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Mass determination and model prediction of retired blades from wind turbine repowering or dismantling using a GIS database

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Abstract. Existing estimations of waste from wind energy infrastructure that is headed for, flowing through, or having reached the terminus of various post-processing pathways have primarily relied on reported capacity to extrapolate the material weight of turbine components. This data can be used to project future streams of composite blade material coming from wind farm repowering and decommissioning and inform policies to optimize or improve certain blade End of Life (EoL) options. However, rated capacity alone is insufficient to quantify or characterize the dynamics of US wind fleet retirement, since turbines are often repowered with new blades but their capacity remains the same. This research demonstrates an alternative method, comparing various mass estimation techniques and identifying blade models that have been retired or are soon to enter waste pathways due to turbine repowering by spatiotemporal comparison of periodic versions of the United States Geological Survey (USGS) Wind Turbine Database (USWTDB). These analyses are used to compile a list of turbine and blade models that will be at the forefront of national repowering and decommissioning movements in the near future. Mass of future waste flows are totalled and can help inform protocols and frameworks for blade material EoL processes.

1. Background

Significant investment in wind energy since the early 2000s indicates that there will soon be a large volume of wind energy related waste heading for processing [1, 2]. In addition to landfill disposal, there are a variety of ways in which blade waste may be discarded or repurposed for material value: incineration, mechanical recycling, thermal recycling, chemical recycling, or cement co-processing among others [3]. By far, landfill disposal of wind blades is cheapest and most simple, offering an attractive option to economic stakeholders [4]. However, landfill disposal of wind energy material poses environmental harm and degrades the value of wind energy as a clean, renewable source [5]. Several groups have expressed interest in implementing a circular economy solution to the prevailing issue of wind energy waste which would enhance the engagement of the wind energy sector with environmental goals [6]. In 2023, Vestas, the largest global wind turbine manufacturer, reported research that could establish a process which would allow the company to break down the epoxy resin of old blades, generating new raw materials [7]. Previous research by the Re-Wind Network and others indicates there may be additional reuse options for EoL blades, such as girders for pedestrian bridges or as poles for electrical transmission lines [8, 9] amongst others. These options utilize the existing structural features of the blade but verify their capacities for appropriate alternative loading conditions.

Blades are generally considered to be in the EoL stage once they can no longer perform their original functionality of generating the greatest possible profit for wind farms [10]. A variety of factors can lead to the decrease in generated value - over their useable life, blades may experience loading fatigue or material erosion, which reduces the performance of turbines. Wind farm owners can make the choice to 'repower' by removing underperforming blades or turbines and fitting new machinery onto existing towers. Generally, farms are permitted to use wind blades until their Design End of Life (DEoL) which is about 20 years. After this time has elapsed, DEoL can be extended by re-permitting or retrofitting. The variety of criteria for blade EoL makes it difficult to predict the future decisions of wind farm repowering or decommissioning.

Previous research has investigated circular economy systems and used GIS to develop EoL removal and disposal routes. A global wind inventory for future decommissioning (GoWInD) has been proposed using QGIS to create a framework where the decommissioning of individual wind infrastructure components is handled with spatiotemporal considerations, aiding the logistics of transportation, and recycling or disposal [11]. Other research has used USWTDB data to project the total mass of future blade waste based on existing national capacity and conversion from power rating to blade mass [3]. Prospective material flows as well as total waste inventory can be deduced from existing data on wind infrastructure and numerical models relating blade size and rated power [12].

The total capacity of US wind energy is reported by a number of organizations. The USWTDB web viewer reports the total GW to be 138 GW [13]. The International Energy Agency (IEA) reports 143.9 GW of onshore wind energy capacity in 2022 while American Clean Power (ACP) reports a capacity of 140 GW [14, 15]. The U.S. Energy Information Administration (EIA) reports 137.6 GW in June of 2022, while Wood Mackenzie, a global consultant and research group, reports 148 GW in 2022 [16]. There is clearly a discrepancy in these reports indicating that total national capacity can be (and is) quantified in a variety of ways.

Data used in this research was obtained from the USWTDB repository. Versions of the data from 2014 and 2022 were used. Both database versions include information on rated power, rotor diameter, location, and a unique identification number for cross referencing among other fields. This research employs Quantum GIS (QGIS), a free and opensource mapping software system, and MATLAB, to investigate the characteristics of blades approaching their EoL stage.

2. Identification of dismantled turbines and potential EoL blades by temporal comparison

The USGS maintains current and historic repositories of geographic locations of installed wind turbines with fields for information on the features of each turbine. Instead of describing whole farms, which are often constructed entirely of the same model of turbine, the database compiles reports of individual turbine locations and verifies existence with satellite imagery [13]. Due to this method of documentation, several locations are missing complete data entry, as characterization of each turbine in the US is tedious, but at a minimum each existing turbine is listed with its longitude and latitude. With these records it is possible to compare the change in on- and offshore existing turbine locations. New installations and past removals can be identified, and changes in the information about turbine type, blade length, and capacity can be used to determine which locations have been repowered.

In this study, the July 2022 USWTDB version (the most recent version at the time this project was started) was compared to the March 2014 version. The 2014 data was selected because it contained relatively thorough data compared to prior versions. Additionally, the 2022 data listed a field specifically for cross-referencing to the 2014 version, which meant that the matching of geographic locations of turbines could be further verified. The comparison of these two years was used to group turbines into 4 categories: 'new' turbines installed after 2014, turbines that were dismantled before 2022, turbines that have been repowered between 2014 and 2022, and turbines that have not been repowered but existed in 2014 and 2022. Figure 1 uses a Venn diagram to represent the categorization of all turbines in these two lists.

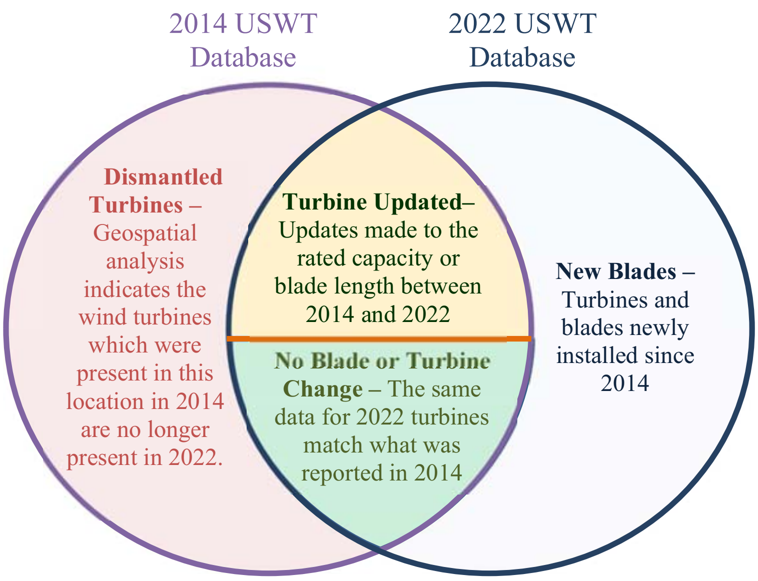

Figure 1: Venn diagram analogy of turbines between 2014 and 2022

Locations were matched by longitude and latitude with a resolution of 0.0001 degrees, which is roughly equal to 11.1 meters [17]. This resolution was necessary because the recorded location points were not identical, likely due to discrepancy from areal imagery across the different years. These location-based matches were verified with comparison of the 5-digit cross identification field provided by the USGS for the 2014 repository.

Figure 1 depicts the sectioning of turbines across the two data versions. The full circle on the left is all 2014 turbines while the right circle is all 2022 turbines. The far-left crescent represents locations that were dismantled between 2014 and 2022 since they are listed in the first but are not present in the second. Blades from this section by implication have been sent to EoL processing. In the far-right crescent are new turbines that were installed after 2014. In the bottom of the overlap between 2014 and 2022 are turbines which have no recorded change in their rated capacity or rotor diameter, they are considered to have not yet been repowered. By contrast the locations that reported an increase of 20kW or greater or whose rotor diameter increased by more than 2 meters between 2014 and 2022 are considered to have been repowered. Figure 2 uses another Venn diagram to represent the criteria for determining which turbines have been repowered.

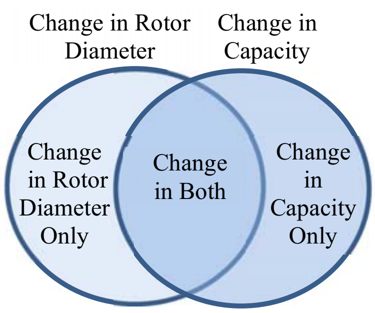

Figure 2: Venn diagram analogy for all turbines considered to be repowered

In Figure 2, the left circle represents all turbines whose rotor diameter was recorded to increase by 2 meters or more between 2014 and 2022 while the right circle is all turbines whose capacity increased by 20kW or more. In the left crescent are turbines who *only* record changes in rotor diameter while the right is turbines with *only* a recorded increase in power rating, the intersection contains turbines who saw an increase in rotor diameter *and* capacity change. Thus, the overall criteria for a turbine to be considered repowered is to record a reasonable increase in its rotor diameter *or* capacity between the two years. An increase in rated capacity is a direct indication of repowering while an increase in blade length would enhance the performance of turbines without being reflected in the capacity value. All turbines whose information did not change, or whose change was less than the criteria values, are still contenders for future repowering projects as their performance had not substantially changed since installation. The not-yet-repowered turbines and their attached blades are those due for updates in the near future and are the source of the next generation of blade waste material.

2.1. Mass Estimation

In this research, the weight of blade waste is compared using two methods. The first approach uses a high estimate of 15 metric tonnes per MW of power produced and a low estimate uses 10 tonnes per MW [2, 18]. The second technique uses a polynomial relationship to determine the weight of blades from their length according to the Equation 1 (where W is blade weight in tonnes and L is length in meters) [19]:

$$W = 0.0036L^2 + 0.0258L \tag{1}$$

The attempt to estimate the mass of various groups introduces an issue as the USWTDB has many entries missing data for the capacity rating and rotor diameter fields among others. In fact, in 2014 only 87% of turbines listed their rated capacity and 85% listed rotor diameter. Due to the missing information, the total weight was found by treating the ratio of weight determined to the percent of information present as a proportion of the total weight, described in Equation 2

$$\frac{Sum\ of\ Reported\ Capacity}{Actual\ Percent\ Reported} = \frac{Total\ Capacity}{100\%\ Reported} \tag{2}$$

Using this method, the total weight of blade material from 2014 and 2022 in each of the four categories (new, dismantled, repowered, not repowered) was estimated using the available information on each turbine's capacity rating and blade length and extrapolated to develop the total mass in each group in Table 1. The weight estimates for dismantled turbines used information taken from the 2014 lists while all other categories took information from the 2022 data.

Table 1: Mass estimates of each year and categorical group using rated capacity and blade length

Group	Number of Turbines	Low Tonnage Estimate from Power Rating	High Tonnage Estimate from Power Rating	Tonnage Estimate Based on Blade Lengths
2022 Turbines	72,130	1,449,000	2,173,500	2,132,800
2014 Turbines	48,976	658,900	988,350	883,480
New	34,035	829,300	1,243,950	1,344,100
Dismantled	10,881	39,710	59,565	49,844
Not Repowered- No Change	30,830	491,300	736,950	605,830
Repowered - Change in Blades OR Capacity	7,265	127,900	191,850	192,960

Between 2014 and 2022 the number of online wind turbines increased by nearly 50%, but the capacity more than doubled. This reflects the engineering advancement in turbine efficiency and airfoil design of blades. Blade weights calculated from length for all the 2022 turbines, all 2014 turbines, dismantled turbines, and not repowered turbines (first, second, fourth, and fifth rows respectively) fell within the high and low tonnage estimates resolved from capacity rating. By contrast, new and repowered turbines (third and sixth rows respectively) saw that the weight estimate based on length exceeded the high estimate based on rated capacity. Newly installed turbines and those that have been repowered are implied to be fitted with the most up-to-date technology. The length-based estimate for all 2022 turbines heavily favored the high tonnage capacity-based estimate, that is, the length estimate was only 1.8% less than the high tonnage capacity estimate. This signals that using an estimate of 10-15 tonnes of blade material per MW of power may be minimizing the actual weight of potential blade waste. At the very least there is an observable mismatch between weight estimates derived from blade length and turbine power rating for the most recent wind energy technologies that is not observable for older turbines.

In Table 1, the weight of repowered turbines was calculated with 2022 data so as to present the most recently available information at these locations, but it is also pertinent to look at the change in weight between 2014 and 2022, and even within the different attributes that signal repowering has occurred. Table 2 analyzes the change in weight based on blade-length calculations while Table 3 considers the change in capacity rating.

Table 2: Change in blade weight of repowered turbines from 2014 and 2022 estimated from length

Group	Weight in Tonnes in 2014	Weight in Tonnes in 2022	% Change in Weight
ALL Change in Capacity	78,384	98,456	25.61
ALL Change in Blades	130,830	169,910	29.87
Change in Capacity ONLY	22,034	22,036	~0
Change in Blades ONLY	67,154	84,703	26.13
Change in Both Blades AND capacity	55,165	75,409	36.70
Repowered – Change in Blades OR Capacity	154,050	192,960	25.26

Table 3: Low and high estimates of blade weights estimated from information on rated capacity

Group	2014 Low Tonnage Estimate	2014 High Tonnage Estimate	2022 Low Tonnage Estimate	2022 High Tonnage Estimate	% Change in Weight
ALL Change in Capacity	58,820	88,230	64,390	96,585	9.469
ALL Change in Blades	108,400	162,600	112,300	168,450	3.598
Change in Capacity ONLY	14,050	21,075	14,680	22,020	4.484
Change in Blades ONLY	57,270	85,905	57,270	85,905	0
Change in Both Blades AND Capacity	43,960	65,940	48,830	73,245	11.08
Repowered-Change in Blades OR Capacity	123,300	184,950	127,900	191,850	3.731

The consistent observation that blade weights increased for turbines identified as repowered affirms that there have been updates made in these locations between 2014 and 2022. However, the overall increase in weight of repowered turbines determined from the change in blade lengths was 25% while the increase in weight developed from rated capacity was only 3.7%. The length-based estimation for 2014 blades (that were removed) consistently falls within the high and low estimates derived from capacity rating. For the 2022 repowered turbines, or the new turbine and blade models that were fitted to existing towers, the length-based estimate is greater than the high tonnage estimate for every category except for the case where *only* blades were updated on an existing turbine. This indicates that for modern turbines and blades, capacity-based estimation doesn't completely account for the mass of newly installed blades. In both Table 2 & 3, the category with the greatest increase in blade weight was for turbines whose blade length and capacity reported changes between the two years, which could be explained by the fact that updating turbine *and* blades onto a pre-existing tower reflects an extreme form of update so increase in blade material was substantial.

2.2. *Turbine and blade models due for update*

It is also of interest to understand what turbine models are most frequently updated and what they are updated to. Using histograms, Figure 3(a) displays the top 10 original models that were updated after 2014 while 3(b) reports the most common turbines that are the result of repowering.

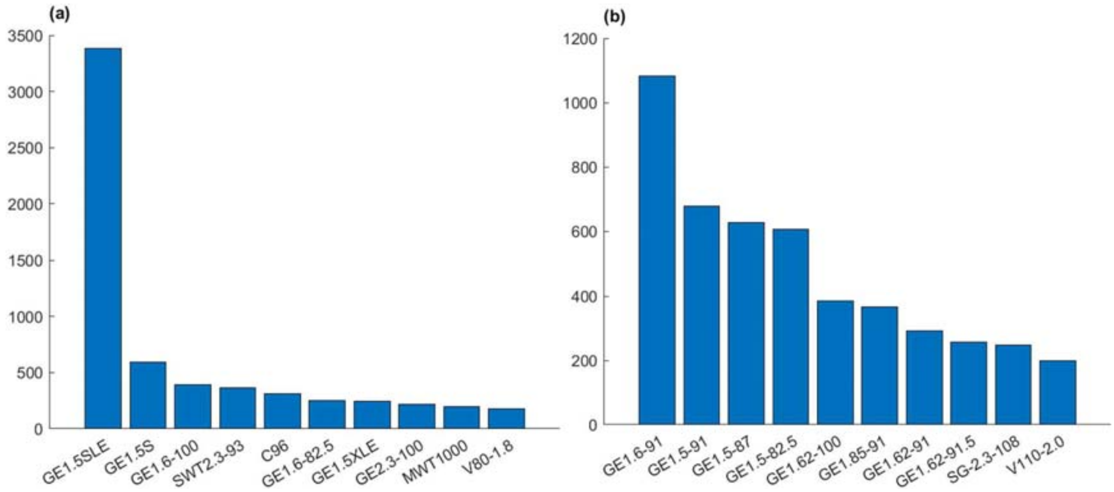

Figure 3: (a) the 2014 turbine models that were updated and (b) the 2022 turbine models that are the result of repowering

Figure 3(a) states the most frequently observed models that have already been repowered. Although the specific turbines identified by this process have been repowered recently, implying they will not be repowered again soon, the models found on this list can be understood to signal the present trend in what is being updated by most repowering projects. Figure 3(b) indicates which models farms are most often updating to, once old technology has been removed. The most commonly updated turbine model between 2014 and 2022 was the GE1.5SLE, this turbine is commonly fitted with 77.0-meter rotors (also known as the GE37 blade [20]). The most common result of the updates were various GE turbines in the 1.5-1.8 series fitted with rotors at least 82.5 meters in diameter. Around 3,500 GE1.5SLE, 500 GE1.5S, and 250 GE1.5XLE turbines were repowered between 2014 and 2022 and the 8 models representing the most likely outcome of repowering on 2022 were GE turbines and blades, so it seems as though these updates match up. Other turbines models that were updated include the Siemens Gamesa SWT2.3-93, the Clipper C96, and the Vestas V80-1.8.

The next cohort to examine are the turbines who persisted between 2014 and 2022 but were not updated – these turbines are due for update and will be at the forefront of repowering efforts in the coming decade. Figure 4 shows the top 10 turbines in the not-yet-repowered groups in a histogram. Comparing Figures 3 & 4, it can be observed that the most frequently repowered turbine and the most popular model due for future repowering is the GE1.5 turbine fitted with GE37 blades. These are locations with short blades, underproducing power compared to industry standards, that will have to modernize in the coming years. Although the GE37 is most often fitted to turbines rated for 1.5MW, there are a total of 6,612 instances of 77.0-meter rotors fitted to turbines in the 1.5-1.7 series. Since the Re-Wind network is a blade-centric research project rather than a turbine-centric one, it is of more interest to consider the blade model that will be entering post-processing streams than the turbine model they are coming from.

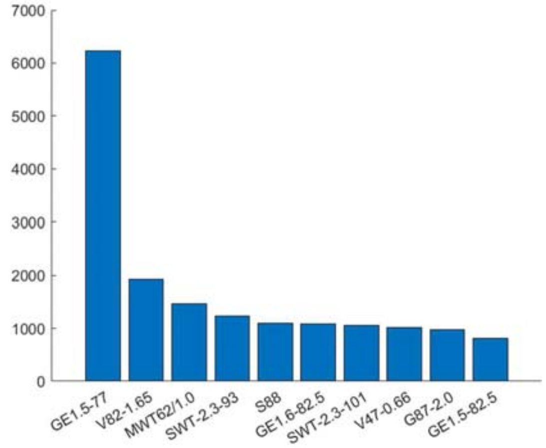

Figure 4: Top 10 most common models in the group of turbines due for future repowering

Notably on the list of to-be-repowered turbines are Vestas V82 and V47 turbines, Siemens Gamesa SWT2.3-93 and SWT2.3-101 turbines which use B45 and B49 blades, and GE 82.5-meter rotor diameters fitted to turbines of various ratings. Other assorted models come from smaller wind turbine manufacturers and the problems associated with repowering these models is unlikely to proliferate. It is pertinent to consider the spatial distribution of these models in the US so as to understand which regions should be expecting large inflows of blade waste, Figure 5 displays the geographic locations of each of the top models from Figure 4.

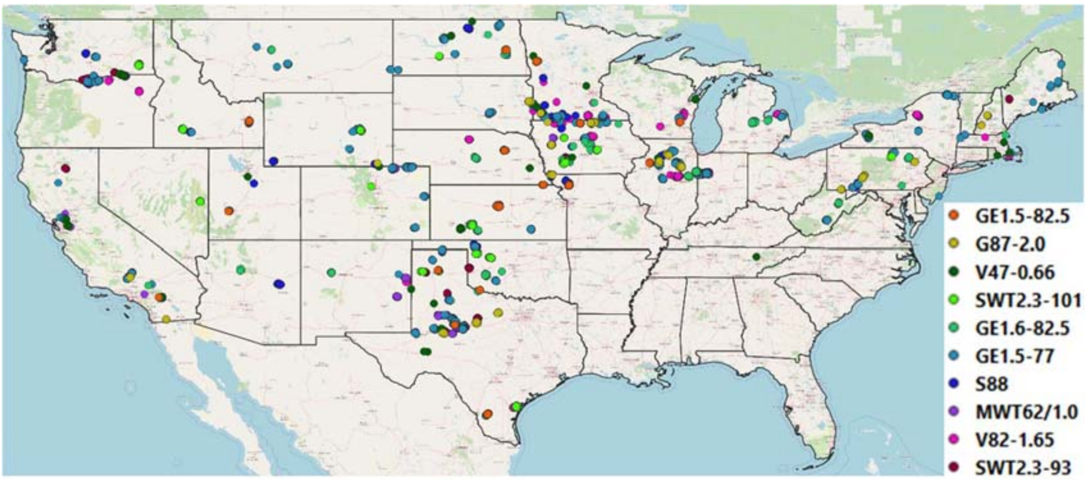

Figure 5: QGIS rendered map of all onshore US locations of turbine models likely for repowering

3. Discussion

In the interest of establishing economic circularity of wind blade materials, it is crucial to understand the features and constituents of future repowered and decommissioned blade groups. Making predictions on the type and total mass of blades coming out of service helps stakeholders plan for uses and processing procedures for blades, tailored to the specifics of the structure and material composites. In the above analysis, blade weight estimates from US turbines that have been completely dismantled, repowered, or installed after 2014 were determined, as well as a cohort of turbines with blades that are expected to be repowered in the near future. It is estimated that there are roughly 163,010 to 244,515 tonnes of blade waste currently in landfills or having been sent to EoL processing. This number comes from combining the weight of blades from dismantled turbines and the weight of blades identified as having already been repowered (where the weight is taken from 2014 data). In the next decade or so an additional 491,300 to 736,950 tonnes of blade material can be expected to enter waste streams from the cohort of turbines that are older and are due for repowering.

Significant turbine and blade models ideal for repowering in the near future have been identified. Most notably are GE1.5 MW turbines associated with the GE37 blade model, which represent 9.23% of current online blades and roughly 99,350-149,025 tonnes of material. In addition to the GE37 are Vestas V47 and V82 blades, Siemens Gamesa B45 and B49s, Mitsubishi MWT62/1.0 turbines, and other GE blades corresponding to 82.5-meter rotors (among other turbines and blades). These models are recognized as key groups to be removed and replaced from operating turbines due to their collective features of underperformance, mechanical issues, or outdatedness. Future work should investigate the rates at which certain blade models are replaced over time and should analyse additional years of data to make these predictions. For more details see [21].

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