes grinding or shredding requires different safety concerns and approaches due to the styrene content or the possible toxicity [26], [27], impacting on the operational costs. To account for these WTBs architectures specifics, Fig. 5 shows that for the overall EoL WTBs mass 45% of the mass belongs to glass fibre reinforcements and 15% of the mass belongs to the carbon fibre from hybrid reinforcements blade architectures combining glass and carbon fibre. Moreover, 25% of the mass belongs to epoxy resin matrixes and 15% of the mass belongs to polyester/vinyl ester resin matrixes.

In perspective, EU generates 80 million tons of packaging waste [28] yearly. If the total EoL WTBs mass of 7.6 million tons generated by 2050 is compared in weight with the total yearly packaging waste mass, it represents around 10% of the yearly packaging waste. However, in terms of volume the comparison is not as favorable. Since the average density of an intact blade is 33 kg/m^3 [8], and the average compacted packaging waste density is 750 kg/m^3 [29], the total EoL WTBs mass generated by 2050 represents twice the volume of the total European yearly compacted packaging waste, leading to a total EoL WTBs volume of 228 million m^3 generated by 2050.

4 CONCLUDING REMARKS

The disposal of wind turbine blades (WTBs) intact or as large segments in landfills has an impact in the landfilling capacity due to their substantial volume and relatively low weight. Moreover, the EU legislation is shifting in this sense, which advocates for sustainable waste management practices. The volume of end-of-life (EoL) WTBs is projected to rise significantly over the next few decades, with a predicted cumulative total of 7.6 million tons and 228 million m^3 in the European context by 2050. Given the vast quantities of composite EoL WTB mass that will need to be managed, it is essential to explore circular technologies that consider both cost and environmental impact constraints.

This study offers a comprehensive overview of WTB waste streams in the European context, breaking down the primary materials, technologies, and WTB architectures used in the blade manufacturing sector. By forecasting the rate of EoL material and the volumes that will require processing through circular supply chain logistics, this study aims to inform the selection of the most effective circular technological routes for managing EoL WTBs mass. This will ensure the optimal use of resources while minimizing environmental impacts and costs. The adoption of a circular approach to EoL WTB mass management holds the potential to enhance the sustainability of the wind energy industry.

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