INSTITUTO POLITÉCNICO DE BRAGANÇA
Escola Superior de Tecnologia e Gestão

Wind Turbine Blade Waste: A Quantifying Model

Lucas Lisboa da Fonseca Santos

Thesis presented to the School of Technology and Management in the scope of the Master in Renewable Energy and Energetic Efficiency.

Supervisor:
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"Perfection, goal that always changes. Can pursue, cannot obtain"

- Abathur

Abstract

This thesis presents a model for the prediction of waste generated through end-of-life wind turbine blades. The methodology utilised was based on acquiring information - mainly rated power and blade weight - on 355 real wind turbine models and dividing them into categories. The resulting model, presented in equation form, was tested through a case study and then compared to similar works. The main conclusions were that the model has a higher resolution, - compared to similar models published by different authors - 15, thus more precise, proving to be a tool that can be utilised in the decision-making of organisations such as governing or environmental agencies and wind turbine manufacturers.

Keywords: Model, wind turbine, blade, rated power, weight, waste, end-of-life, wind turbine blade

Resumo

Nesta tese apresenta-se um modelo para previsão de resíduos gerados por pás de turbinas eólicas após seu ciclo-de-vida. A metodologia utilizada foi obtenção de dados - principalmente potência instalada e peso das pás - de 355 modelos reais de aerogeradores, dividindo-os posteriormente em categorias. O modelo resultante, apresentado em forma de uma equação, foi então testado por meio de um estudo de caso e comparado com trabalhos semelhantes. A principal conclusão é de que se trata de uma ferramenta com alta resolução, - comparado com modelos similares escritos por diferentes autores - 15, logo mais preciso, que pode ser utilizada na tomada de decisões de agências governamentais e ambientais, assim como fabricantes de turbinas eólicas.

Palavras-chave: Modelo, turbina eólica, rotor, potência instalada, peso, resíduo, fim de vida útil, pás de turbinas eólicas

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Chapter 1

Introduction

The objective of this work is to create a model, with higher theoretical accuracy when compared to similar models, to predict the amount of solid waste that already has been and will be generated from wind turbine blades after their life-cycle, thus helping decision making of both industry-based companies - to evaluate the future of the materials currently used to manufacture wind turbine blades - and also assist governing bodies to elaborate laws and resolutions towards better practices concerning waste management.

Wind energy is becoming an increasingly important source of electricity in Europe and around the world. In 2021, wind energy made up 15% of the total supply of electricity in Europe, and this number is expected to continue to rise in the coming years, with the expectation that it reaches 36% until 2050 [1][2]. This growth can be attributed to a number of factors: (a) lowering production costs; (b) environmental awareness and restrictions; and (c) advances in technology.

(a) Wind energy is becoming more cost-competitive with traditional sources of electricity, such as coal and natural gas. The global average installation cost of onshore wind turbines has decreased significantly in recent years - over 70% since 1983 (from 5,179 to 1,473 USD/kW in 2019), Figure 1.1, making wind energy more affordable. This has led to increased investment in wind energy projects, which in turn has helped driving down costs even further, making it an attractive option for a wider range of energy consumers.

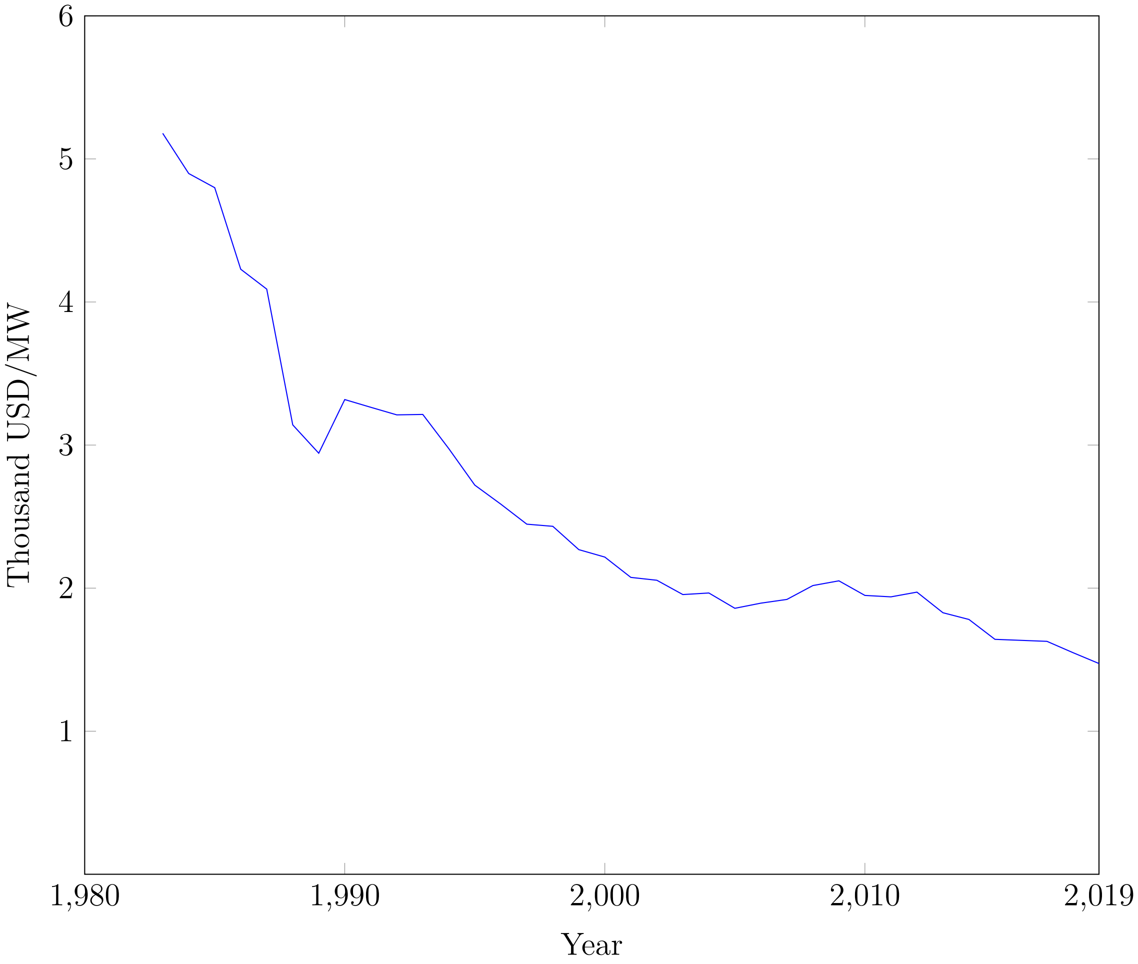

Figure 1.1: Global weighted-average onshore wind project costs 1983-2019 (price in US Dollar 2020), adapted from Irena (2020) [3]

(b) There is growing concern about the environmental impact of fossil fuels, such as greenhouse gases emission, and provoking respiratory issues due to the decrease in air quality. Wind energy is a clean, renewable source of energy that produces no emissions or pollution. As a result, many ambitious targets - such as the Paris' agreement, have defined road maps towards the increased use of wind energy, whereby it may supply 36% of electricity generation by 2050, reducing the reliance on fossil fuels.

(c) Finally, advances in technology are making wind energy more reliable and efficient, evidence of that is the fact that countries with big energetic consumption, such as China and United States are the top countries in installed wind capacity - 40% and 17% respectively as of 2021 [4]. Modern wind turbines are capable of generating more electricity than ever before, and they are designed to operate in a wide range of environment conditions. For example Finland, an inherently cold country with a mean annual temperature bellow 5°C, had a 75% increase in wind power capacity in the year of 2022 [5], targeting a further 3200 MW increase up to 2025. This has made wind energy a more viable option for utilities, who need a consistent and reliable source of electricity to meet the demands of their customers.

While the technology for higher power output has evolved, the materials utilised in the construction of the wind turbines have not. Wind turbine blades have been manufactured with the same materials since the first commercially mass produced models sporting rated power of 50 kW installed back in 1983. Its life time has not yet presented a significant change, remaining an average of 20 years.

Wind turbine blades are typically made of fiberglass, a type of composite material. Such materials are manufactured by combining two or more different materials to create one with improved properties, such as strength, stiffness, and durability. The combination of glass fibers and a polymer resin used in fiberglass allows it to be molded into complex shapes, while also providing strength and resistance to wear and tear.

While fiberglass has many desirable properties for use in wind turbine blades, it also has some drawbacks. One of the biggest challenges with fiberglass is being a material that presents challenges in its end-of-life solutions for large scale. This is because the material is composed of multiple components that are difficult to separate, and the polymer resin used in the composite can be difficult to break down.

Currently, there are no technologies that can effectively and economically recycle wind turbine blades on a large scale. As a result, the majority of wind turbine blades are currently disposed of in landfills at the end of their useful life. This is not a sustainable solution, as it can lead to environmental pollution and resource depletion. Besides, countries such as Germany have banned composite materials from being sent to landfills after its end-of-life [6].

To address this issue, researchers and industry experts are exploring new ways to recycle wind turbine blades. Some of the approaches being investigated include mechanical recycling, which involves grinding the blades into small particles that can be used as filler materials in other products. Other alternative, chemical recycling, which involves breaking down the composite material into its component parts using chemical processes; this method have been predominantly used in laboratory scale rather than industrial [7].

Overall, while the waste resulting from wind turbine blades is difficult to be dealt with using current technologies, ongoing research and development into new methods of dealing with it, and material technologies are exploring ways to make wind energy more sustainable and environmentally friendly in the long term.

The prediction model concocted for this thesis was made possible by the existence of publicly available data - the main sources of it being:

1. Wind turbine models database (available in: https://en.wind-turbine-models.com/turbines).
2. The U.S. Wind Turbine Database (available in: https://eerscmap.usgs.gov/uswtdb/data/).

Those were the free data sources with the most complete information about the necessary technical information on the turbine blades.

This thesis is composed of 5 chapters, divided as follow:

Chapter I - Introduction: objectives, basic concepts and preamble to the main theme;

Chapter II - Theoretical Fundamentals and State of the Art: mathematical concepts utilised, the state of the art, a comparison with recent articles that share the theme, how they deal with similar issues;

Chapter III - Methodology: materials and methods, how the results were reached, current databases;

Chapter IV - Results and Discussion: analysis of the data acquired and its results. At the end of this chapter a case study is discussed, presenting the opportunity to put the prediction model presented on this thesis to practical use and also compare it to similar works;

Chapter V - Conclusions and Future Works.

Chapter 2

Theoretical Fundamentals and State of the Art

The best way to measure the weight of wind turbine blades of a determined data set is to acquire the actual weight of each blade and then multiply it by the number of repetitions. Assuming that all wind turbines are the same model, the total weight of wind turbine blades in a wind farm will be from equation 2.1:

$$T_{weight} = N_{blades} \times N_{turbines} \times W_{blade} \tag{2.1}$$

Where:

- T_{weight}: waste to be calculated;
- N_{blades}: number of blades of the wind turbine model;
- $N_{turbines}$: number of turbines on the particular wind farm;
- W_{blade}: weight of each wind turbine blade.

But alas, information is not always easy to acquire, nor always free of costs; and even with it in hands, when dealing with a large number of repetitions (for example: wind farms of a large area or country), it just is not always practical to apply it to the data set, specially a sizeable one, if there is a model available that can achieve accurate results.

The mathematical fundamentals utilised in this work were fairly simple. With the data sorted, for each category a median of the respective values contained in it was calculated. This generated a coefficient that can be utilised to predict the weight of a wind turbine blade with similar rated power.

A median was used to filter the outliers - if an average was used, the outliers would have a bigger impact on the final product than they should.

Wind turbine blades are a critical component of a wind turbine that capture the kinetic energy of the wind and convert it into rotational motion to generate electricity. The fundamental aspect regarding the evolution of the wind turbine blade are its size and materials. Here is a brief overview of the fundamentals of wind turbine blades and their technological evolution thus far:

- **Size** The size of the blades has also increased significantly over the years: while the earlier commercial models measured around 15 meters, the latest models have far exceeded 100 meters, with some being over 200 meters long.

- **Materials** The materials used to construct wind turbine blades have evolved over the years, with early blades typically made from wood, but quickly changing to composite materials such as fiberglass, carbon fiber, and epoxy resins. These materials provide high strength-to-weight ratios, corrosion resistance, and durability. In recent years, there has been increasing research into the use of sustainable materials such as bioplastics and recycled materials to make wind turbine blades. Siemens Gamesa have launched a line of recyclable wind turbine blades - RecyclaBlade - but it still remains to be seen how wide the range in which this material will be utilised, and even then it will not solve the issue of the remainder of the waste originated from 40 years of composite materials in the industry.

- **Technological Evolution** Wind turbine blades have undergone significant technological evolution over the years. Early wind turbine blades were typically simple

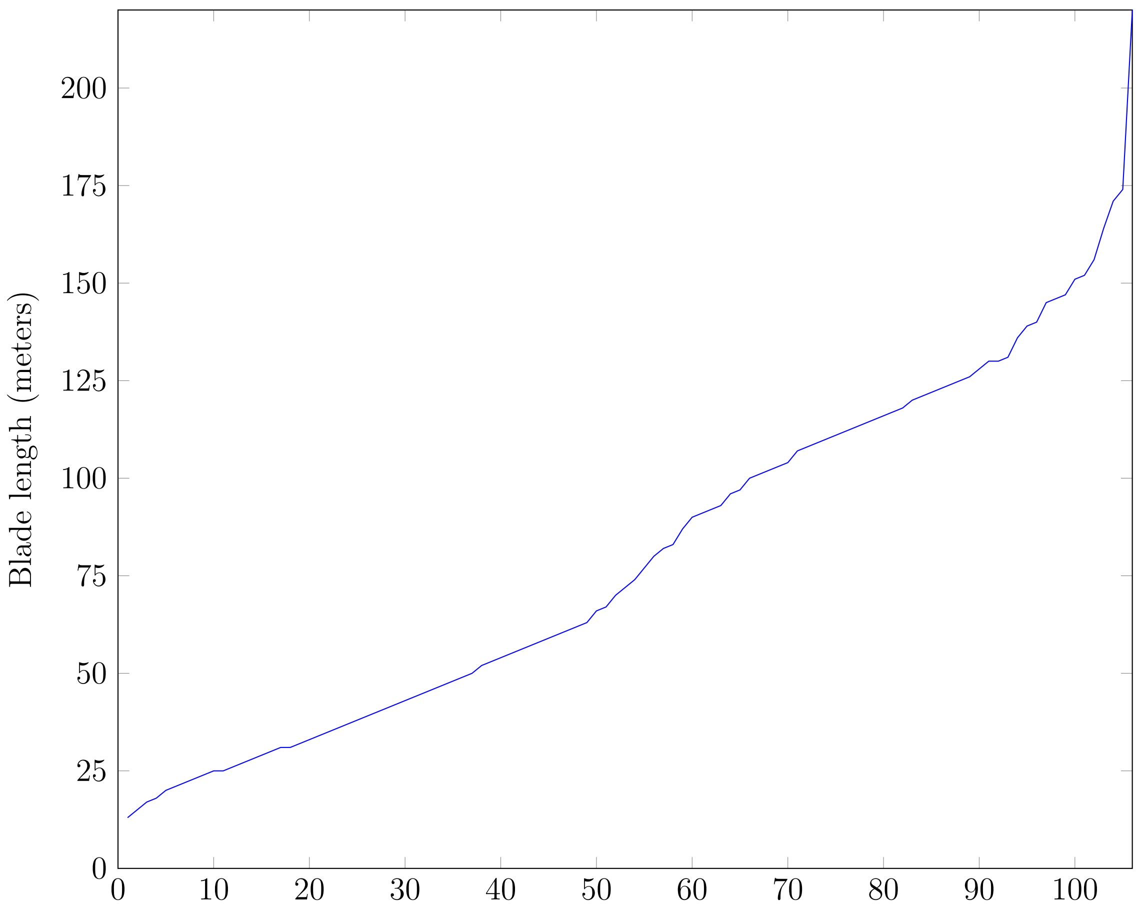

Figure 2.1: Size evolution on wind turbine blades

in design and made from wood or metal. In the 1980s, composite materials such as fiberglass and carbon fiber were introduced in the industry, leading to significant improvements in blade performance and durability. In recent years the current manufacturing materials have remained mostly the same.

Overall, the fundamentals of wind turbine blades have evolved significantly over the years, with modern blades being larger, stronger, and more efficient than earlier designs.

State of the Art

In this section, scientific articles sharing a theme with this thesis were analyzed. The criteria being how often the article was cited in works following its publication date. A

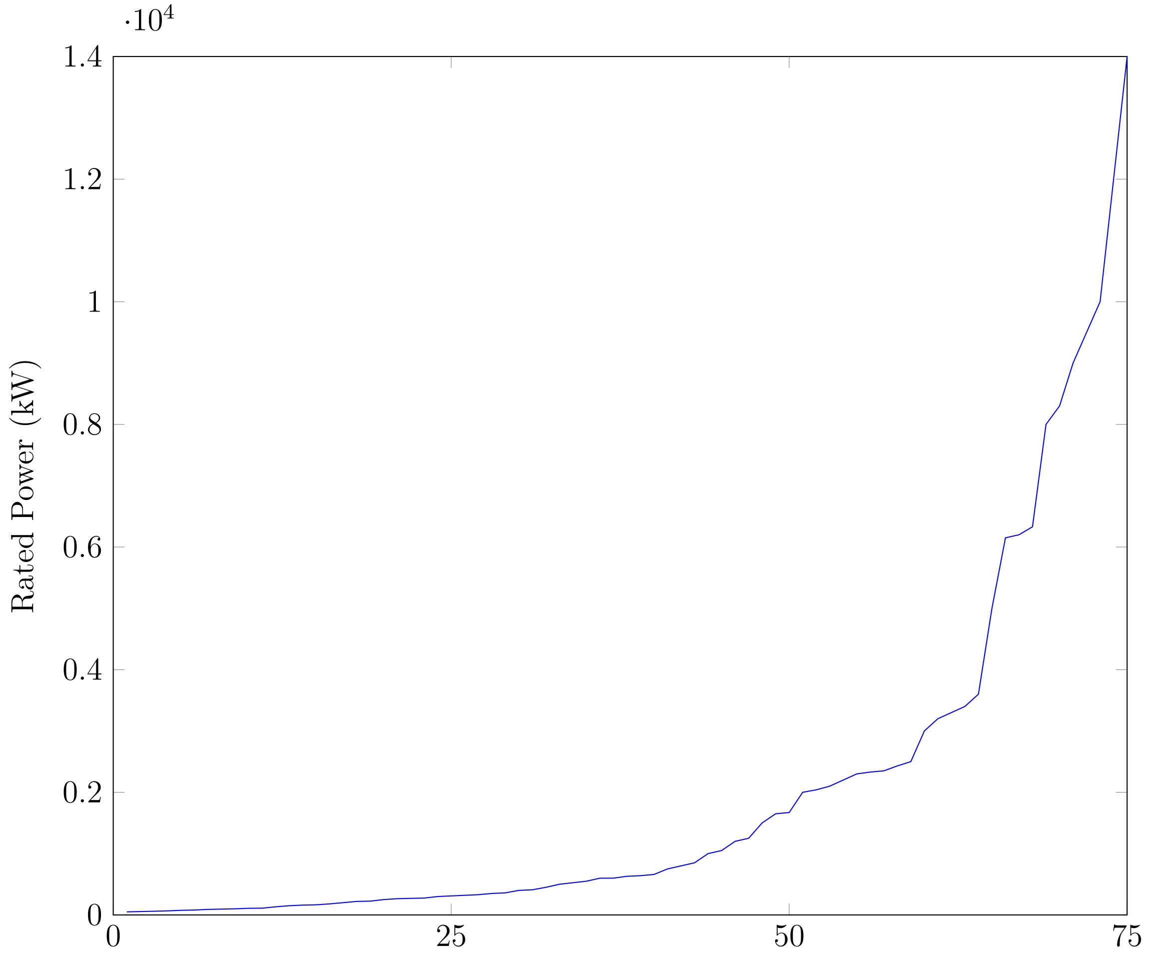

Figure 2.2: Rated power evolution on wind turbines

summary of this analysis is presented on Table 2.2. A quantitative analysis can be seen later on Chapter 4.

Albers [8] Presents a thorough overview about the problem: growing trend of wind turbine use, explanation of the blade's components. Although the article presents a graph comparing weight and diameter of approximately 79 wind turbine blades, the author reaches an estimation that for every 1 kW of installed power there is 10 kg of rotor blade material. It is not clear if this prediction has taken in consideration the aforementioned models' data, since the graph does not show the rated power of said turbines. This article presents some compelling arguments to try and shift focus towards the lack of sustainability of this material, such as comparing the weight of the generated waste to of how many citizens would generate in a year; it also points to the lack of technologies for its disposal - which persists up to now (consider that this article is from 2009).

Andersen [**9**] This article focus on the whole of the wind turbine waste (excluding foundation). The predicting model is the same for calculating either nacelle, tower or rotor weight, based on the diameter, and is presented in form of the equation 2.2:

$$m_{part} = 10^{a} \times d^{b} \tag{2.2}$$

Where: m_{part} = Calculated mass of turbine part (kg); d = Rotor diameter (m); a = Intercept value (0.3 for the rotor); b = Scaling factor (2.22 for the rotor). The goal in this work being calculate the mass of every component. By utilising a Swedish database, the authors were able to obtain the total weight in regards to the wind turbine parts, which the author manages to achieve, along with a prediction of how much this number is expected to grow in the following years and decades. The author also presents the weight discriminated by material in each of the wind turbine parts.

Liu [**10**] The model presented by this author shares similarities with the one presented on this thesis, such as the employment of a statistical method with input from external sources and the categories division based on rated power; but differ in some aspects like the use of average instead of median for the calculation of the data between the rated power intervals. This article's data is in the ranging size of 800 kW to 8 MW, divided into five categories, 2.1.

The main focus of this article is not the creation of a predicting model, but rather a larger scope: the totality of waste derived from wind turbine blade, including not only the after life, but the whole specter of it, which the author divides into four stages: manufacturing, transport and installation, operation and maintenance, and end-of-life. At the end of this article the author presents an estimation of the total

Table 2.1: Liu's prediction model

Rated Power (MW)	**Total Blade Mass (ton)**
≤ 1	8.43
1-1.5	12.37
1.5-2	13.34
2-5	13.41
≥ 5	12.58

waste generated, worldwide, up to 2050.

Lefeuvre [11] It is important to notice that this particular article focuses on carbon fiber, a material that has been utilised on wind turbine blades - albeit only recently. The issue is that, like glass fiber, is a composite material, thus presenting the same challenges regarding its end-of-life. For an environmental perspective, both materials are not ideal due to the lack of technologies for its final destination. The author present two approaches: top down and bottom up; the first is based on the consumption of composite material expected, based on estimations on literature; the second calculates based on the wind turbine blade itself. For the quantitative analysis, the model created by Albers is utilised. The article then projects the waste generation for the whole world, and utilises projections to amplify the results up to the year of 2050.

Sommer [12] An important point that this author, like Lefeuvre, stresses is the distinction between different types of composites: carbon and glass based. Their estimation is based on the distinction of the different types of material, which is a valid point that few authors do, so that those materials have distinct densities, which would accrue disparities in the calculations if that distinction is ignored. An interesting point is the distinguishing on calculations based on the amount of information given - the author divide, decreasingly, it in four segments: straight forward, main construction materials, Liu's case and Alber's case. The first two scenarios assume that the user have a certain amount of information, while the remainder resort to prediction models from another authors.

Lichtenegger [13] The author uses external sources to find the installed capacity of each region, then interpolate up to the year 2050. The prediction model is only explained in the appendix, and it is presented in the form of a linear regression; to reach it, 167 turbines with information regarding the weight were used. Another set containing 546 wind turbines (that did not have information regarding the weight) were used, in which a relationship between other characteristics (rotor weight) was used in order to infer the missing information. Those results are then applied to find how much waste would be generated in each European country up to 2050. The author then compares their results with Liu's and Alber's models.

Cooperman [7] This article includes a brief overview of current methods of disposal for wind turbine blades' end-of-life, such as: landfill, incineration, cement coprocessing, mechanical recycling, high-voltage fragmentation, thermal recycling, chemical recycling, reuse and repurposing, lifetime extension and design for circularity. The study is to predict waste in 2050, so an estimation was required. The object of study is the United States, thus utilising The U.S. Wind Turbine Database, along with the prediction model from Liu. The volume of waste was then calculated, in order to compare what effect it would have on their landfill capacity nationwide. There is also a cost prediction, taking into consideration the tear down the equipment, cut, transportation and the gate rate from the landfill.

Table 2.2: Article comparison

Author	**Title**	**Year of publication**	**Analysis**
Albers [8]	Recycling of wind turbines rotor blades - fact or fiction?	2009	The author presents a fairly accurate prediction (regarding lower rated turbines) that was subsequently cited by several authors afterwards, which was that for every kW of installed capacity, waste of 10 kg would be generated.
Andersen [9]	Wind turbines' end-of-life: Quantification and characterisation of future waste materials on a national level	2009	A mathematical model is presented, but with fewer turbine models, so the author has to resort to assumptions to fill in the gaps.
Liu [10]	Wind turbine blade waste in 2050	2017	Due to a higher resolution, has a theoretical better scalability (duo to the range of models used in the research) than the other papers cited.
Lefeuvre [11]	Estimation of glass and carbon fiber reinforced plastic polymers and related waste generated by the wind power sector until 2050	2019	The author compares models previously published, choosing to ignoring models built prior to 2010 as not containing glass fiber in their composition (the material has actually been commonly used in commercial models since the 80's).
Sommer [12]	Offshore and onshore wind turbine blade waste waste from end-of-life rotor blades of wind power plants within the European Union	2020	Uses a mix of information from the same source and presents some critiques and suggestions.
Lichtenegger [13]	Anticipating in-use stocks of carbon fibre reinforced material forecast at a regional level in Europe until 2050	2020	This article makes some questionable assumptions, as using an outdated model as a basis and as the present article and a paid database. The author compares his results with Albers and Liu, but does not show the specifics to reach the results.
Chen [14]	Modeling waste generating and end-of-life management of wind power development in Guandong, China, until 2050	2021	The article approaches the overall theme, just not specifically the blades.
Cooperman [7]	Wind turbine blade material in the United States: Quantities, costs and end-of-life options	2021	Uses Liu's model to reach the results for the object of study.

Chapter 3

Methodology

Developing a model to predict the amount of wind turbine blade waste generated in a given time period requires a multi-step process, them being:

1. Data Collection: Gather as much data as publicly available on the number of wind turbines in operation, the types of turbines being used, weight, size and installed capacity. The data was collected mostly from a wind turbine database [15] and reports such as the European Offshore Wind Farms map from WindEurope [16].

2. Data Preprocessing: The collected data may contain errors or inconsistencies, so it needs to be preprocessed to ensure that it is clean and accurate. This may involve removing outliers, filling in missing values, and standardizing the units of measurement.

3. Organizing: Gather all the data in a single archive. In this case, an Excel sheet containing all the information obtained, was organized by: manufacturer, model, blade height and weight, installed capacity and the material they are made of.

4. Model Selection: To measure the tendency of wind turbine blades throughout the years it was necessary to plot the data and find which method is more fitting.

5. Model Deployment: Once the model is evaluated, it can be deployed in a real-world application. For example, it could be used by wind turbine manufacturers,

governments, or environmental organizations to predict the amount of blade waste generated by wind turbines in a given time period.

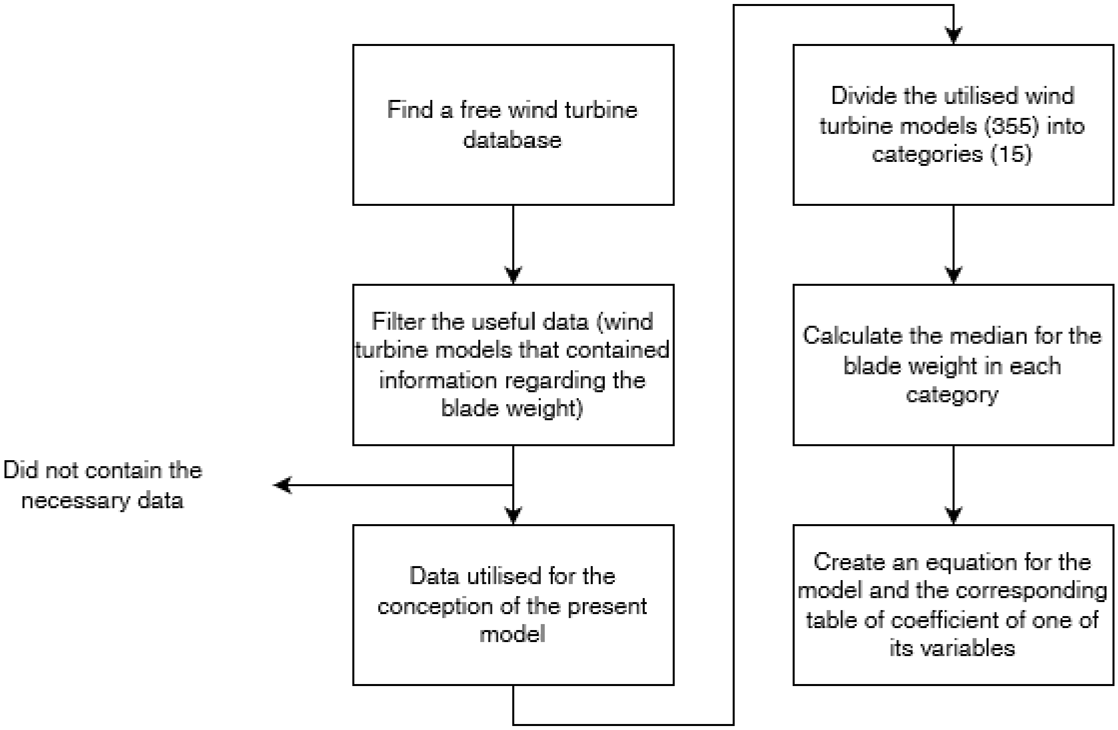

Figure 3.1: Methodology Diagram

For the conception of this model, the first step taken was to acquire real and publicly available data from wind turbines from aforementioned sources. The main information utilised were manufacturer and model, rated power of the corresponding wind turbine along with its blade weight and height.

An example of a source behind pay-wall that was utilised in similar models is 'The Wind Power' - available at [thewindpower.net]. The Wind Europe website [windeurope.org] offers an interactive map of onshore wind farms in Europe, but its access is also paid.

In the database utilised, from a total of 2346 - as of January 25^{th}, 2023 - distinct models from a plethora of manufacturers, 355 had information regarding both the weight and rated power of the wind turbine blade. Although a small percentage compared to the total of models available - 15% - that number is still vastly superior, six times that of the author with the higher sample dimension so far, Table 3.1.

Table 3.1: Quantitative analysis of prediction models

Author	**Sample Dimension**	**Resolution**
Albers [8]	-	1
Liu [10]	56	5
Current Model	355	15

The first conception of this prediction model was made by plotting all of the 355 unique models' weight and rated power, Figure 3.2.

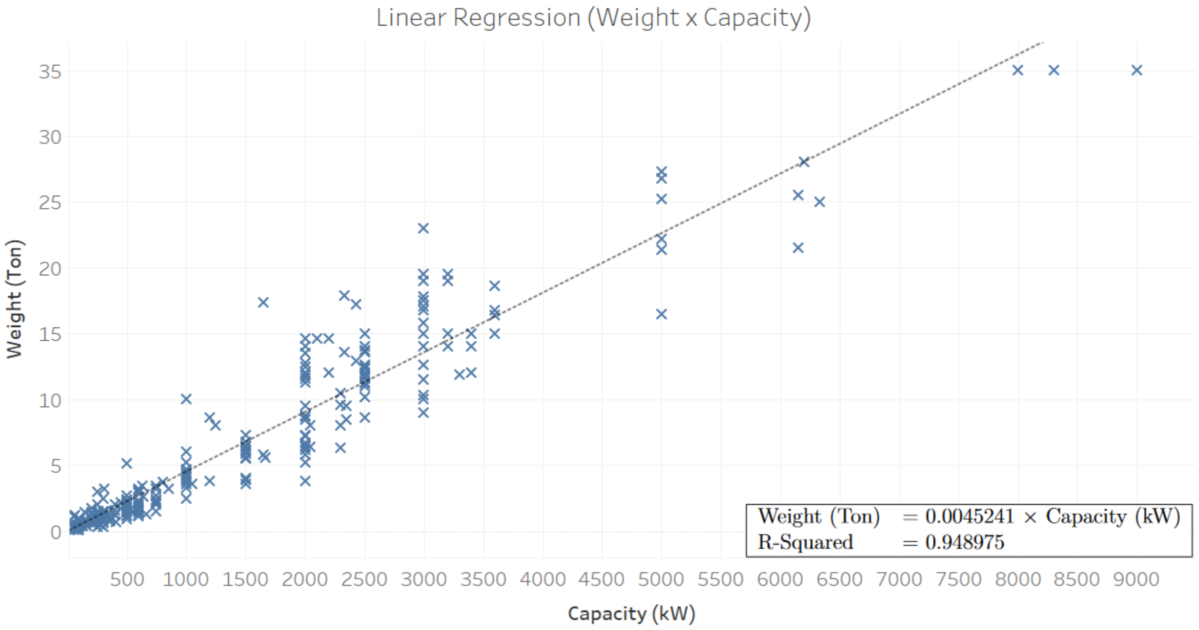

Figure 3.2: Linear regression

The equation 3.1 was created based on the linear regression shown on Figure 3.2. This can be used to estimate the weight of a blade, a wind farm, or even bigger data sets based on an information that is easy to find (installed capacity), simulating a variable that is difficult to obtain (weight) with an overall reliability degree equal to R^2, in this case, roughly 95%.

$$Weight(ton) = 0.00447281 \times Capacity(kW) \tag{3.1}$$

Where **W** is the blade weight in ton and **C** is its respective Nominal Power in kW.

The result of equation 3.1 is an average based on the interaction between capacity and weight for a large interval, Figure 3.2. Although it is a good starting point for a prediction model, it is one-dimensional as it does not take into consideration the particularities of wind turbine blades of different rated powers. This equation is but a preamble to the prediction model presented on this thesis.

To achieve a higher precision, the acquired data needed to be divided into categories, but due to its wide range on both dimensions (weight and rated power), how to categorise it in a non arbitrary manner? The solution was to have in each category a similar sample dimension, Table 3.2, then a median (of the weight values contained in said category) was calculated in each interval. A median was utilised instead of an average to limit the influence of possible outliers. The resolution reached in this model was 15 - a number multiple times bigger than similar works, Table 3.1.

A box-and-whisker graph is plotted in Figure 3.3, containing all 355 wind turbine models data, all turbines are divided by its weight, rated power and its respective rated power category. This graph enables the visualisation of information regarding the minimum and maximum value of weight for each category, along with its median and lower and upper quartiles.

In the Figure 3.3, every wind turbine model is represented by a dot; in each rated power interval the upper and lower quartile are the lines, while the median is the interception between the grey areas of the rectangles. The dots that can be seen outside its respective quartiles are the outliers; this might be the case for models that ended up not being mass produced for reasons such as being too heavy - for example, the 'NASA MOD-2 Boeing' model, weighting a staggering 45.5 tons on each of its two blades - or too expensive.

For a matter of comparison, Table 3.2 shows the ratio Weight/Rated power: how much blade weight in each category would it be required to achieve 1 MW of installed capacity.

Table 3.2: Rated power categories

N°	**Rated Power (kW)**	**Ton/MW**	**Sample dimension (units)**
1	50-100	3.0	31
2	101-200	4.0	21
3	201-300	2.7	44
4	301-400	3.0	11
5	401-500	3.6	26
6	501-750	2.6	52
7	751-1000	4.0	21
8	1001-1500	3.9	21
9	1501-2000	4.3	33
10	2001-2500	4.8	37
11	2501-3000	4.7	19
12	3001-4000	3.8	12
13	4001-6000	4.0	12
14	6001-8000	3.2	9
15	8001-10000	3.5	6

It is interesting to note that the ratio only starts to achieve a degree of stability as of 10 MW of rated power, meaning: as the blade weight increases, the industry is starting to shift its focus as to reduce this proportion, in an attempt to achieve higher efficiency. That can be better visualised on Figure 3.4.

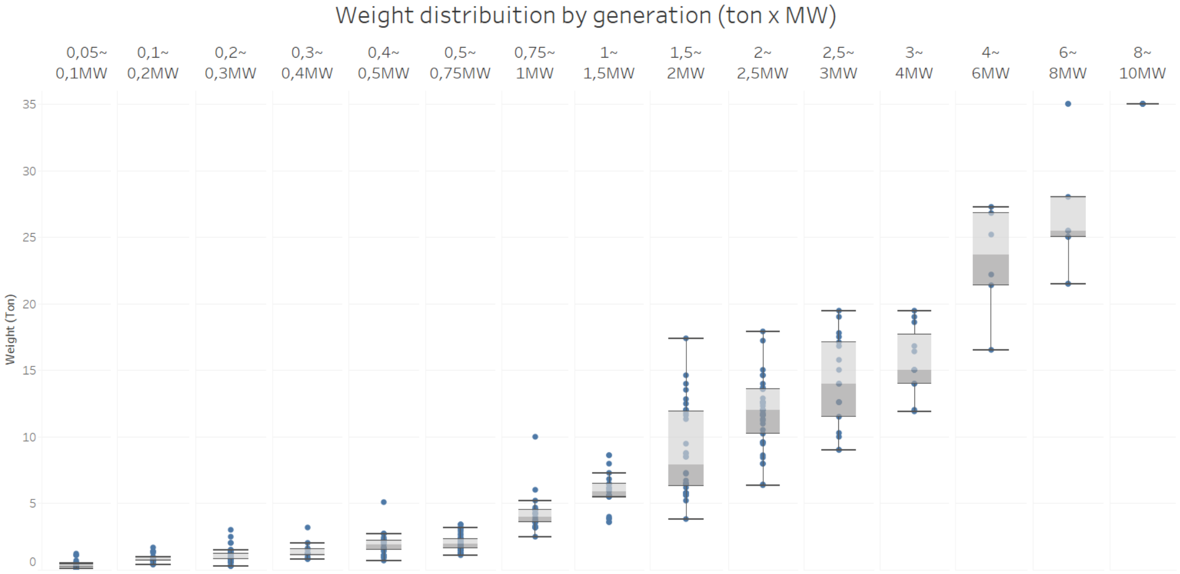

Figure 3.3: Weight distribution by rated power

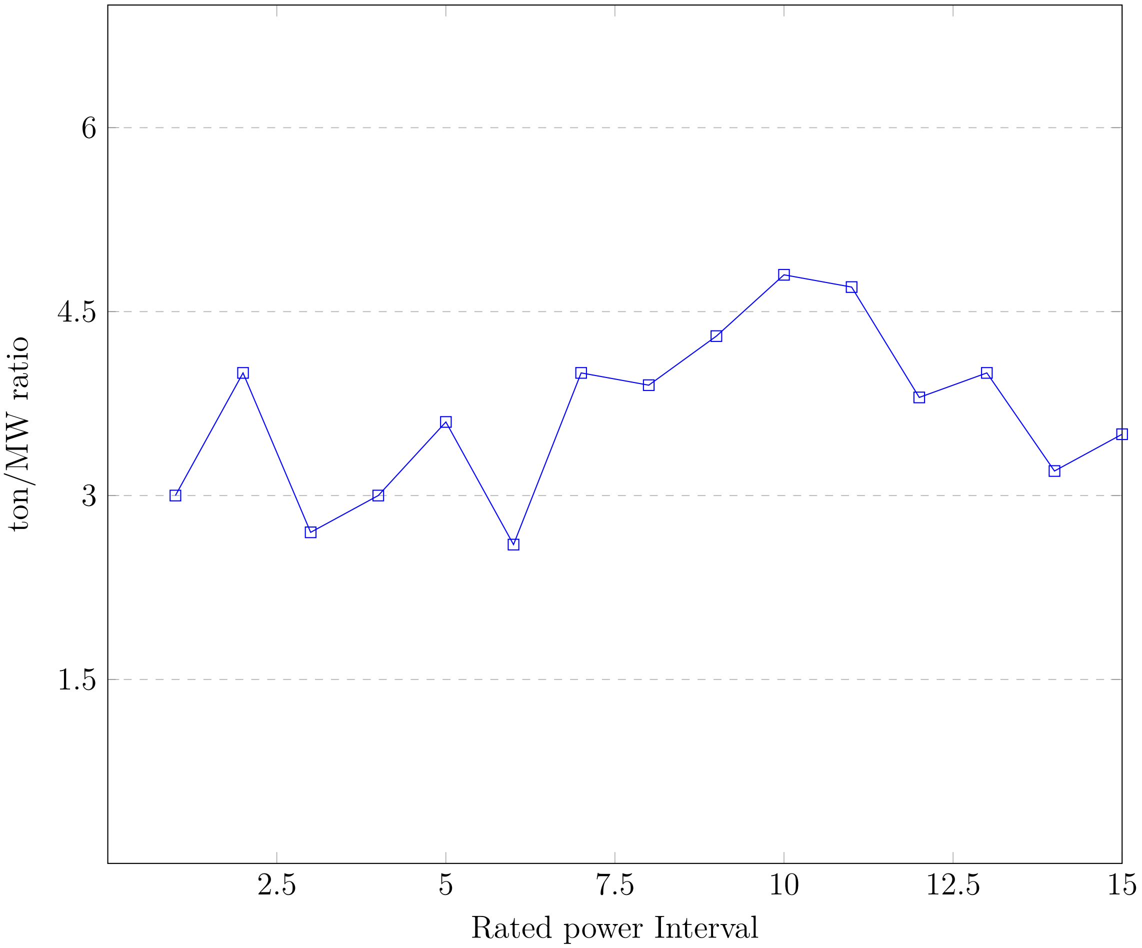

Figure 3.4: Weight (ton) per 1 MW for each rated power interval

Chapter 4

Results and Discussion

The prediction model presented on this chapter presume that one would already have information regarding both rated power and number of installed turbines. For it to be applied on a particular case (for example a wind farm), both of those variables are expected to be known.

While Figure 3.3 enabled the construction of the prediction model, it is necessary a mathematical representation for it to be a functioning tool. Equation 4.1 and Table 4.1, - a coefficient to be used as one of the equation's variables - were created to achieve the final estimation.

As this model is capable of being be used in a wide range of situations, - such as predicting the generated waste of entire regions or even countries - it is presented in a summation format. Its upper limit, k, is not defined, rendering the equation capable of being applied to the largest of the circumstances.

$$\sum_{i=1}^{k} W = 3 \times (MMW_i \times N_i) \tag{4.1}$$

Where:

- W: waste, in tons, to be predicted;
- MMW_i: Median Model Weight, Table 4.1, that should consulted based on the

already known rated power. This number is the median value of the weight of blades contained in the equivalent rated power interval;

- N_i: number of wind turbines in the wind farm where the model is being applied.

All the variables are multiplied by 3 as it is the most common number of blades amongst the wind turbines researched - based on the research for this thesis this has been proven the case for over 85% of the cases, and even on the models that had fewer blades, not all were commercially produced.

Since this model is capable of dealing with situations where multiple rated power turbines are present, table 4.1 has its last column blank, so that the number of occurrences of a determined rated power can be written in it.

Table 4.1: Rated power coefficient

i	**Rated Power (kW)**	**Median Model Weight (ton)**	N_i
1	50-100	0.30	
2	101-200	0.80	
3	201-300	0.80	
4	301-400	1.20	
5	401-500	1.80	
6	501-750	1.95	
7	751-1000	4.00	
8	1001-1500	5.90	
9	1501-2000	8.50	
10	2001-2500	12.00	
11	2501-3000	14.00	
12	3001-4000	15.00	
13	4001-6000	23.70	
14	6001-8000	25.50	
15	8001-10000	35.00	

A practical example of the model being applied would be as follows:

The wind farm London Array, commissioned in 2013, located in the Thames Estuary, North Sea, has 175 wind turbine installed - each with a rated power of 3.6 MW.

- MMW_{12} is 15 - consulting Table 4.1 for the corresponding rated power interval (between 3001 and 4000 kW);
- N_i is 175 - the number of turbines installed in this facility.

Applying the model:

$$W = 3 \times (15 \times 175) \tag{4.2}$$

Based on the prediction model, it is expected that, by the year 2033 - 20 years after its commissioning - 7920 tons of wind turbine blade waste material is going to be generated from this particular wind farm.

The application of this high resolution model, allows one to easily predict the amount of waste from wind turbine blades from a wind farm based on a small amount of data.

The advantage of a prediction model being that it can be applied to a variety of data sets, as long it fits the criteria of the model itself.

The hardship of the prediction model presented on this thesis was to acquire the data regarding the basic characteristics of as many wind turbines as possible. Its core idea being it is based on real, publicly available information.

4.1 Case Study - Offshore wind farms in Europe

The data set of offshore wind farms in Europe contains a total of 6132 wind turbines and 128 wind farms, commissioned between 1995 and 2023, in a total of 12 European countries, Table 4.2. It is publicly available at the WindEurope website.

The historic data presented on this data set starts from the first recorded offshore wind farm in Europe, Tunø Knob in Denmark, 1995, up to the latest, in 2023: Neart na Gaoithe, United Kingdom.

The main objective in including a case study on this thesis is not only utilise the model to predict results in a real-life environment with contemporary data, but also to compare the results produced with similar models created by different authors.

Table 4.2: Offshore wind turbines in Europe

Country	**Installed capacity (MW)**	**Turbines connected**
United Kingdom	14,152	2,708
Germany	7,689	1,501
Netherlands	3,003	627
Denmark	2,306	630
Belgium	2,261	399
France	978	143
Sweden	192	80
Norway	94	13
Finland	71	19
Ireland	25	7
Portugal	25	3
Spain	5	2
Italy	0	0

Applying the current model to the offshore dataset results on the Figure 4.1, where the bars are the waste predicted to be generated each year - as in, 20 years after the commissioning date of the wind park - and the line is the accumulated waste throughout the years, culminating in the final result of 377,052 tons.

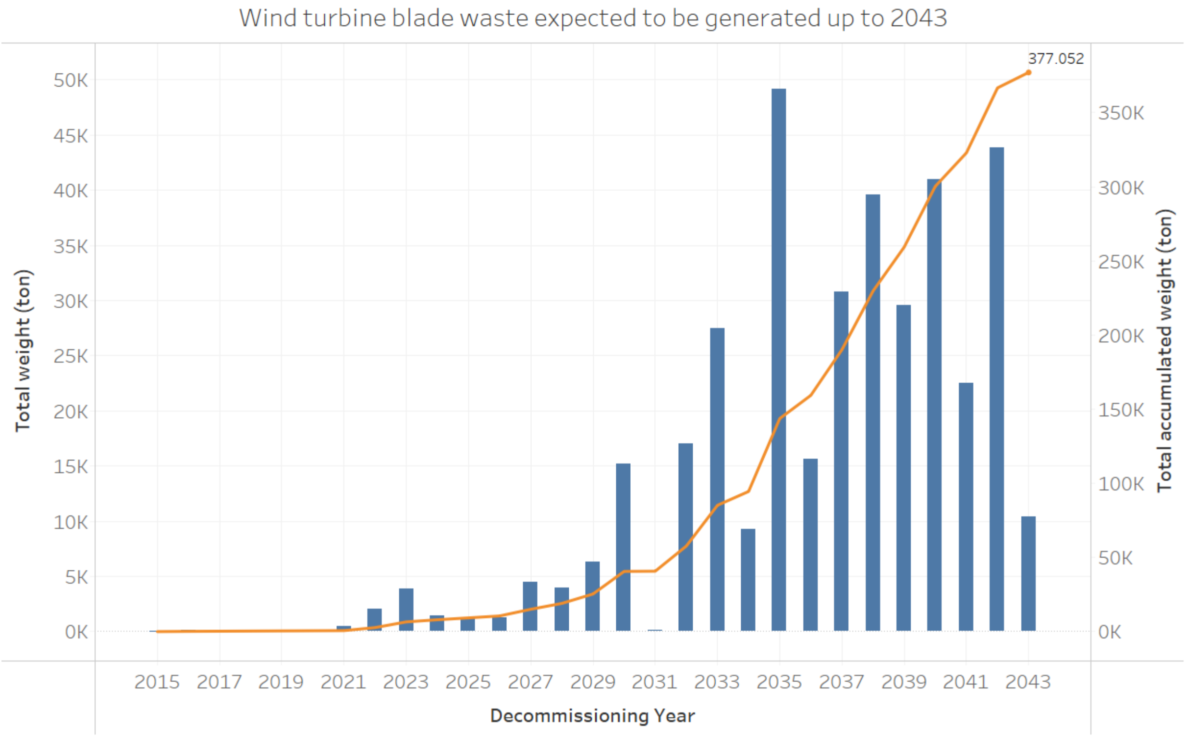

Figure 4.1: Wind turbine blade waste expected to be generated up to 2043

Table 4.3 compares the results between prediction models presented by different authors. Those represent the different author's estimations that, by the year of 2043 (assuming an average of 20 years of life expectancy for all wind turbines) that amount of waste is going to be generated. The standard deviation was calculated utilising the current model as baseline.

Table 4.3: Case study - result comparison between authors

Author	**Sample Dimension**	**Resolution**	**Estimated Weight (t)**	**Standard Deviation**
Albers [8]	-	1	924,020	145%
Liu [10]	56	5	239,791	-37%
Current Model	355	15	377,763	0%

Why is there such a big difference between the estimated results from those three models? The answer lies in the sample dimension and resolution of each one: while the other author's models might have been more accurate when they were published, ever since then technology have advanced.

Focusing only on the data from Germany on this offshore wind dataset presented on Table 4.2, an approximate amount of 95,000 tons (applying the current model) is expected to be generated up to the year of 2040 (twenty years after the commissioning date of the most recent wind farm).

Currently a company named Geocycle, located in Lägerdorf, Northern Germany, operates a cement-processing plant that is able to process up to 10,000 tons of waste derived from wind turbine blades per year [6]. With the amount of waste generated up to the year 2040, this process would take over nine years to handle all of the offshore wind turbines currently installed in Germany at a cost of over 14 million euros (150 €/t [6]), and that is taking in consideration only the gate fee, not pre-cut and transportation costs.

The total expenditure on dealing with this waste issue is in the hundreds of million of euros, considering that the offshore section of the wind industry in Germany is approximately 14% [17]. Even then, that is with the hypothesis that such processing plants are available, willing, and prepared to deal with that demand. It is important to mention that such methods are the exception to the rule: the vast majority of this waste currently has no reliable way of being dealt with; in fact, the existence of such companies might be a reflection of this country's policy - prohibition - towards the disposal of composite material in their landfills [6].

For a matter of comparison, it is possible to present the results achieved in a measure of volume instead of weight. Laboratory analysis indicate that the glass fiber contained in most wind turbine blades has a density of approximately 1.29 $g.cm^{-3}$ [18]. Applying that value to the final result in table 4.3 for the current model, a total volume of 487,315 m^3: that would be the equivalent volume of shredded glass fiber. This way of presenting the results also helps in decision making, since the capacity of a landfill is generally expressed in volume, not weight.

Overall, the wind turbine blade waste is currently a challenge to being dealt with, as no current technology has enough readiness level and large-scale availability. Furthermore, countries such as Germany, Austria, Finland and the Netherlands have already forbidden this waste from being landfilled [6]. In this thesis this waste has been shown a growing concern that demand a solution sooner rather than later, as to prevent a snowball effect, with hundreds of thousands blades waiting to be given and end-of-life solution.

4.2 Model limitations

As is the case of any model that aims reach a prediction, - and what more, one that relies on an estimation of a missing variable (blade weight) - the one presented on this thesis possesses limitations.

Repowering - the act of replacing older turbines with newer models in the same location - presents a possible complication on this model, since the installed capacity per year, at least in some reports such as from WindEurope [17], include the repowered units; but, as table 4.4 shows, the proportion of repowered units in comparison to the total installed capacity of the year in case remains, up to 2021 at least, insignificant in the bigger picture (at most just over half percent in 2017), so that it will not undervalue the model created.

Table 4.4: Percentage of repowered wind turbines in Europe per total installed capacity

Year	**Repowered capacity (MW)**	**Installed capacity (MW**	**Percentage of repowered**
2015	500	147,000	0.34%
2016	700	161,000	0.43%
2017	1000	177,000	0.56%
2018	450	189,000	0.24%
2019	180	204,000	0.01%
2020	350	219,000	0.16%
2021	500	236,000	0.21%

Chapter 5

Conclusions and Future Works

The presented model was created from information regarding 355 wind turbine models divided in 15 rated power categories, its resolution, in an attempt to be as much precise as possible for the use in multiple situations. That is, to comprise the higher possible spectrum of rated power, lower and higher without compromising its results.

This model predicted an approximate 335 thousand tons to be generated up to the year 2042 on offshore wind turbines only. That is a waste that currently has no large-scale technologies of being dealt with: the most common end-of-life destination being landfills. Countries such as Germany have already banned it from their landfills, with the expectation that more European countries follow suit, it is important to be able to predict, as accurately as possible, just how much waste is going to be generated.

The prediction model presented on this thesis was created to provide entities - such as wind turbine manufacturers, government agencies or environmental organisations - with a reliable decision making tool. This high-resolution medium aims to influence the next steps to be taken to address this growing concern of waste generation. That is hardly possible if the model utilised presents a high deviation from when that waste is generated.

Analysing Table 4.3, there is a big deviation between the values obtained through different models for the waste expected to be generated; this proves to be a challenge for any manner of planning that one would attempt to achieve.

It is important to note that the accuracy of the prediction model depends on the quality and completeness of the data used to create it. Therefore, it is important to continually update the model with new data as it becomes available to improve its accuracy and relevance.

In the developing of this thesis, data was acquired regarding the current state of wind farm development in different countries. This material can be used along with the prediction model presented to further prove its effectiveness in real-world situations, helping in the decision-making and the next steps that should be addressed to accommodate such volume of waste - legislation and industry-wise.

The next step will be a deep-dive in the information on The U.S. Wind Turbine Database, made available by the United States Geological Survey, USGS. The objective is to make use of its rich and publicly available data and analyse the current and future state of the waste generation in the wind industry with the help from the present model.

Subsequently, it is of interest of the author to gather as much information made available by individual European countries and create a similar database as the one of the USGS for the whole Europe. It is imperative that such information be publicly available to facilitate the decision making of governing bodies.

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