Wind Turbine Blade Waste in 2050

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Abstract

Wind energy has developed rapidly over the last two decades to become one of the most promising and economically viable sources of renewable energy. Although wind energy is claimed to provide clean renewable energy without any emissions during operation, but it is only one side of the coin. The blades, one of the most important components in the wind turbines, made with composite, are currently regarded as unrecyclable. With the first wave of early commercial wind turbine installations now approaching their end of life, the problem of blade disposal is just beginning to emerge as a significant factor for the future. This paper is aimed at discovering the magnitude of the wind turbine blade waste problem, looking not only at disposal but at all stages of a blade's lifecycle. The first stage of the research, the subject of this paper, is to accurately estimate present and future wind turbine blade waste inventory using the most recent and most accurate data available. The result will provide a solid reference point to help the industry and policy makers to understand the size of potential environmental problem and to help to manage it better. This study starts by estimating the annual blade material usage with wind energy installed capacity and average blade weight. The effect of other waste contributing factors in the full lifecycle of wind turbine blades is then included, using industrial data from the manufacturing, testing and in-service stages. The research indicates that there will be 43 million tonnes of blade waste worldwide by 2050 with China possessing 40% of the waste, Europe 25%, the United States 19% and the rest of the world 16%.

Keywords : Composites waste, Decommissioning, End-of-life, Wind Energy, Wind turbine, Wind turbine blade waste.

List of Abbreviations

- AWEA--American Wind Energy Association
- BoM--Bill of Materials
- CWEA--Chinese Wind Energy Association
- EoL--End-of-Life
- EWEA--European Wind Energy Association
- GWEC--Global Wind Energy Council
- IEA--International Energy Association
- kt--Kilo tonnes
- Mt--Million tonnes
- MW--Mega watts
- NREL-- United States National Renewable Energy Laboratory
- O&M--Operation and Maintenance
- PTC--Production Tax Credit for Renewable Energy
- WT--Wind Turbine
- WTB--Wind Turbine Blade

1. Introduction

Wind energy has become one of the most promising renewable energy sources over the last two decades with the installed capacity increasing from 7,600 MW in 1998 to 364,270 MW in 2014 (GWEC 2015). The capacity is expected to continue to increase, although rates may vary in different geographical areas. The Global Wind Energy Council (GWEC) predicts that the global annual growth rate of wind power will exceed 12% between 2013 and 2018 (GWEC 2014b). The European Wind Energy Association (EWEA) predicts that by 2020 there will be 192 GW of wind capacity supplying 14.9% of global electricity in 2020 (EWEA 2014). The International Energy Association (IEA) estimates that 15% to 18% of global electricity will be produced from wind energy in 2050 (IEA 2011). Despite these disparities, all the predictions indicate that wind energy will continue to develop rapidly over the next decade.

Although wind energy is often claimed to provide clean renewable energy without any emissions during operation (U.S. Department of Energy 2015), a detailed ecological study may indicate otherwise even for this stage. The manufacture stage is energy-intensive and is associated with a range of chemical usage (Song et al. 2009). Disposal at end-of-life must also be considered (Ortegon et al. 2012; Pickering 2013; Job 2014). A typical wind turbine (WT) has a foundation, a tower, a nacelle and three blades. The foundation is made from concrete; the tower is made from steel or concrete; the nacelle is made mainly from steel and copper; the blades are made from composite materials (Vestas 2006; Tremeac & Meunier 2009; Guezuraga et al. 2012). Considering these materials only, concrete and composites are the most environmentally problematic at end-of-life, since there are currently no established industrial recycling routes for them (Pimenta & Pinho 2011; Job 2013). Composite materials are energy intensive to manufacture and some of the material has high value, which means they have strong recycling potential in terms of both environmental and economic prospects (Shuaib et al. 2015). This study focuses on the composite component of wind turbine blades, looking at the waste inventory of all stages of their lifecycle. Composites account for more than 90% of the weight of WT blades (Liu & Barlow 2016b). At present, most of the blades are made from polymer composite reinforced with mainly glass fibre, some carbon fibre and the hybrid combination of glass fibre and carbon fibre (Collier & Ashwill 2011). High-grade epoxy and polyester are the mainstream resins used. Commonly adopted manufacturing processes use Pre-impregnated fabric (Prepreg) and Vacuum assisted resin transfer molding (VARTM) (Gurit Composites 2009). It is recognised that the materials and manufacturing techniques will evolve over time, but predictions vary. Some predict that the proportion of carbon fibre will increase (NEEDS 2008; McKenna et al. 2016) and will lead to more serious environmental impact from blade (Liu & Barlow 2016a). However, current trends have provided no clear support for this trajectory, so it may be that manufacturers are impeded by the high cost of carbon fibre (Liu 2016).

A few studies have been carried out on different aspects of the ecology of wind energy. For the blade waste volume, Red estimates there will be 260,000 tonnes material used to manufacture wind turbine blades in 2008 and this number will increase to 1.18 million tonnes in 2017 (Red 2006). Albers notes that every one-kilowatt of wind power needs ten kilograms of WT blade materials (10 kg/kW or 10 t/MW), predicts that there will be nearly 50,000 tonnes of blade waste in 2020 and that this number will exceed 200,000 tonnes in 2034 (Albers 2009). Andersen adopts Albers' blade material demand figure of 10 t/MW and predicts that the amount of blade material that will need to be recycled annually is 400,000 tonnes between 2029 and 2033. It will increase to 800,000 tonnes per year by 2050 (Andersen et al. 2014). It is clear that there will be a significant number of end-of-life WT blades needing to be decommissioned over the next two decades. It should be noted that the wind power industry has developed rapidly in both scope and technology in this period (Sieros & Chaviaropoulos 2012; Siemens AG 2014), which is not taken into account by these previous studies. Liu and Barlow attempt to tackle this issue but only provide general information about the blade size increasing and lifecycle contributing factors (Liu & Barlow 2015). The more detailed analysis of the present study includes such significant factors as the effect of increased turbine size on blade masses, the variation between different geographical regions, and consideration of waste generation over the whole life cycle.

Presently, most WT blade waste is sent to landfill, but this is not an environmentally benign solution, and indeed many European Union countries have forbidden the landfilling of composite waste (Pickering 2006). Awareness of this issue is rising and has been highlighted in recent wind power studies. Hayman raises the recyclability problem of wind turbine blades and Larsen summarises a few possible recycling options for WT blades (Hayman et al. 2008; Larsen 2009). Both of them point out that the relatively short history of the WT industry and low production volumes lead to there being no successful industrial scale WT blades recycling processes that have yet been well-defined and established. Other studies also explore possibilities for reusing the composite WT blades including remanufacture and reuse as structural components in buildings, bridges or artificial reefs (Asmatulu et al. 2013; Falavarjani 2012). A few ideas have been proposed and have been trialed in laboratories, but none of these has emerged as the industrial path of choice for end-of-life WT blades either because of technical or economical problems. At the moment, wind turbine blade manufacturers and governments lack detailed information about this potential blade waste problem. They are aware that end-of-life materials management needs to be addressed, and are keen to know how serious a problem it will be and what options will be available. A comprehensive answer is needed for this question, including how much waste will be generated in the future, its environmental impact, and the range of possible options for dealing with the waste.

1.1. Research objective

This study aims answer the first part of the question above which is trying to quantitatively and comprehensively understand the life cycle waste inventory of WT blades using accurate and state-of-art data. This paper provides a full evaluation of the material flows associated with all stages of the lifecycle of WT blades, estimated over a timeframe extending to 2050. Material is used in the manufacture of the WT blades and during their service life, to repair damage for example. At the end of their service life, the blades are decommissioned and become end-of-life waste material. The magnitudes of all these material usage and waste streams are estimated using current global data and growth predictions under different scenarios.

1.2. Paper structure

Research methodology and the logic behind the calculations are introduced in section 2. The blade material required per unit rated power is analysed in section 3.1 followed by the estimation of total blade material usage presented in section 3.2. Then the lifecycle waste contributing factors from manufacture to end-of-life are discussed in section 3.3. The waste inventory and model limitations are presented in section 3.4 and 3.5 respectively. Finally, conclusions are presented in section 4.

2. Methods

The calculation starts from the manufacture stage. An estimation of the amount of material used for WT blades globally requires a statistical method with input from many different sources. We need to know the amount of blade material required per unit wind power, and to quantify how this changes over time with the evolution of turbine design and especially size.

The blade material usage is related to blade size and the blade size is normally determined by its rated power. Generally, a high rated power wind turbine needs large blades and this goes with high blade material usage. Nevertheless, the relation between blade size and rated power is only roughly proportional, not directly proportional. In order to analyse the relation between blade rated power and blade weight, we collect blade weight data for 56 models produced by 14 wind turbine blade manufacturers and divide them into five classes. In each class, the blade masses are summed then divided by the sum of the turbine rated power to obtain the average blade material required per unit rated power (tonnes/MW) (section 3.1).

The size of the wind power generation capability is then estimated. Data on the current annual wind power installed capacity and average rated power of new installed turbines is provided by wind power associations, together with some predictions for the future growth of the industry. These are used with the blade material per unit rated power to calculate the total blade material usage. For each specific year and region, we use the average rated power in this region at this year to find the matched blade material required per unit installed capacity (t/MW). We then use the unit material requirement multiplied by the installed capacity (MW) to get the total blade material usage (t) for this region during this period of time (section 3.2). This blade material will become the end-of-life (EoL) waste when the blades are decommissioned.

EoL waste does not constitute the full blade inventory. Wastes arise from the whole blade lifecycle including the manufacture, transportation, operation and maintenance and end-of-life. We use the percentage of blade weight to represent waste levels, since the amount of those wastes is proportional to the blade size (the larger the blade, the more waste when the waste level is fixed). Waste sources in addition to EoL waste are manufacturing in-process waste, defective blades, testing blades, routine maintenance, accidental damage and blade upgrading. Details are explained in section 3.3.

Figure 1: Logic flow of waste inventory estimation.

Finally, we sum the waste generated in each region and each year to estimate the total amount of WT blade waste material that will be generated over the period 2018 to 2050. Parts of this will arise from manufacture of new blades and in-service waste, but the picture will be increasingly dominated by the end-of-life waste as WT blades are decommissioned (section 3.4).

2.1. Data sources

The installed wind power capacity data are publicly available from multiple wind energy associations. Blade specifications including the model, weight, rated power and length are partially publicly available from wind turbine specifications database websites and blade manufacturers' advertising materials; however this has been augmented using 21 confidential bills of materials received directly from wind turbine blade manufacturers through site visits and interviews with technical directors. Data on manufacturing waste, operation and maintenance waste and end-of-life waste have been collected through interviews with blade manufacturers and wind farm operation and maintenance (O&M) service providers and analyzed by the researchers.

3. Results and Discussion

3.1. Blade mass per unit rated power

The first step was to collect data on 56 mainstream wind turbine blades (WTB) ranging in size from 500 kW to 8 MW, and originating mainly from US, Europe and Asia WTB manufacturers. The blades are classified into the following size ranges: less than 1MW, 1 to 1.5 MW, 1.5 to 2 MW, 2 to 5 MW and larger than 5 MW. There is a continuing trend for wind turbines to up-scale, so usually the more up-to-date turbines have higher rated power and larger blades. The less than 1 MW class covers most of the early experimental turbines and the early stage commercial turbines. The 1-1.5 MW, 1.5-2 MW and 2-5 MW classes cover most of the matured and maturing commercial onshore wind turbines models and is also projected to cover future onshore turbines for the next ten years. The larger than 5 MW class is an offshore wind turbine class.

The finished blade masses from the different manufacturers are presented in Figure 2, as a function of the wind turbine rated power. A clear trend linking blade size and power rating can be seen, although there is quite a lot of variability in the data mainly because the blades are manufactured at different times and designed to be used in different wind speeds. An average value of blade mass per unit rated power is needed for subsequent analysis, and is calculated for each of the turbine size class ranges. For each turbine size class, the blade masses are summed then divided by the sum of the turbine rated power to obtain the blade mass per unit rated power (tonnes/MW). The results are presented in Figure 3. It can be seen here that the standard errors in all groups are lower than 1 which shows that there is no extreme data in the sample that has been selected. Additionally, as shown in figure 4, the blade mass best fit polynomial curve is very close to the United States National Renewable Energy Laboratory's (NREL) prediction (Fingersh et al. 2006) on the blade mass scaling curve. This indicates that the blade mass sample is appropriate and representative.

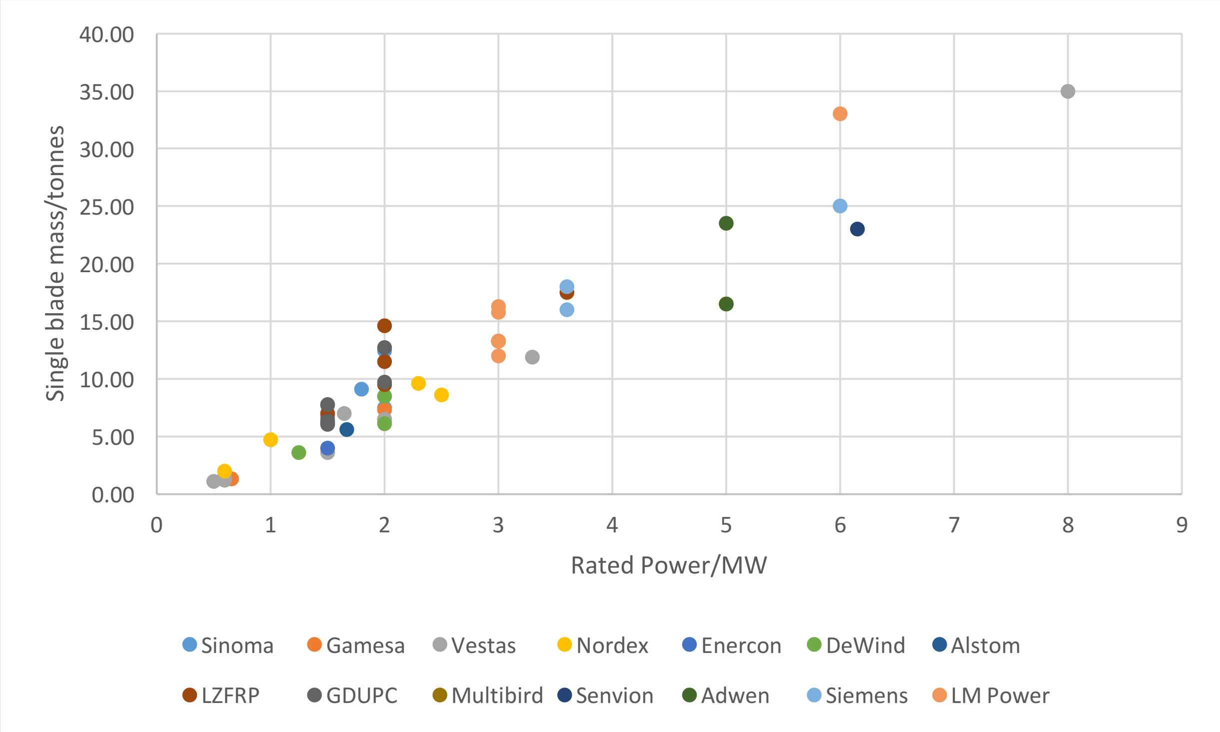


Figure 2: Blade mass VS blade rated power. Modified from: (Liu & Barlow 2015).

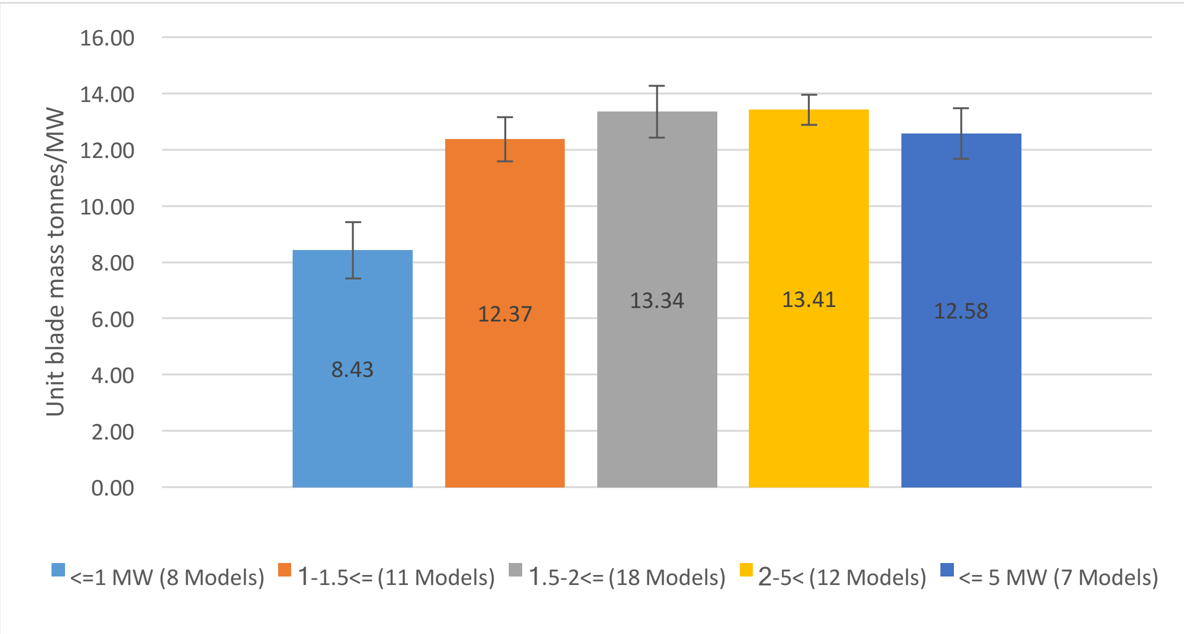


Figure 3: Blade mass per unit rated power for the different turbine size classes.

The mass per unit power is lowest for the smallest wind turbines, <1MW, and it increases with the size of blades to reach the highest value in large onshore blades, 2-5 MW. Simple geometric arguments indicate that when the blade length is doubled, the blade volume is increased by 2^3, 8-fold. So for the same material and same design, the blade mass would increase 8-fold. In fact, as shown in figure 4, the blade mass does indeed increase with size, but at a lower rate than predicted by the conventional mass scaling law. As shown in figure 3, the blade mass per unit rated power of the most up-to-date super-large offshore blade (> 5MW) is even slightly lower than the large blade class (2-5 MW). These mass reductions are due to developments in blade technology leading to more efficient structural design, lower safety factors, lighter materials and improved manufacturing techniques (Liu 2015). The results of blade mass per unit rated power (8-13.4 t/MW) are similar to Henning's results (10 t/MW) (Albers 2009), but our result have improved accuracy and have also considered the effect of wind turbine upscaling.

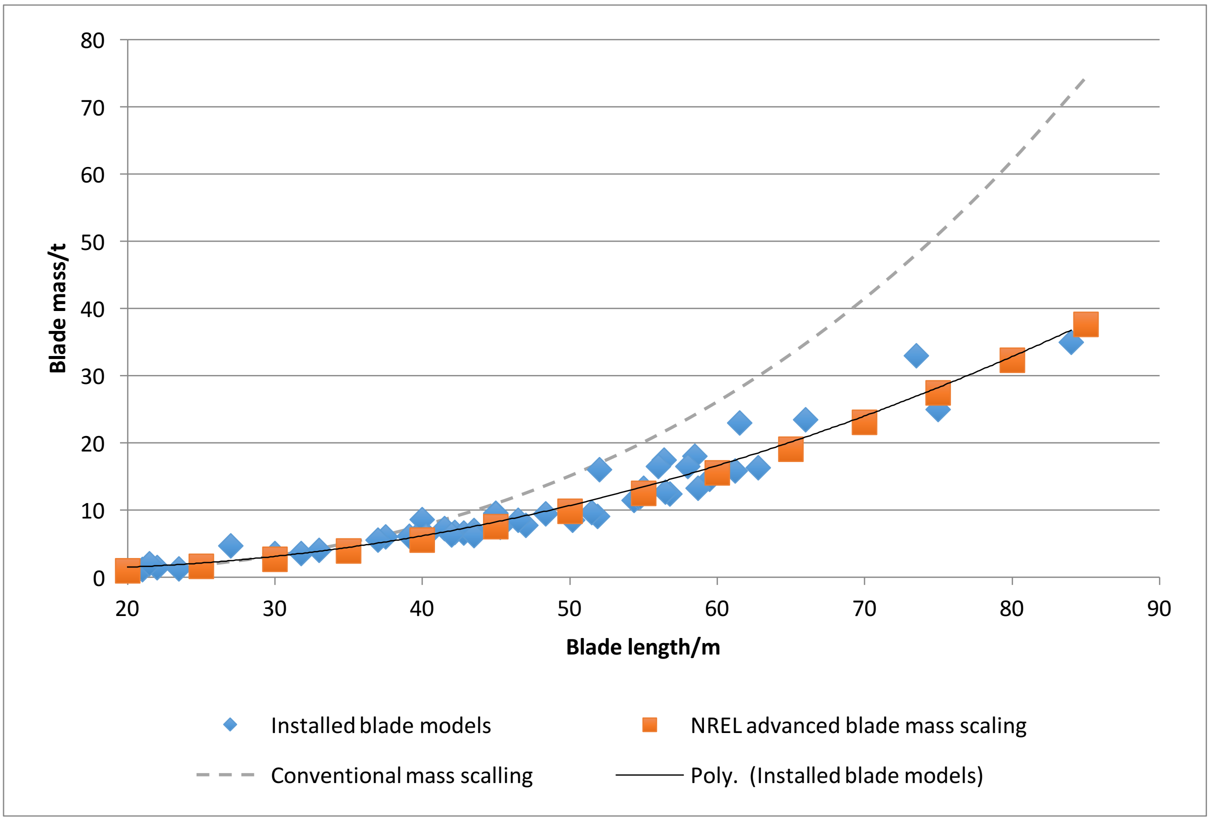


Figure 4: Blade mass VS blade size. Modified from: (Liu & Barlow 2015).

3.2. Total wind turbine blade material usage

The amount of blade mass per unit rated power (t/MW) has been calculated above. We need this number for the matched average rated power with the installed capacity (MW) to estimate the total material usage for each region at any specific time. The average rated power for a single new installed turbine and annual installed capacity depend on regional features.

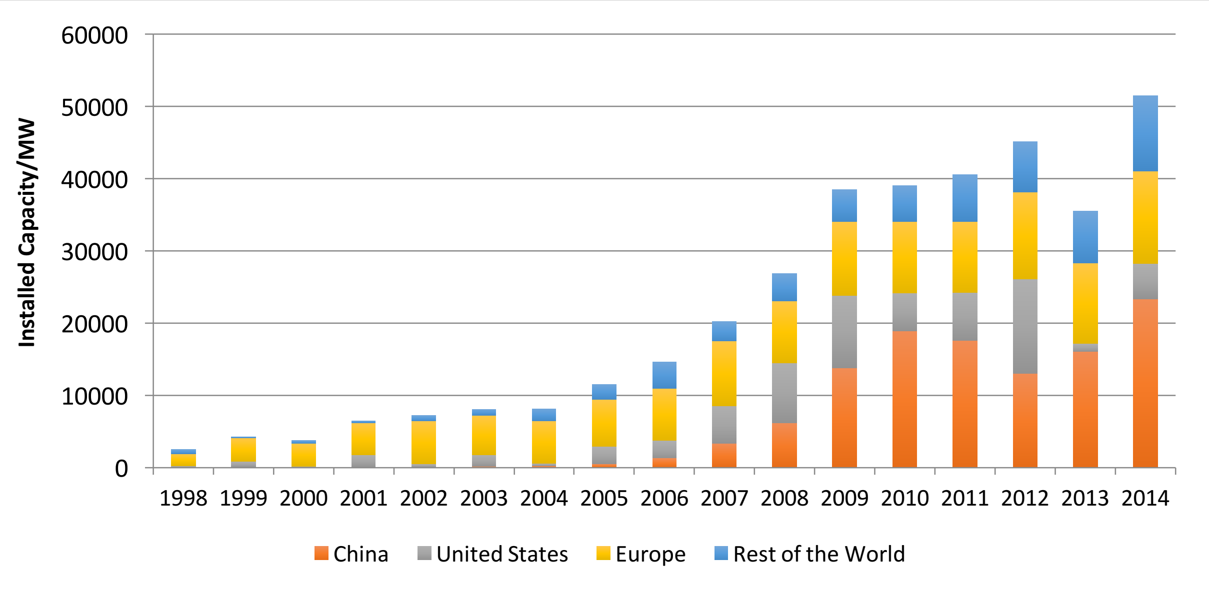


Figure 5: Annual installed capacity by region. Source: (Liu & Barlow 2015).

Each region has its own strategy for developing wind power and exhibits different features which will affect the blade waste level. Europe, China, United States and rest of the world are selected as the four major wind energy markets based on their similar large volume installed capacities. The data before 1998 is available for Europe and United States only, but is not comprehensive for all regions. The installed capacity before 1998 is very small compared to the later installed capacity which means the effect on the final results of the missing data is negligible. Hence, we decided to discard data from before 1998 and consider only the waste levels after 1998. Note that the latest 2015 data is not yet available. Therefore, the wind power installation historical data range was selected to be from 1998 to 2014.

Based on information from American Wind Energy Association (AWEA), Chinese Wind Energy Association (CWEA), European Wind Energy Association (EWEA) and Global Wind Energy Council (GWEC) (Anthony 2014; GWEC 2014a; EWEA 2013; CWEA 2014), as shown in figure 5, it can be seen that the commercial wind energy industry started first in Europe where more than 50% of global new wind turbines were installed between 1998 and 2006, and the growth rate has continued steadily since then. The new installed wind turbine sizes are increasing. The average rated power of new installed wind turbines in Europe exceeded 1 MW in 2000, 1.5 MW in 2006 and 2 MW in 2010 (Vitina et al. 2015; IRENA 2012; Woebbeking 2012). Unites States also started developing wind energy early, installing 20% of the global new turbines in 1999. In contrast to the stable European market, the US wind market shows large fluctuations. The annual installed capacity is strongly affected by the Production Tax Credit for Renewable Energy (PTC) (Wiser & Bolinger 2015). At the peak, US installed 177.6 GW wind energy in 2012, equivalent to 29% of the global market share, but it then dropped severely to 14 GW in 2013. Its average new installed wind turbine rated power exceeded 1 MW in 2000, 1.5 MW in 2006 and 2 MW in 2015 (Wiser & Bolinger 2015). Wind energy started late in China with only 617 MW wind energy installed before 2005 (1.5% of Global installed capacity by the end of 2004). Driven by a rapid increase in demand for electricity and a strong renewable energy policy, China wind power then experienced meteoric growth. The cumulative installed capacity doubled every year during the period 2005 to 2009 and by 2010 China was the largest installed wind power capacity country. The average new installed wind turbine rated power for China exceeded 1 MW, 1.5 MW and 2 MW in 2007, 2010 and 2014 respectively (Liu 2014). For the rest of the world, the installed capacity has been steadily increasing since 2001. It is very hard to find out the average new installed wind turbine rated power for every single country. Hence we assume the average new installed wind turbine rated power to be the same as the global mean value from GWEC and to exceed 1 MW, 1.5 MW and 2 MW in 2007, 2010 and 2014 respectively (GWEC 2013; GWEC 2014a).

Class	Unit blade mass/ t/MW	China	US	Europe	Rest of World
Up to 1 MW	8.43	Pre 2006	Pre 1999	Pre 1999	Pre 2006
Between 1 MW and 1.5 MW	12.37	2007-2009	2000-2005	2000-2005	2007-2009
Between 1.5 MW and 2 MW	13.34	2010-2013	2006-2014	2006-2009	2010-2013
Between 2 MW and 5 MW	13.41	2014-Post	2015-Post	2010-Post	2014-Post
Less or equal to 5 MW	12.58	Offshore	Offshore	Offshore	Offshore

Table 1: Average new installed single turbine capacity and blade mass per unit rated power.

From above, the blade material usage is obtained from 1998 to the end of 2014 based on the historical data. Installing capacity prediction is required in order to find the blade material usage for the future. Because the wind energy market is strongly affected by energy policy and may show large fluctuations from year to year, we decided to use the average of the last three years installed capacity plus a growth rate predicted by the appropriate wind energy association to estimate an annual installed capacity for the year after the latest available data. For example, in order to estimate the 2015 installed capacity we therefore average the installed capacity of 2012, 2013 and 2014 and then multiply by the predicted growth rate (100+14)%. Having established 2015 as the reference year, installed capacity for subsequent years is estimated using only the predicted growth rate. The growth rate affects future wind power installed capacity and the installed capacity is the biggest factor determining the waste inventory, so an accurate growth rate is crucial to this study. The future growth rate is a prediction which is based on assumptions and is full of uncertainties. Optimistic, normal and pessimistic scenarios are commonly used to cover all the possibilities. Different wind energy associations give different growth rate predictions. Normally local energy associations are likely to provide more accurate growth rate data than global predictions as the local energy association are more familiar with local situations. We have attempted to find growth rate predictions for each region, but only European and global data has been identified. So we have used the growth rate for Europe from the EWEA prediction, and have used the GWEC global growth rate prediction for the other three regions.

Here, we adopt the same growth rate scenario settings as GWEC did and the scenarios as '**Base**', '**Moderate**' and '**Advanced**' from GWEC are adopted for growth rate scenarios in this study. Three scenarios are defined as follows: "*The '**Base**' scenario is based on an assessment of current directions and intentions of both national and international energy and climate policy, even though they may not yet have been incorporated into formal decisions or enacted into law. Examples of this would include the emissions reduction targets adopted in Cancun in 2010, the various commitments to renewable energy and efficiency at national and regional levels, and commitments by governments in such fora as the G-8/G-20 and the Clean Energy Ministerial. The '**Moderate**' scenario has many of the same characteristics as the Base scenario, taking into account all policy measures to support renewable energy either already enacted or in the planning stages around the world, but at the same time assuming that the commitments for emissions reductions agreed by governments at Cancun will be implemented, although on the modest side. At the same time it takes into account existing and planned national and regional targets for the uptake of* *renewable energy in general and wind energy in particular, and assumes that they are in fact met. The '**Advanced**' scenario is the most ambitious, and indicates the extent to which the wind industry could grow in a best case 'wind energy vision', but still well within the capacity of the industry as it exists today and is likely to grow in the future. It assumes an unambiguous commitment to renewable energy in line with industry recommendations, the political will to commit to appropriate policies and the political stamina to stick with them. It also assumes that governments enact clear and effective policies on carbon emission reductions in line with the now universally agreed objective of keeping global mean temperature rise below 1.5-2°C above pre-industrial temperatures.*"(GWEC 2014a).

By applying the growth rates to the historic installed capacity data, the future installed capacity can be calculated. The historic and future installed capacity form the full picture of installed data. Next, we use the annual installed capacity (MW) multiplied by the blade material required per unit power (t/MW), and from this the total blade material usage in each year can be obtained. The result is shown in figure 6.

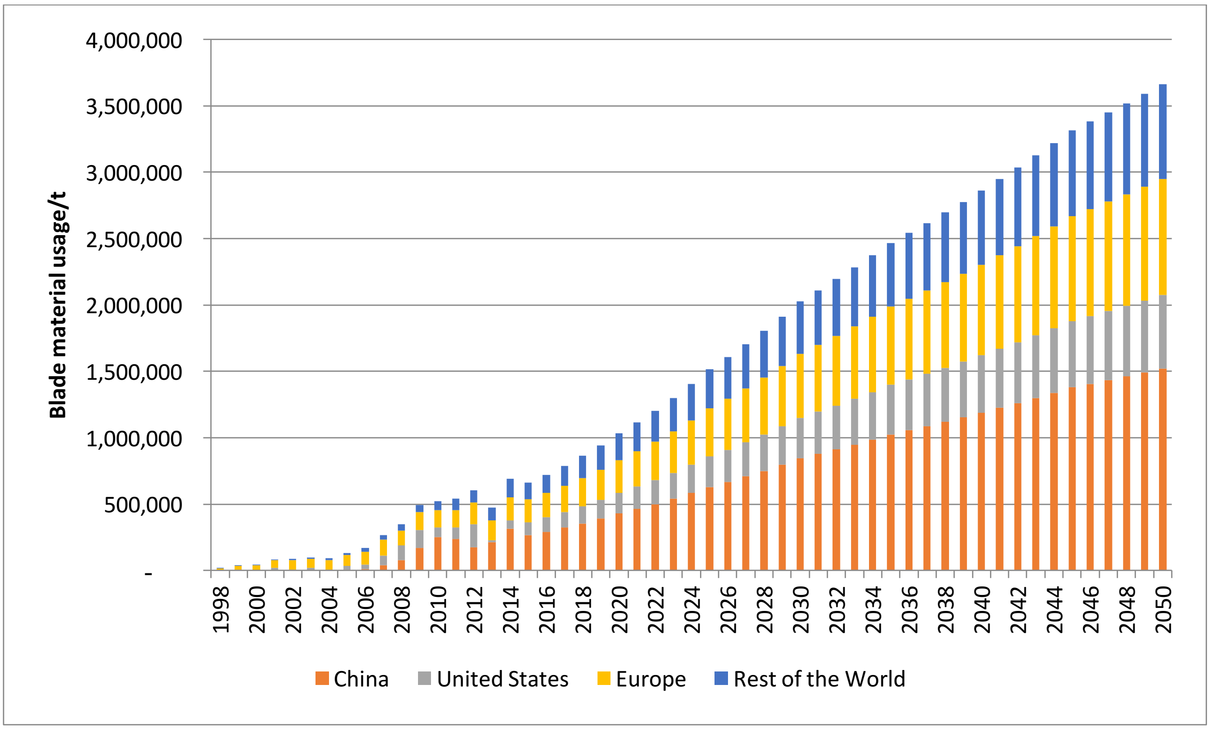


Figure 6: Annual WTB material usage. Data after 2014 is calculated based on the moderate growth rate scenario.

3.3. Waste contributing factors

The total blade material usage calculated above is only a part of the full blade waste inventory. Waste arises from the whole lifecycle of wind turbine blades which comprises four stages: manufacturing, transport and installation, operation and maintenance, and end-of-life. The blades themselves become waste at the end of their service life, and are expected to form the largest fraction of the total blade waste, but smaller amounts of waste arise in the other stages in amounts that are proportionally related to the amount of blade material (the materials actually present in the finished blade). For example, the amount of manufacturing in-process waste is reported in terms of hundreds of kilograms per blade. We can then represent the manufacturing in-process waste as a ratio of the finished blade weight (%). We use the finished blade weight as the reference value for material usage and multiply this by a combined factor that includes all the other waste contributing factors.

All of the contributing factors in the four stages affect the blade waste, and the numbers may vary. For example, the in-process waste is affected by the worker's skills, the blade manufacturing technology used and the manufacturing management practices at the site. Hence, the waste contributing factors vary from region to region, manufacturer to manufacturer and model to model. In order to consider these variations, we set three scenarios for each factor to give a better understanding of the full picture of blade waste inventory. The '**Central**' scenario is expected to be the closest to reality and with the highest probability, i.e. the most likely case. The '**Low**' and '**High**' scenarios represent the lowest and highest possible waste levels respectively.

Manufacturing in-process waste is estimated by subtracting the mean finished blade mass from the bill of materials (BoM). The difference is the amount of material wasted during the manufacturing process. The bill of materials contains the quantity and the types of raw materials used in manufacture including the fibre fabric, resin, structural adhesives, core, paint, metal accessories and manufacturing process consumable materials. It does not include working protection consumables such as gloves, masks and containers and packaging. Analysis of 21 BoMs provided by three blade manufacturers for blades manufactured from glass fibre and epoxy resin using VARTM technology revealed that the in-process waste was between 12-30%, with median of 17%, of finished blade mass (Liu 2015). We assume that waste levels are comparable for other manufacturers using the same manufacturing technology. The other manufacturing technologies may bring different waste levels. For example, the fibre usage of a 45-metre blade with embedded bolts is 450 kg lower than the same model finished using bolt hole drilling. Another example of variation is that Siemens makes the blade in an unibody without structural glue (IntegralBlade® technology). This technology improves the blade integrity and is also able to reduce the blade weight and the waste in polish and adhesives (Siemens AG 2015). LM Power uses polyester resin rather than the more commonly used epoxy resin and so may have different resin usage level to other manufacturers (LM Power 2014). New direct infusion technology, used by some manufacturers, can use a smaller pipe for resin transfer which could reduce the resin residue waste (Bland 2015).

The major in-process wastes are the dry fibre off-cuts, cured composite off-cuts from the blade edge and root, resin residue in flow mesh and container and the dust from the polishing process, in proportions shown in Figure 7.

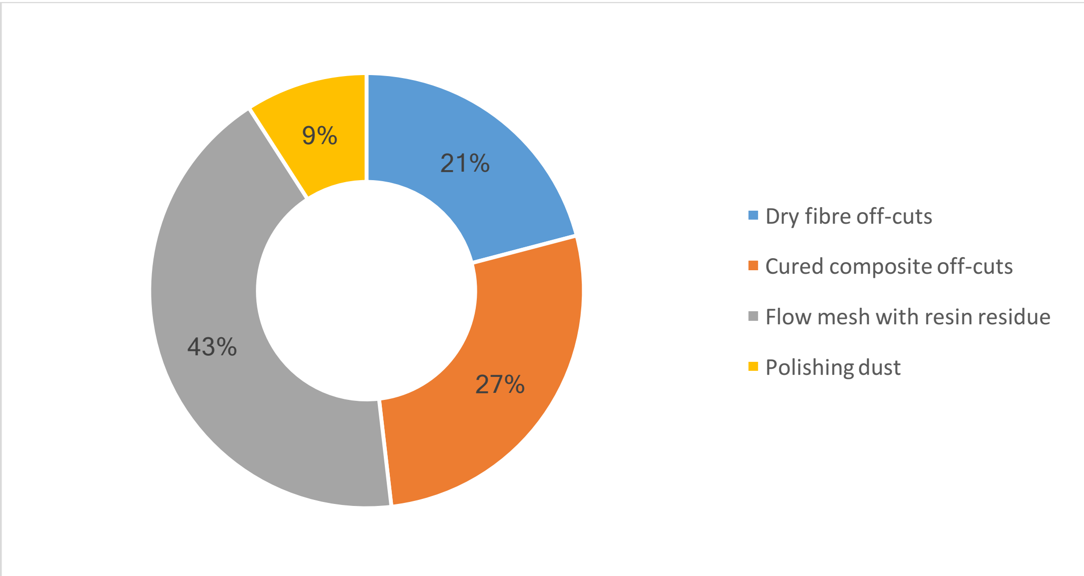


Figure 7: Manufacturing in-process waste by weight.

Defects and testing blades are another two waste sources arising during the manufacturing stage. Defects are identified by inspections at various times during the manufacturing process. Small defects could be small regions with poor resin permeability or slight bias in centre of gravity; such defects are quite common and can be remedied during the manufacture stage. Defects requiring discard of the whole blade or a whole blade component are extremely rare and vary from model to model depending on the maturity of the model. When new blade models are introduced there may be high failure rates of this type, due to difficulties in manufacturing techniques and the unfamiliarity of workers with the new model. The rate of defects requiring discard of the whole blade is typically around 0.05% to 0.2% (Liu 2015). They are assumed to be 0.05% for the low scenario, 0.1% for the central scenario and 0.2% for the high scenario in calculations.

Due to the certification requirements, a small number of blades is made for mechanical testing purposes. For static tests they will typically be loaded up to 150% of their designed loads for performing the stiffness and strength tests required for blade certification and Finite Element Model validation (MTS Systems Corporation 2012). New blade models also need fatigue testing involving the automated cyclic loading of blades, typically at their resonant frequency as a means of exciting the blade and achieving the desired strain rate. Some of these static and dynamic testing blades cannot be used in-service for electricity generation after the tests, and hence are treated as testing blade waste, accounting for around 0.1% of all blades (Liu 2015). The testing blade waste taken to be 0.05% for the low scenario, 0.1% for the central scenario and 0.2% for the high scenario.

Some blades are damaged through improper hoisting, during transport or during the installation process, but this rate is very low (Liu 2015). Waste generated in this stage is assumed to be zero in this study.

Routine maintenance, accidental damage and blade upgrading are the three major waste sources in the operation and maintenance (O&M) stage for WTB. Routine maintenance includes cleaning, minor and major repairs. The repair of minor flaws or stone damage is very common for most blades. Generally, 15 kg fibre, resin and coating paint is enough for each of these minor repairs. Minor defects may occur a few times during the blade lifetime (Zhang 2016). We assume they occur 2, 3 and 5 times for the low, central and high scenarios respectively, which is equivalent to 30 kg, 45 kg and 75 kg material consumption. Major repairs only happen on specific blade batches and are usually caused by manufacturing defects or design defects. Such repairs typically involve re-strengthening work on major structures such as shell bonding, shear web bonding or the blade root. Each major repair job consumes tens to hundreds of kilograms of fibre, resin and adhesives (Zhang 2016). In this study, the major repair material consumption each time is taken to be 50 kg in the low scenario, 100 kg in the central scenario and 150 kg in the high scenario. And the repair demand rates for low, central and high scenarios are taken to be 5%, 10% and 20%. The total material consumption for minor and major repairs is therefore equivalent to 0.5%, 0.9% and 1.6% of the 1.5 MW blade manufacturing material under our low, central and high scenarios.

Quite a few blades break in accidents due to extreme weather: a severe gust or high shear event can lead to loads that exceed the blade design strength. Incorrect operation can also lead to excessive loads on the blades and may considerably shorten the blade life. Examples include incorrect shutdown sequencing, incorrect pitch set or failure to maintain yaw alignment during high winds (Malkin et al. 2015). A report indicates that those causes are responsible for 1-3% of annual blade failures in the first ten years of operation; the highest failure rates usually occur in the initial five years (Malkin et al. 2015). Some failures need major repairs and some of them require blade replacement. Such blades are treated as accidental O&M waste. The waste rate is 1%, 2% and 3% of blade manufacturing material for the three scenarios.

Blade upgrading is another driver of waste during the operation stage. With developments in blade aerodynamics, the newest blades are able to capture more energy for the same wind turbine compared to the blades made previously. The improved electricity generating capacity means that some blades are replaced before they reach the designed lifetime, which then leads to extra waste. Some blade manufacturers also provide an aerodynamic efficiency upgrading set which can be installed on blades to increase annual energy production by 2-4% (AEP) (Siemens AG 2014). Such blade upgrade materials should be taken into account in the waste inventory, but no information is available about the proportion of blades upgraded and the amount of material involved. We assume the upgrading waste is 2%, 5% and 10% of blade manufacturing material for the low central and high scenarios respectively.

The wind turbine design lifespan is about 20 years. Currently, there is no large scale commercial wind farm has that has yet reached its design lifetime, so no one has experience about the potential for wind turbine life extension. Gamesa presented their research about the possibility of life extension at EWEA 2015 (Gamesa Corporación Tecnológica 2015). They mentioned that life extension for the tower and nacelle are relatively straightforward but this is much more difficult for the blades. Their oldest blades have been in operation for 17 or 18 years. Some them have already suffered defects or fatigue problems at the shell bonding and root connections which require major work to repair. Gamesa predict that some blades could be used for more than 20 years, and maybe up to 25 years, but it is not possible to extend the life to more than 27 years. Based on the above, we propose 18 years, 20 years and 25 years as the lifespan for blades under our three different scenarios.

To summarise, the in-process waste and defective blade waste are generated during the blade manufacturing process. Testing blade waste is generated before volume production begins. The time differences here are small, so we assume these three type of waste are generated at the same time, which is the first year of the lifetime of the blade. The routine O&M waste is generated by the maintenance and repair which happen through the whole blade lifetime, but generally small-scale repair and maintenance work happens more frequently in the initial few years. The accidental O&M waste is also mainly generated in the initial few years. Hence, we assume all the O&M waste is generated in the sixth year. The main purpose of blade upgrading is to improve the power generation efficiency. Blade upgrading is driven by relatively slow progress in aerodynamics research and blade technology. When advances are made, it may take some time for the market to accept change and respond. We assume that blade upgrading, with associated waste generation, will not take place until the 16th year of the lifetime of the blade. Based on the conclusions from Gamesa, we conclude that a proportion of blades develop serious defects and need major repair or to be decommissioned in the 17th/18th year after commissioning (high scenario). Most blades have a design lifetime of 20 years. These will be decommissioned in their 21st year (central scenario). As mentioned above, Gamesa also predicts that it will be possible to extend some blade lifetimes to 25 years without major defects arising. In this case, blades will be decommissioned in their 26th year (low scenario) (Gamesa Corporación Tecnológica 2015).

All these waste contributing factors are summarised in table 2 and the calculation logic is presented in figure 8. The combined factors for waste generated in the first three lifecycles stages, manufacturing, transport and installation, operation and maintenance, are 15.6%, 25.1% and 45.0% for low, central and high scenarios respectively

Lifecycle	Manufacturing			Service			End-of-Life	Total
	In-process waste	Testing blade waste	Defective blade waste	Routine O&M waste	Accidental O&M waste	Upgrading waste	Year in which EoL waste generated	
Year of Generation	1^{st}	1^{st}	1^{st}	6^{th}	6^{th}	16^{th}	18^{th}-26^{th}	
Low scenario	12%	0.05%	0.05%	0.5%	1%	2%	26^{th}	15.6%
Central scenario	17%	0.1%	0.1%	0.9%	2%	5%	21^{st}	25.1%
High scenario	30%	0.2%	0.2%	1.6%	3%	10%	18^{th}	45.0%

Table 2: Summary of waste contributing factors. Percentage represents % of finished blade mass.

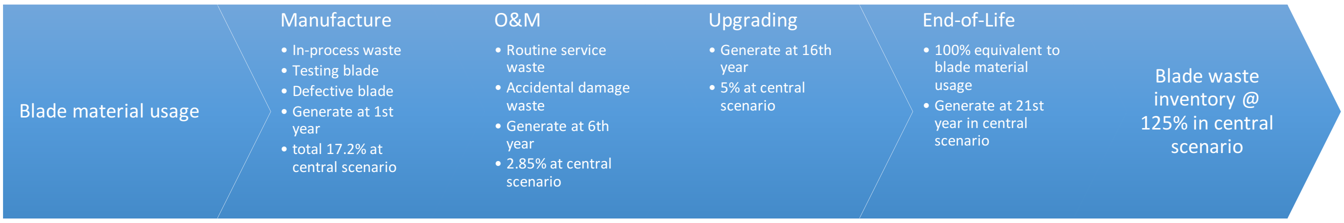
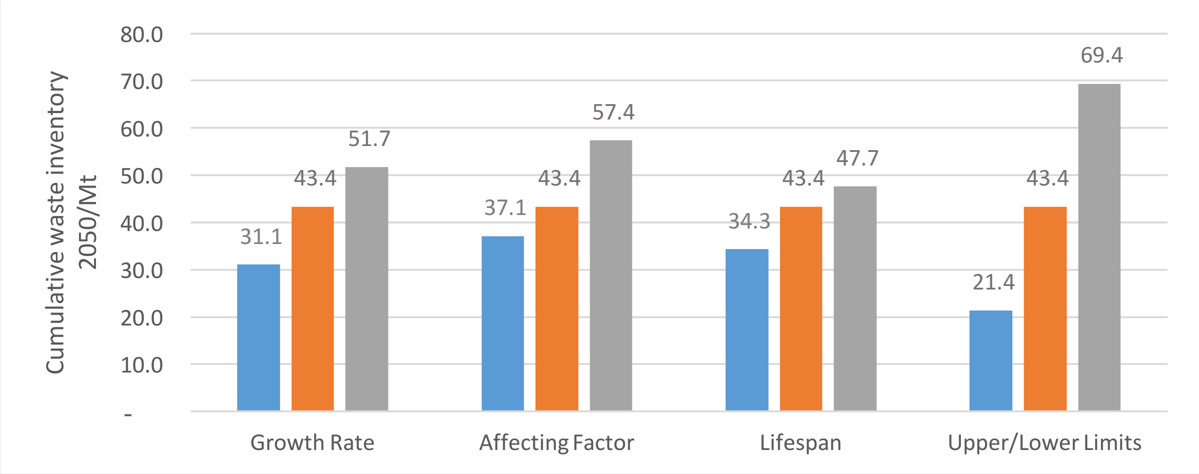


Figure 8: Waste generation flow from manufacture to end-of-life.

3.4. Waste Inventory

The blade waste inventory consists three types of waste: Manufacturing waste, Service (O&M) waste and EoL waste. Manufacture waste is the waste generated in manufacturing stage and consists mainly of dry fibre offcuts, composite offcuts, resin residue and vacuum consumables. Service waste is the material used during the lifetime of the blade for routine maintenance, repair of accidental damage and blade upgrading and is mostly fibre fabric and resin. EoL waste refers to the retired blades, so mainly comprises composite material (93%), with 2% PVC, 2% balsa and around 3% metal, paint and putty (Liu & Barlow 2016b).



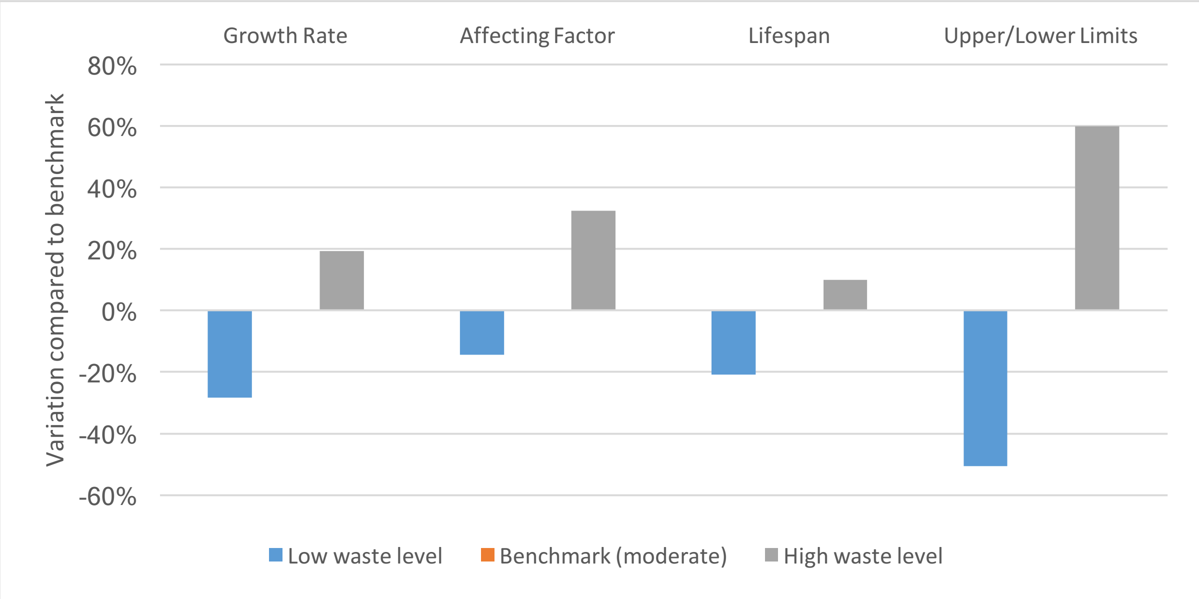


Figure 9 Upper: Global wind turbine blade waste 2050 in million tonnes (Mt), showing the effect of three different projection scenarios for each of three governing factors. "Affecting factor" includes waste contributing factors during both manufacture and O&M. The final column shows the maximum and minimum waste values obtained by combining the factors. Lower: Waste variation compared to benchmark in %.

The upper part of figure 9 presents the estimated global wind turbine blade waste inventory in 2050 under different scenarios. 'Growth rate' is the predicted annual wind power installation growth rate. The 'affecting factor' includes the waste contributing factors during manufacture and the O&M stage. 'Lifespan' is the wind turbine blade operation duration. Firstly, we aim to identify the most likely waste weight in 2050. We therefore ascribe all the variables to the most likely setting: the growth rate is set to the moderate scenario and the waste affecting factors and lifespan are set in the central scenario. This leads to an estimate of the most likely blade waste weight of

43.4 Mt in 2050. An analysis is then performed by looking at the 'best' and 'worst' cases. For the 'best' case, all the factors are chosen to benefit low waste volume such as low manufacturing in-process waste rate, low new installed capacity and long blade lifespan, giving a lower limit of blade waste at 21.4 Mt. For the 'worst' case, factors are set in favour of high waste volumes including the highest waste rates, high new installed capacity and short lifespan, giving a blade waste upper limit of 69.4 Mt.

The lower part of figure 9 presents the sensitivity analysis of variables. It shows the results variation in percentage (%) compared to the most likely scenario as a benchmark. The growth rate is mainly affected by the amount of wind turbine capacity installed, then the number of blades manufactured and finally the blade material usage. The higher the growth rate, the more of the newer models of turbines installed, the larger will be the amount of waste in the future. In the base scenario, the total waste will reduce 28% compared to the benchmark. In the advanced scenario, it will increase 19%. Affecting factors are related to the manufacturing waste and O&M waste rates. With the high-level in-process waste management and high quality blade (less repair required), the low waste scenario will apply. In this case the total waste inventory is 14% less than the benchmark. By contrast for the high scenario, the waste is 32% higher than benchmark. On the other hand, if the blade service time is increased beyond the design lifetime, the demand for new blades will be lower. The waste can be reduced by up to 21% if the blades can serve for as much as 25 years. Conversely, if the blade lifetime falls below the design lifetime, the waste inventory may rise 10%. When all factors are considered, the waste inventory in the lowest waste case is 51% lower than the benchmark and the highest waste case is 60% above than benchmark. There is a factor of up to 3.2 difference between the best and worst scenarios, so there can be significant benefits from advances such as improvement to the blade manufacturing technology to reduce in-process waste. Whatever scenarios are chosen, however, the total waste will be a few tens of million tonnes in 2050 which will lead to serious environmental problems unless proper solutions can be found.

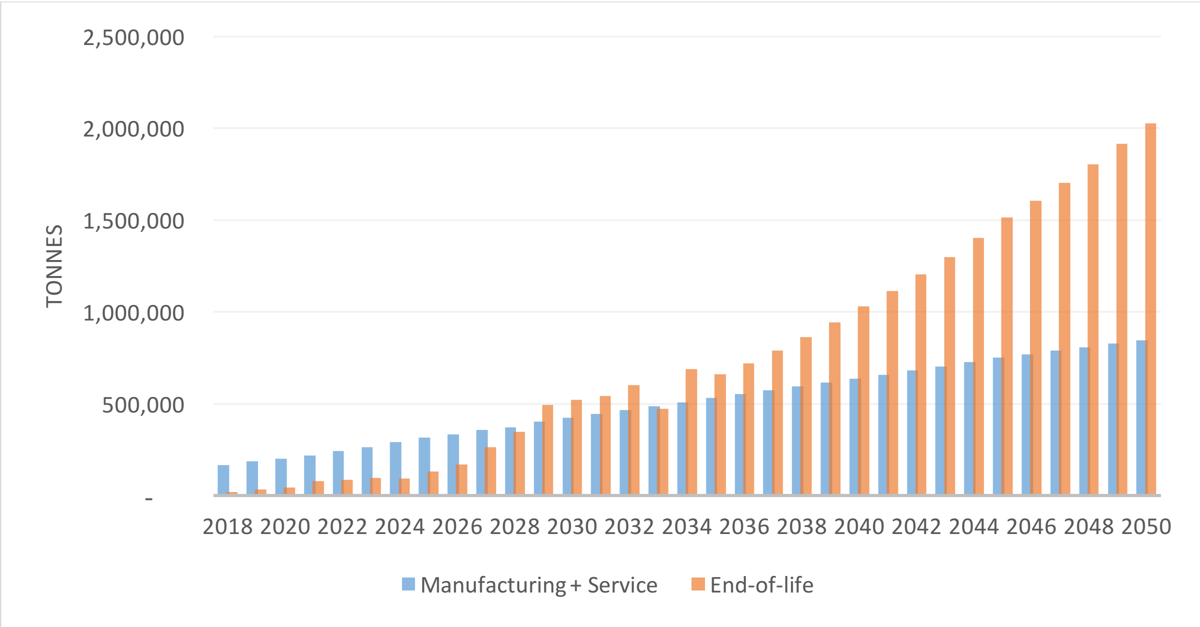


Figure 10: Global wind turbine blade waste projection up to 2050.

We will now look at the waste types and the regional features. In the following discussions, we use the most likely case (43.4Mt), moderate scenario for growth rate, and central scenario settings for the other variables. As shown in figure 10, the annual scrap from manufacturing and service steadily increases from 2018 with the growth of new turbine installation. It reaches 500 kt in 2034 and will keep increasing with the growth in blade manufacturing. By contrast, end-of-life waste starts in 2018 under the central scenario since the wind turbine installation data starts from 1998 and the design lifetime is 20 years. It increases sharply to 500 kt per year in 2029, overtaking the sum of all the other waste sources to form the largest waste source at that time. This end-of-life waste stream will annually generate more than 2 Mt blade waste in 2050.

The EoL waste in central scenario between 2020 and 2026 is close to the data estimated by Albers (Albers 2009). After 2027 our EoL waste data is higher since the up-to-date installed capacity is adopted and the accuracy of blade material per MW installed is improved. For the EoL waste between 2029 and 2033, our results (around 500,000 t) are 20% higher than Andersen's prediction (400,000 t) (Andersen et al. 2014). This is because the unit blade material demand during 2009 to 2013 is 12-13 t/MW which is higher than Andersen's 10 t/MW. The unit blade material demand is more accurate in our research as it is directly calculated from multiple real blade model weights rather than estimated from more generic data. For 2050, Andersen estimates the blade waste will exceed 800,000 tonnes per year. This figure assumes that the cumulative installed capacity by 2030 will be 80 GW, and that 1/20 of this will be decommissioned by 2050. Our prediction is based on a more detailed model which includes estimates for annual changes in installation capacity.

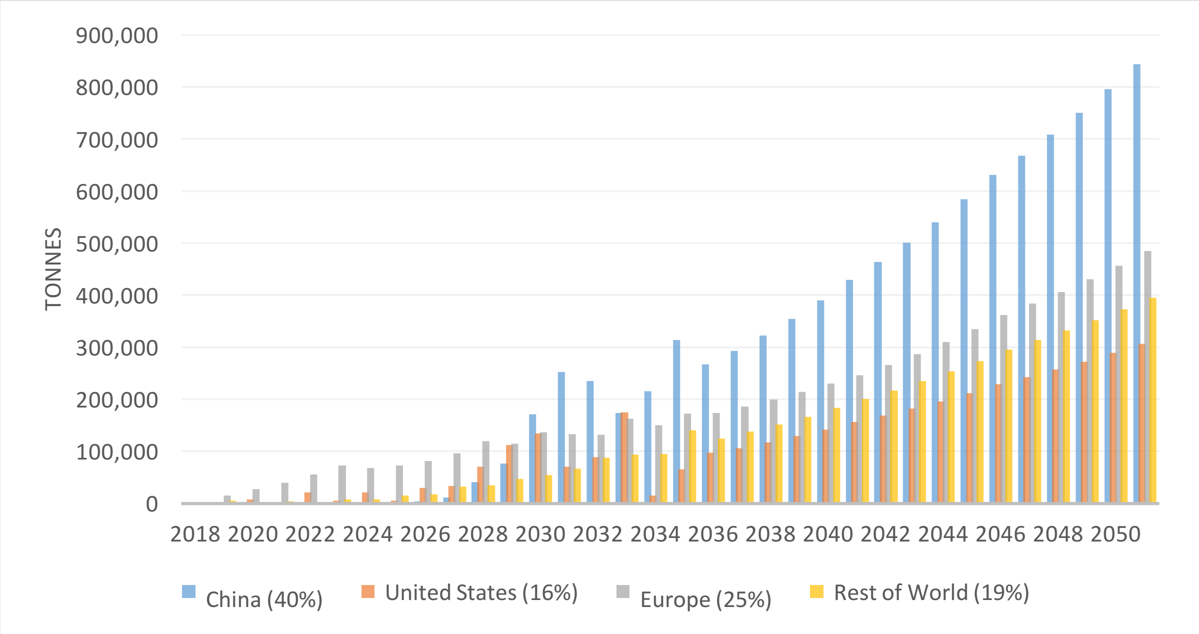


Figure 11: Regional blade waste projection.

The regional variations are illustrated in Figure 11. China will need to process 40% of the global blade waste; the equivalent figures for Europe and United States are 25%

and 19%. Since Europe started installation of large scale wind farms earlier than other regions, it will meet the end-of-life waste problem first. Two years from now, there will be 15,000 tonnes of end-of-life blades needing to be processed, increasing to more than 50,000 tonnes in 2022.

3.5. Model limitations

A number of assumptions and approximations have been carefully made in this work. We have used different scenarios to demonstrate the sensitivity of the analysis to the various factors, but the uncertainties in some of the predictions result in large ranges in the estimates. The accuracy of results relies strongly upon the input data availability and quality. A key uncertainty is the wind energy growth rate prediction. Accurate regional growth rate predictions are not available, so in this study we have used the single figure of the global growth rate to provide estimates for the growth in China, US and the rest of world. As the growth rates strongly affect the total waste inventory, more accurate predictions should be used in the analysis once they can be identified. The other main area of interest is that we did not consider the effect of transition to other manufacturing technologies such as unibody manufacture technology because of lack of information: the bills of materials from manufacturers are classified (current data has been gained through personal contact). Further information would be required to investigate this aspect further. Another potential area for refinement is that in the current work we have not included offshore (> 5MW) turbines in the final waste inventory estimation. The reason is the current offshore installed capacity is much smaller than onshore and the forecasts for future growth are very confused. Most estimates, however, predict that offshore capacity will not exceed 5% of the total wind energy market, so the effect of the omission is expected to be limited. This could be reviewed when further data becomes available.

4. Conclusion

This paper has systematically analysed and predicted the amount of global wind turbine blade waste that will be produced up to 2050 using the best available data from wind energy associations and blade manufacturers. Manufacturing waste, service waste and end-of-life waste are the three major sources of blade waste. Over the lifetime of the turbine, waste generated during manufacturing and service adds between 16% and 45% of the mass of the wind turbine blades. Sensitivity analysis of the contributing factors reveals the most significant elements and provides insight into where the wastes could be minimised. The balance between the waste generated by the different contributing factors changes over time. Manufacturing and service waste are currently the largest contributors, but end-of-life waste is increasing rapidly and is projected to equal manufacturing and service waste in 2028. The waste stream after this time is dominated by the end-of-life blades which will become the biggest problem. The results show that the end-of-life waste stream will annually generate more than 2 Mt in 2050 and cumulative blade waste in 2050 will lie between 21.4 Mt to 69.4 Mt with the most probable waste level being 43.4 Mt. Europe will face the problem first and ultimately China will have the largest waste inventory.

Having quantified the amount of waste associated with wind turbine blades, the next stage of the current research will be to use the material flow data to estimate the environmental impact of wind turbine blade manufacture and use in terms of CO_2 emissions and energy consumption. Finally, end-of-life options for decommissioning wind turbine blades will be explored with the aim of providing environmentally favourable guidelines for managing wind turbine blade waste.

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