sustainability

MDPI

Review

Sustainability Implications of Current Approaches to End-of-Life of Wind Turbine Blades—A Review

Emma L. Delaney [1,2,*], Paul G. Leahy [3], Jennifer M. McKinley [1], T. Russell Gentry [4], Angela J. Nagle [3,5], Jeffrey Elberling [6] and Lawrence C. Bank [4,*]

1 Geography, School of Natural and Built Environment, Queen's University Belfast, Belfast BT7 1NN, UK; j.mckinley@qub.ac.uk
2 Aquatera Ltd., Old Academy Business Centre, Stromness, Orkney KW16 3AW, UK
3 School of Engineering & Architecture, University College Cork, T12 K8AF Cork, Ireland; paul.leahy@ucc.ie (P.G.L.); angie@bladebridge.ie (A.J.N.)
4 School of Architecture, Georgia Institute of Technology, Atlanta, GA 30332, USA; russell.gentry@design.gatech.edu
5 BladeBridge, Rubicon Centre, Munster Technological University Campus, T12 P928 Cork, Ireland
6 Siemens Gamesa Renewable Energy, Inc., 4400 Alafaya Trail Q2, Orlando, FL 32816, USA; jeffrey.elberling@siemensgamesa.com
* Correspondence: edelaney05@qub.ac.uk (E.L.D.); larry.bank@design.gatech.edu (L.C.B.)

Abstract: In recent years, the sustainability of wind power has been called into question because there are currently no truly sustainable solutions to the problem of how to deal with the non-biodegradable fibre-reinforced polymer (FRP) composite wind blades (sometimes referred to as "wings") that capture the wind energy. The vast majority of wind blades that have reached their end-of-life (EOL) currently end up in landfills (either in full-sized pieces or pulverized into smaller pieces) or are incinerated. The problem has come to a head in recent years since many countries (especially in the EU) have outlawed, or expect to outlaw in the near future, one or both of these unsustainable and polluting disposal methods. An increasing number of studies have addressed the issue of EOL blade "waste"; however, these studies are generally of little use since they make predictions that do not account for the manner in which wind blades are decommissioned (from the time the decision is made to retire a turbine (or a wind farm) to the eventual disposal or recycling of all of its components). This review attempts to lay the groundwork for a better understanding of the decommissioning process by defining how the different EOL solutions to the problem of the blade "waste" do or do not lead to "sustainable decommissioning". The hope is that by better defining the different EOL solutions and their decommissioning pathways, a more rigorous research base for future studies of the wind blade EOL problem will be possible. This paper reviews the prior studies on wind blade EOL and divides them into a number of categories depending on the focus that the original authors chose for their EOL assessment. This paper also reviews the different methods chosen by researchers to predict the quantities of future blade waste and shows that depending on the choice of method, predictions can be different by orders of magnitude, which is not good as this can be exploited by unscrupulous parties. The paper then reviews what different researchers define as the "recycling" of wind blades and shows that depending on the definition, the percentage of how much material is actually recycled is vastly different, which is also not good and can be exploited by unscrupulous parties. Finally, using very recent proprietary data (December 2022), the paper illustrates how the different definitions and methods affect predictions on global EOL quantities and recycling rates.

Keywords: end-of-life; wind turbine blades; uncertainties; blade waste forecast; recycling

check for updates

Citation: Delaney, E.L.; Leahy, P.G.; McKinley, J.M.; Gentry, T.R.; Nagle, A.J.; Elberling, J.; Bank, L.C. Sustainability Implications of Current Approaches to End-of-Life of Wind Turbine Blades—A Review. *Sustainability* **2023**, *15*, 12557. https://doi.org/10.3390/su151612557

Academic Editor: Mohamed A. Mohamed

Received: 25 June 2023
Revised: 4 August 2023
Accepted: 15 August 2023
Published: 18 August 2023

1. Introduction

A typical wind turbine is designed for around 20 years of service meaning that many of the first-generation wind farms are at or approaching their end-of-life (EOL) stage. Approximately 85–90% of the wind turbine can be recycled including the tower, foundation and nacelle, which are made up of metals (steel, copper or aluminium) and concrete [1]. The blades, however, are composed of fibre-reinforced polymer (FRP) composite materials (including glass and carbon fibres, thermosetting polymers, epoxies and structural adhesives), core materials (including balsa wood and/or polymeric foams) and some metals such as steel, aluminium or copper [2–4]. This mix of materials presents a challenge for recycling and is energy-intensive to separate [5]. Until recently, the EOL stage was not considered a problem or priority, which resulted in a lack of industry guidelines and standard procedures for the removal and disposal of these blades when decommissioned [6,7]. Recent media have highlighted the growing concern as many of the blades are being sent to landfill sites across the US [8]. Current EOL technologies that may be considered are reuse, repurposing, recycling, recovery, co-processing, incineration or landfilling [9]. Some of these EOL technologies also require a continuous supply of material and therefore may be hindered by fluctuations and insufficient supplies [10]. Accurately predicting EOL blade material becomes a crucial aspect for the planning and development of sustainable circular strategies as well as to motivate governments and policy makers to take action to prevent a large build-up of blade materials [11]. Some EOL technologies are capital-intensive, and a lack of certainty in EOL blade material flow represents an investment risk for commercial processors. A number of journal and magazine articles have addressed the issue of blade waste material; however, there are still many uncertainties associated with the EOL material forecasts [12].

There are several variables that lead to significant uncertainty when forecasting the future EOL blade waste and recycling potential. The variables that need to be considered include: (1) The definition of end-of-life and how it impacts the wind turbine lifespan. (2) The estimation of current and future amounts of wind blade waste, including the timeframes for which blade waste predictions are made, the mass conversion factors, the location or geographical region in which a turbine reaches its EOL and the knowledge of how many blades have actually been decommissioned. (3) The recycling technology and potential material that can be "reused". Each of these variables will be explained in detail, and an assessment of how they impact the EOL blade material forecast will follow.

2. Defining End-of-Life and How It Impacts the Wind Turbine Lifespan

There is no clear definition of end-of-life (EOL) for wind turbine blades. There are several scenarios that EOL may refer to that are used by researchers in the field. In what follows below, the prior work published in a large number of research studies in the field is reviewed. The prior studies have been divided into different categories based on the focus of the study to try and develop a better understanding of the EOL issue.

The *Design End-of-Life* is the time in which the Original Equipment Manufacturer (OEM) advises a wind turbine blade has reached its design lifespan. A typical wind turbine blade is designed for 20 years in service with reference to structural safety levels [13]. Throughout the operational life, blades are exposed to extreme weather conditions and fatigue loading, which may result in wear-out and damage. Blades require frequent maintenance to ensure they last for their design life. As the blade ages, it becomes less efficient, and maintenance costs begin to increase. At this point, a wind farm owner may consider repowering or decommissioning the turbines or replacing the blades. Some wind farm owner-operators may continue to operate beyond the design life with a permit extension. This process may be complicated due to technical, economic and legal constraints, and may depend on the condition of the blades as they must have an adequate structural life remaining. Some OEMs now have lifetime extension programs for their turbines. Siemens Gamesa Renewable Energy (SGRE) aims to extend some of their turbine lifespans by 10 years, meaning turbines would operate for a total of 30 years [14]. General Electric (GE) has doubled the life expectancy of the GE 2.7–116 MW turbine model by promoting a 40-year lifetime certificate [15]. Other OEMs may also offer extension exercises, whereby the blades are modified to extend the life of the blade. These retrofits may include increased blade lengths or turbine upgrades to allow increased power outputs from the turbine [16]. In both these scenarios, the blade continues to serve its original purpose on the original turbine. Other factors such as planning permissions and land lease may also influence wind farm life extension. In most cases, wind farms have temporary planning consent for around 20–25 years; however, in some cases, planning consent is granted in perpetuity, allowing wind farms to operate beyond the typical expected lifespan [17].

The *Functional End-of-life* refers to when a wind turbine blade can no longer perform its key purpose on the original wind turbine due to in-service damage. Typically, this occurs before the design life is reached. [18]. This may result from manufacturing defects, extreme weather conditions (e.g., lightning strikes or intense rainfall), leading edge erosion, trailing edge erosion as well as other structural deterioration [19]. It is estimated that around 1–3% of blades are replaced annually as a result of extreme weather conditions [20].

The *Location End-of-Life* refers to when the wind turbines are dismantled, and undamaged blades with resale value are removed and sold on the second-hand market as spare parts or for re-instalment at a new location usually with less mature markets such as Latin America, Africa, India and Eastern Europe [7]. Due to a lack of infrastructure and high costs associated with acquiring the most up-to-date technologies, some countries face additional challenges in generating more sustainable power. Reconditioned wind turbines can provide an opportunity to reach the increasing demand for power in an affordable way due to the reduced investment costs [21]. The market for second-hand blades is mostly aimed at small-scale, older blade models with blade sizes (<50 m) and power capacities ranging from 50 kW to 1 MW [22]. This is because power grids are often less well developed, and therefore, modern turbines with a capacity larger than 1 MW are too technically advanced and often require specialist equipment, which may not be accessible in some countries [21,23]. Many turbines reaching these markets have been in operation for around 15 years with the possibility of an additional 10 years in operation at their new location. Blades need to be inspected, tested and repaired (if necessary) before they are shipped. This means that the EOL waste will be produced in another country and contributes to the uncertainties of EOL material forecasting due to the variation in the geographical and temporal blade quantities [24,25].

The *Economic End-of-Life* refers to the time when it becomes more economical to replace a wind turbine even when the service life is less than 20 years (i.e., repowering). Many wind farms are located in areas with prime wind resources, and due to the lower performance of the older turbine models, these valuable sites are not reaching their optimum energy yields [26]. Some wind farm operators may therefore decide to repower their wind farms with newer turbine models prior to the expected design lifetime with the aim to exploit the technology innovations and increase energy efficiency [27]. A study by Lantz et al. [28] reported that wind farm repowering becomes economically attractive after around 20 to 25 years in service; however, in some cases, it may be possible from 16 years in service. Factors such as wind resource availability, technological advancements, electricity wholesale market prices, whether owners are able to reuse existing infrastructure and the condition of the wind turbines all need to be considered. Himpler and Madlener [29] have found that the optimum time to repower based on the Danish fleet is when the cash revenues are double that of the investment costs. Their study suggests that this could take place after around 11 to 15 years in service. It has been argued that some wind farms can be repowered as early as 13 years based on around 10 years for payback and approximately 3 years for profit [30,31]. Research by Lacal-Arántegui et al. [32] found that in a Denmark wind farm, repowering occurred after around 15 to 18 years in service, and in Germany, around 15.9 years in service. It is clear that the best time for a wind farm to be repowered varies between different locations and wind farms.

The *Stockpiled End-of-Life* occurs when a decommissioning contractor decides to stockpile the blades with the hope that a more cost-effective alternative becomes available or when landfilling is not an option [33]. This option impacts the EOL blade material forecasts as it delays the stream of decommissioning blades. Repurposing and recycling developments are often hindered by the fluctuations and inconsistencies in annual blades volumes.

Stockpiling could provide a potential solution by storing the blades in years of excess material and for use in years with lower material [24]. A stockpiling strategy may be hindered by the cost or availability of adequate storage space, as well as the legal status of EOL blades if it is classified as "waste" rather than spare parts.

The *Abandonment End-of-Life* refers to when some of the older, first generation (1970s and 1980s) wind farms are no longer functioning and are abandoned in place. Evidence of this can be seen in the US with up to 4500 turbines littering the landscape in the Tehachapi region in California, US [34]. This is likely to result from the lack of laws and regulations enforcing developers to take responsibility. While conscientiously written leases state that all equipment and foundations should be removed and the land should be restored to the original condition, these were not always honoured as some companies declared bankruptcy before decommissioning was reached [35]. Additionally, some wind turbines are run-to-fail, meaning that they are left to continue running with little maintenance until the maintenance costs are more than the earnings or until the turbine is considered unsafe [32,36].

Depending on which category the EOL scenario falls into, the sustainability of the outcome differs greatly. In many of the categories listed above (Design EOL, Location EOL, Stockpiled EOL and Abandonment EOL), the wind blade does not actually get sent to a disposal method at the assumed EOL time (commonly assumed to be 20–25 years) at all, and it is incorrect to count these as immediate EOL quantities. The problem of stockpiling is ubiquitous and has other issues related to land use and sustainability and leads to community complaints. Blades are often stockpiled for many years and even decades in some cases, while owners (typically recyclers) wait for more palatable solutions than landfilling or incineration. Clearly, the problem of eventual disposal is still important in these cases, but their resolution is not immediate, and new technologies that could deliver a sustainable non-polluting processing and recycling of thermosetting polymers are emerging (to be discussed in the next section).

The category of the most immediate concern is that of Economic EOL. When a wind farm is repowered, and its older turbines are removed (in part or in whole), there is a tremendous time pressure to remove and dispose of the turbine parts (including the blades) as soon as possible. Wind farm owners typically enter into a contract with decommissioning contractors to "get rid of the turbines" in a short time and, in the past, have often not paid close attention to the details of where the blade material eventually ends up.

3. Estimating the Current and Future Amount of Wind Blade Waste

Many authors have provided estimates of the amount of wind blade waste that has been or will be generated in the future. However, it is very important to note that when comparing different estimates (or future predictions), the methods used to make these predictions can vary by orders of magnitude since the methods used to make these predictions can vary by multiples of each other due to the following factors.

3.1. The Time Horizon for Which End-of-Life Predictions Are Made

The target year for which EOL predictions are made varies depending on the study. Some studies calculate future blade material up to a target date based on the existing wind farm installations (referred to as "Method 1" herein). In this method, only the existing wind farms are included, and an assumed lifespan (usually of 20 to 25 years) is used to calculate the annual or cumulative blade material up to the target date. For example, if the baseline data include wind farm installations up to the end of 2019, then the expected target year for all the blades to decommission would be 2039, based on a 20-year service life [37]. This method does not consider the material that future wind farm installations contribute to the calculations.

Other studies may estimate material predictions using both the current material used in wind blades based on industry or official databases of existing wind farms (e.g., USGS, Wood Mackenzie and The Wind Power) and predict the future blade material used based on numerical or financial models of future wind farm installations acquired from industry or official predictions of future wind power growth (e.g., GWEC, IEA, AWEA (now ACP) and EWEA (now WindEurope) (referred to as "Method 2" herein). The current count and future predictions are added to give the total capacity of installed power, and hence, the number of blades produced or to be produced, which will eventually become waste by a target year. A common target year used for blade waste predictions is the year 2050. Given the prediction chosen, the scenario (typically high, medium or low growth) and the year the prediction was made, the future estimates can vary significantly.

Andersen et al. [38] estimates EOL blade material up to 2050 based on a 20-year lifespan and material predictions up to 2030. Liu and Barlow [18] estimate blade material across the four major wind energy markets (China, US, EU and the rest of the world) and calculate blade waste for onshore wind farms installed from 1998 to 2015, plus the material from future installations of wind turbines up to 2050. They forecast blade material up to 2050 while accounting for three lifetime scenarios (18, 20 and 25 years). Similar to this, Lichtenegger et al. [39] calculate blade material predictions in Europe up to 2050 based on current installations up to 2017 and future estimations up to 2050. Their study accounts for offshore and onshore blade waste and uses a stochastic lifespan. Cooperman et al. [40] conducted a US study and estimated blade waste up to 2050 based on a 20-year lifespan. They then examined the sensitivity of their predictions to alternative lifetime scenarios (20, 25 and 30 years). They also considered the potential volume contribution of blade waste in relation to landfill capacities, adding further complexities to EOL management. The volume of blade material, and not only the weight (mass), has a significant impact on landfill and transportation logistics.

Liu and Barlow [18], Lichtenegger et al. [39] and Cooperman et al. [40] also include in their estimates the material used to manufacture the blades (which is not primarily composite materials), the material used in the operation and maintenance (O&M) phase (including repairs or replacements due to damage) as well as the blades that are decommissioned annually. The additional waste material is typically taken as a percentage of the blade mass. The annual decommissioned quantity is typically taken as 1/20 (5%) of the annual number of blades installed [38].

Finally, some studies make blade waste material predictions for a target date based on a prediction of wind power at the target date (e.g., [41]) (referred to as "Method 3" herein). The predictions using this method will be higher compared to the previous methods since it is a count of all blades in existence at the target date, even though many blades will have already been decommissioned or will only become waste after the target date.

3.2. The Mass Conversion Factors

In addition to the uncertainty of how the waste prediction is made as described above, there is additional uncertainty on how to convert the installed capacity into mass of material (Table 1). The rated power output from a wind turbine is related to the rotor diameter, and therefore, blade material quantities are calculated using a mass-to-capacity ratio of tonnes per Megawatt (t/MW). Most authors assume that the total mass of the blade is considered as waste material. Albers et al. [42] estimate that approximately 1 MW of installed capacity equates to a mass of 10 tonnes of blade material, and that globally, there will be approximately 200 thousand tonnes annually in 2033. Andersen et al. [38] adopt this model; however, they estimate that there will be approximately 400 thousand tonnes annually between 2029 and 2033, increasing to nearly 800 thousand tonnes per year by 2050 based on future wind farm installations. The higher prediction compared to Albers is likely to result from the updated data on actual wind farm installations compared to the lower prediction of future installations from older papers.

Another study attempted to account for the development of wind turbine blades over the years and developed a varying model ranging from 8.43 to 13.41 t/MW [18]. Their study reveals that there will be approximately 500 thousand tonnes per year in 2029, increasing to two million tonnes per year by 2050 with a cumulative total of around

43.4 million tonnes. The work by Bank et al. [41] is in relatively close agreement with Liu and Barlow's study, with predictions of 39.8 million tonnes by 2050 based on a 10 t/MW ratio and using the Global Wind Energy Council (GWEC)'s future "moderate growth scenario" estimates of wind power installations (Method 3). Under the "advanced growth scenario" the cumulative global total would reach as much as 60 million tonnes by 2050 [43]. Another study by Jensen and Skelton [44] estimated the lower and upper limits of composite waste from blades using an estimate of 12 to 15 t/MW. Lichtenegger et al. [39] calculated 12.42 t/MW and estimated a total of 325 thousand tonnes by 2050 in Europe, with the majority coming from Germany.

To date, only a few studies have investigated blade material forecasts at a national scale [45]. Arias [46] developed a mass-to-capacity model of 11.3 t/MW (9.57 t/MW of composite material only) using the top 11 wind power states in the US and applied it to the remaining 39 states. Cooperman et al. [40] also conducted a country-level forecast for EOL blade material based on the US. Their study adopted the model of 8.43–13.41 from Liu and Barlow's study and estimated a cumulative total of around 2.2 million tonnes by 2050 and 3.3 million tonnes when accounting for manufacturing and replacement waste. An EPRI report adopted a 12.5 t/MW model and estimated the cumulative EOL blade waste material in 2050 to be around 2.1 million tonnes based on a 20-year service life [47]. In 2020, the EPRI presented additional blade waste projections for the US [5]. Based on Liu and Barlow's moderate case scenario, they estimated that blade material will reach a cumulative total of 4 million tonnes by 2050 (including manufacturing and in-service waste). Delaney et al. [37] conducted a study based on the Island of Ireland, predicting material quantities using specific masses for each turbine model. Where blade information could not be found, a model of 10.33 t/MW was determined and used to estimate the remaining masses. A total of 53,400 tonnes is expected by 2039 on the island. Rotor blade waste is quantified for Germany up to 2040 using a regression model based on the German wind turbine stock combined with a power-class-based estimation for missing data [48]. The study highlights the importance of characterising blade material by distinguishing between glass-fibre-reinforced plastics (GFRP) and glass with carbon-fibre-reinforced plastics (GFRP/CFRP), which require different recycling strategies.

These studies demonstrate how the mass-to-capacity ratio varies between different geographical regions and how it can affect estimates and predictions. It should also be noted that while blade mass is given in metric tons (1 tonne = 1000 kg = 2200 lb) throughout the world, in the US, the mass (or weight) of waste is given in US (short) tons (1 ton = 2000 lb), a 10% difference that is not insignificant.

Table 1. Summary of the existing literature for blade estimation models.

Site	Lifetime (Years)	Geographical Scale	Method (t/MW)	Future Installations Pleas (Y/N)	Installation Data Years	Target Year	Citation
Onshore	20	Global, Germany	10	Y	Up to 2006	2034	[42]
Both	20	Global	10	Y	2009–2013	2050	[38]
Both	20	Sweden		N		2034	[45]
Onshore	20	US	11.3 (9.57 composite material only	Y	2000–2015	2055	[46]
Both	18, 20, 25	Global, US, Europe, China	8.43–13.41	Y	1998–2014	2050	[18]
Both	20	Global	10	Y	2001–2016	2050	[41]
	20	Europe	12–15	N		2030	[44]

Table 1. *Cont.*

Site	Lifetime (Years)	Geographical Scale	Method (t/MW)	Future Installations Pleas (Y/N)	Installation Data Years	Target Year	Citation
Both	25	Global, Europe, Asia, US	10	Y	2010–2025	2050	[49]
Onshore	20	US	12.5	Y		2050	[47]
Both	16–18	Europe	12.42	Y	1995–2017	2050	[39]
Onshore	20	Ireland	10.33	N	1992–2019	2039	[37]
Both	15, 20, 25, 30	US	8.43–13.41	Y	1981–2020	2050	[40]
Both	20	Germany		N	1995–2020	2040	[48]

3.3. Geographical Locations

The geographical region or location in which a wind turbine reaches its EOL stage will impact the decommissioning process. Each country or region will have different policies, laws, incentives, availability of recycling technologies and economic factors which enable, restrict or encourage different processes for the management of FRP composite material waste. In the US, the landfilling of FRP composite materials is still permitted in most states; however, in the EU, pressures from directives and legislation encouraging more sustainable approaches to EOL blade management are taking effect. This has led to some nations such as Germany, the Netherlands, Austria and Finland to already prohibit the landfilling of composite waste materials [50–52]. Not much is known about policies regarding blade waste disposal in the rest of the world.

In places such as Ireland, lifetime extension exercises have taken place to encourage wind farm operation past 20 years, with some evidence of wind farms operating up to 30 years [37]. Some early wind farm developments were given interminable consent, and therefore, operators may decide to continue operating existing wind turbines and postpone repowering, as repowering would require seeking planning approval, which might not be forthcoming. Lifetime extension programmes have also been encouraged in some European regions such as Germany, Spain, Denmark and the UK [13].

3.4. Knowledge of How Many Blades Have Actually Been Decommissioned

The decommissioning of wind farms is still relatively new with limited data available in databases on how many wind farms have actually been decommissioned worldwide and what has happened with their blades. There are some well-known examples of where onshore wind farms have already been decommissioned and their blades landfilled, incinerated or even stockpiled [8]. To date, seven offshore wind farms are known to have been decommissioned [53].

4. Recycling Technologies and Potential Material That Can Be 'Reused'

A circular economy strategy for blade management involves the reuse of blade material in a new product. Before a waste management strategy is needed, the blades should be used and reused for as long as possible [1]. The reuse potential of wind blades depends on what reuse strategy is chosen as methods yield different amounts of reusable material [18].

The different EOL options for wind turbines blades can be assessed in terms of sustainability using the waste hierarchy. At the top of the hierarchy is the lifetime extension or reuse of the turbines at another site (see Section 2). Next on the waste hierarchy is blade repurposing, which involves the reuse of full blades or large sections of the blade in new industrial or architectural applications. Some examples of repurposing applications include pedestrian bridges (e.g., Blade Bridge along the Midleton-Youghal Greenway in County Cork, Ireland) [22,54,55], power transmission lines [56], children's playgrounds (e.g., Wikado playground, Rotterdam) [57], bicycle shelters (e.g., Aalborg Harbour) [58], affordable housing [41], among others [59]. Full blade repurposing implies that the entire blade will be reused in one or more applications and will therefore yield a 100% reuse potential. In this scenario, different sections of the blade (root, tip or mid-span) could be reused in different applications [60]. Several start-up companies have been launched to commercialize blade repurposing (e.g., Anmet (Szprotawa, Poland), BladeMade (Rotterdam, Netherlands), and BladeBridge (Cork, Ireland)). In some cases, if the second life application requires little processing, testing and fabrication, the blades may be cut and prepared directly on site before being transported to their new location [60].

After reuse and repurposing come material-scale recycling methods. There are three key types of recycling methods based on mechanical, chemical or thermal processes. Mechanical recycling refers to the shredding, cutting or grinding of the blade material, reducing it in size. This material may then be used as a replacement filler for concrete or as a reinforcement in plastics and other products [61–63]. Only 70–75% of the FRP composite material (15% is already discounted since it is not FRP material) can be reclaimed in this grinding process [64–66]. In some cases, the blades may be cut and shredded on site to reduce transportation costs [40]. This may be completed using a mobile waste grinding unit.

The fibres may be recovered through thermal or chemical recycling processes. In the case of thermal recycling such as pyrolysis or Fluidised Bed Combustion (FBC), high temperatures and pressures and vacuum may be used to recover the fibre materials. In the case of chemical recycling, the fibre materials are recovered from the resins using chemical solvents leaving behind the fibres. Co-processing, a form of material recycling, involves the substitution of blade material to replace virgin-mined materials such as clay, sand and limestone used to manufacture cement in a cement kiln. The polymeric materials in the blades provide energy recovery. This process yields a 50% recycling potential since only the fibre portion is recycled [12,67]. The energy recovered from burning the polymer is not considered material recycling however, it may contribute to life cycle assessment (LCA) benefits since many cement kilns are coal- or lignite-fired. While the European Composites Industry Association (EuCIA) encourages the co-processing of blade waste, not all countries have the ability to recycle using this method. There are very little data on which cement kilns are involved, except for a single Holicim plant in Lagerdorf, Germany and a single unidentified plant in Missouri, USA working in conjunction with Veolia [68,69]. This means that for companies in places such as the United Kingdom (UK) blades have to be transported, which can be expensive and energy-intensive [70].

Qureshi [71] provides an up-to-date review of the EOL options for FRP composite materials, including the strengths and limitations of each process in terms of energy demand and costs. The study shows that landfill and incineration are the most common and cheapest strategies for dealing with composite waste material; however, it is recognised that the composites industry needs to find more sustainable and circular practices such as reuse, repurposing and recycling. Beauson et al. [11] provide a review of the legislative and technical challenges of EOL blade management and composite material recycling. Coughlin et al. [5] and Fitzgerald et al. [72] provide estimates of costs and market potential of EOL processes. These factors further contribute to the uncertainties of EOL blade management. More recently, blade material passports [73] have been developed to document the material composition of specific blades with the aim to develop a standardised approach for blade disposal and aid potential recycling processes (e.g., Vestas (Arrhus, Denmark), Siemens Gamesa (Zamudio, Spain) and LM Wind Power (Kolding, Denmark)).

5. Methods and Data

This section aims to show how several key factors influence EOL blade material forecasts. To do this, the upper and lower bounds for the mass-to-capacity models (10 t/MW and 15 t/MW) are assessed against the varying wind turbine lifespans (15, 20 and 30 years). A global wind farm database containing wind farm data, number of turbines, installed capacity, turbine types and commission years was obtained from Wood Mackenzie [74].

At the time of analysis, 2022 was the last full year of data and is used as the cut-off year. The objective of this work is to demonstrate how each of the different factors influence the EOL blade predictions—the actual quantities are based on Method 1 (i.e., no future predictions of new wind farms were made). Quantities of blade material were assessed with breakdowns of each sub-region, including Europe (including the United Kingdom), the United States (US) and China. The global results include the three sub-regions noted above as well as the rest of the world.

Low, common and high scenarios are compared to show the extreme difference between the models. The low scenario refers to the blade mass model of 10 t/MW and the longest blade lifespan of 30 years. The common scenario refers to the 10 t/MW and 20-year lifespan, and the high scenario refers to the highest blade model of 15 t/MW and the shortest lifespan of 15 years.

The amount of material that can be diverted from landfill through reuse strategies are then assessed and compared for the following categories:

Full repurposing: This scenario is based on the full blade being reused in secondary applications (this may include the full blade being reused in one application or sections of the blade being reused in multiple applications), therefore yielding a 100% reuse of the total blade material since the mass of metals, copper and core materials (totalling 15% of the total blade mass) do not need to be removed.

Particles and Filler (mechanical recycling): This scenario yields a 70% reuse of the FRP composite material (which constitutes 85% of the reported total blade mass).

Fibre reuse (co-processing, solvolysis or pyrolysis): This scenario refers to the recovery of the fibre material in the blades. This scenario yields around a 50% reuse of the FRP composite material as only the fibre content in the blade is reused. In the case of the co-processing scenario, only the fibre content in the blade is reused in the cement kiln.

6. Results and Discussion

Based on the data from the Wood Mackenzie [74] database, the Global installed capacity of wind energy reached 864 GW by the end of 2022 (Figure 1). Small wind energy projects began as far back as the 1970s; however, it is likely that many of these were from experimental turbines funded as part of governmental programmes that took place in countries such as the US, Sweden, Germany and the UK due to the increasing oil prices [75]. Wind power began to take off in the 1980s, and at this time, wind farms were being installed in California as part of financial support schemes [75]. The development of commercial wind farm projects continued throughout the 1990s with Europe contributing to the largest proportions of wind farm installations followed by the US. In 2010, China surpassed the US as the single largest contributor to wind farm installations, and in 2016, overtook Europe, becoming the greatest contributor to wind energy installations globally.

Based on the 'common scenario' of 10 t/MW and a 20-year service life, an estimate of around 8.6 million tonnes of blade material will be expected by 2042 globally. Out of this, China contributes to around 40% of the total EOL blade material, followed by the EU at 24%, the US with 18% and the remaining 19% from the rest of the world (Figure 1).

By the end of 2022, around 313 thousand tonnes of blade material are expected to have decommissioned with nearly 74% of this coming from Europe (Figure 2). Between 2023 and 2027, almost 627 thousand tonnes of blade material are expected to be decommission with Europe contributing to the largest proportion. Between 2028 and 2032, around 1.9 million tonnes of blade material are expected. Between 2033 and 2037, nearly 2.4 million tonnes will be generated globally with the largest portion of this coming from China at 36%. In the final decommissioning phase between 2038 and 2042, just almost 3.4 million tonnes of blade material will be expected. During this phase, China contributes to nearly half this material at 48%.

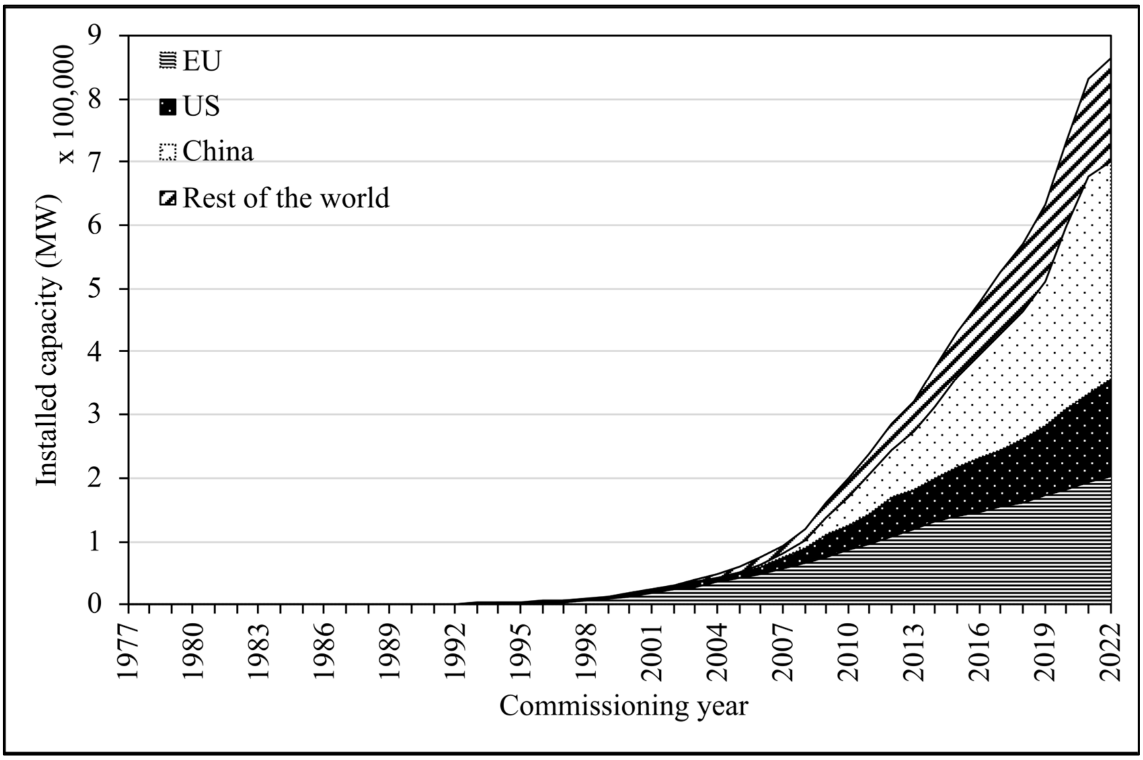

Figure 1. Cumulative wind farm installations with breakdowns for the EU, US, China and the remainder of the world. (Data source: Wood Mackenzie [74]).

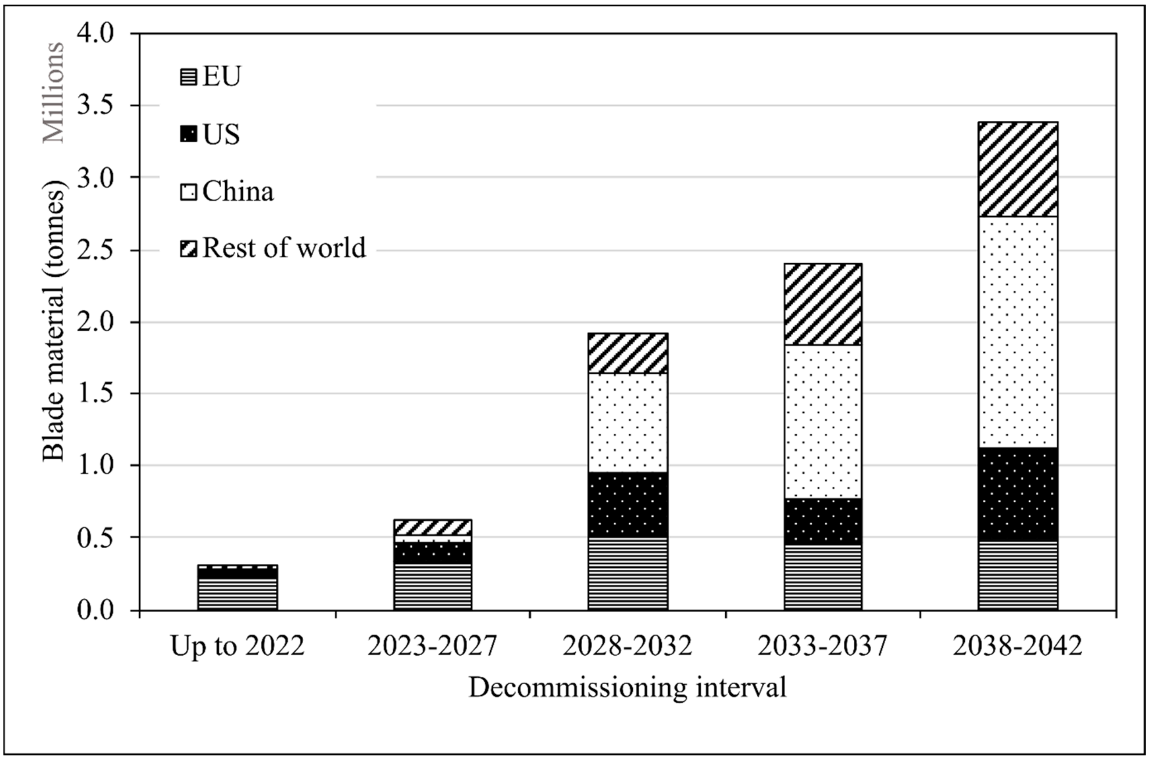

Figure 2. Total end-of-life blade material quantities for each decommissioning interval based on a 20-year service and a fixed 10 t/MW scenario. This graph includes breakdowns for sub regions (EU, US, China and the rest of the world. (Data source: Wood Mackenzie [74]).

Based on a 20-year service life scenario, between 313 and nearly 470 thousand tonnes of blade material are expected to have already decommissioned by the end of 2022 globally (Figure 3a,b). The annual EOL blade material continues to increase up to 2033, where it then experiences a reduction in blade material. This is likely to reflect the market where fewer wind farms were installed in 2013 compared to previous years [76]. The year 2041 will experience the highest EOL material quantities, followed closely by 2040. Again, this is likely to reflect the strong wind power market, with China contributing to the largest proportion of installations during these years.

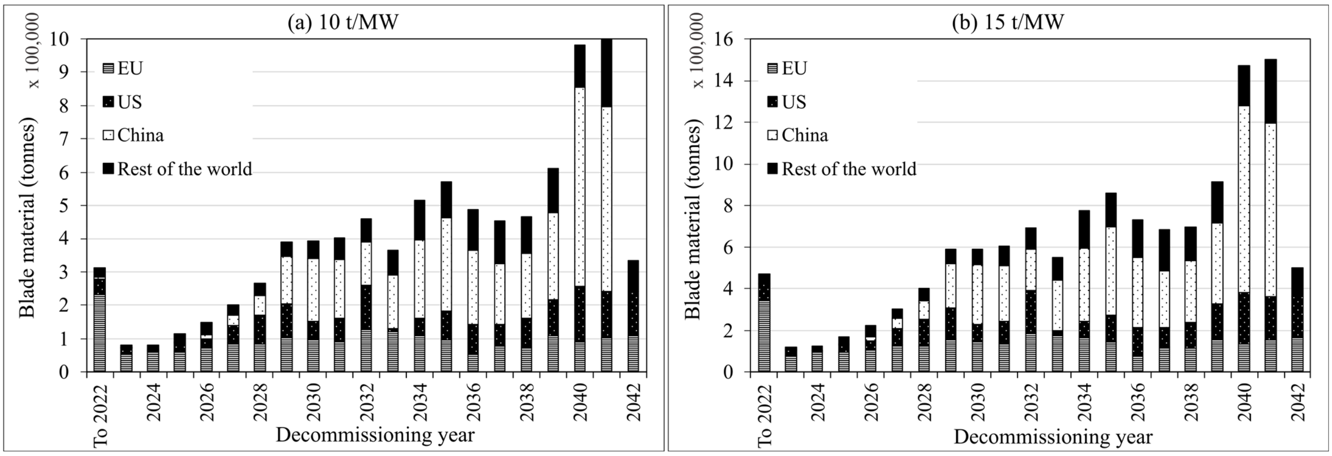

Figure 3. Global annual blade EOL material quantities with breakdowns for sub-regions (EU, US and China) based on a 20-year service life. (**a**) Based on 10 t/MW; (**b**) based on a 15 t/MW model (Data source: Wood Mackenzie [74]).

The sensitivities of the cumulative EOL blade material quantities for global, the EU, US and China are compared for the low (10 t/MW) and high (15 t/MW) mass models while also accounting for constant 15-, 20- and 30-year lifespans (Figure 4a–d). These graphs enable the extreme case scenarios to be compared to show the large scale of uncertainty between the different blade modelling methods. Under the highest scenario (15-year, 15 t/MW), globally, all blades installed up to the end of 2022 will be expecting to have decommissioned by the end of 2037, contributing to nearly 13 million tonnes (Figure 4a). Under the lowest scenario (30-year, 10 t/MW), blades will not expect to decommission until around 2052 and will contribute to 8.6 million tonnes.

Using the common scenario, an assessment of the potential material that can be diverted from landfill is provided for Global material including breakdowns for the EU, US and China (Figure 5a–d). If all material is disposed of through landfill or incineration processes, a 0% reuse potential for the FRP composite material will be achieved. If all material is repurposed in a second-life application, the full 8.6 million tonnes of blade material can be diverted from landfill globally, compared to just under 6 million diverted through mechanical recycling (particles and filler) and 4.3 million tonnes from fibre reuse.

It is also important to gain an understanding not only of the amount of blade material by weight but also the actual number of turbines (and associated blades). Table 2 provides a summary of the cumulative number of blades for each service life with breakdowns for the sub-regions. Based on a 20-year service life, nearly 168 thousand blades (29 thousand turbines) globally should have reached their EOL stage by the end of 2022, with 98 thousand from the EU, just under 43.5 thousand from the US and just under 2500 from China.

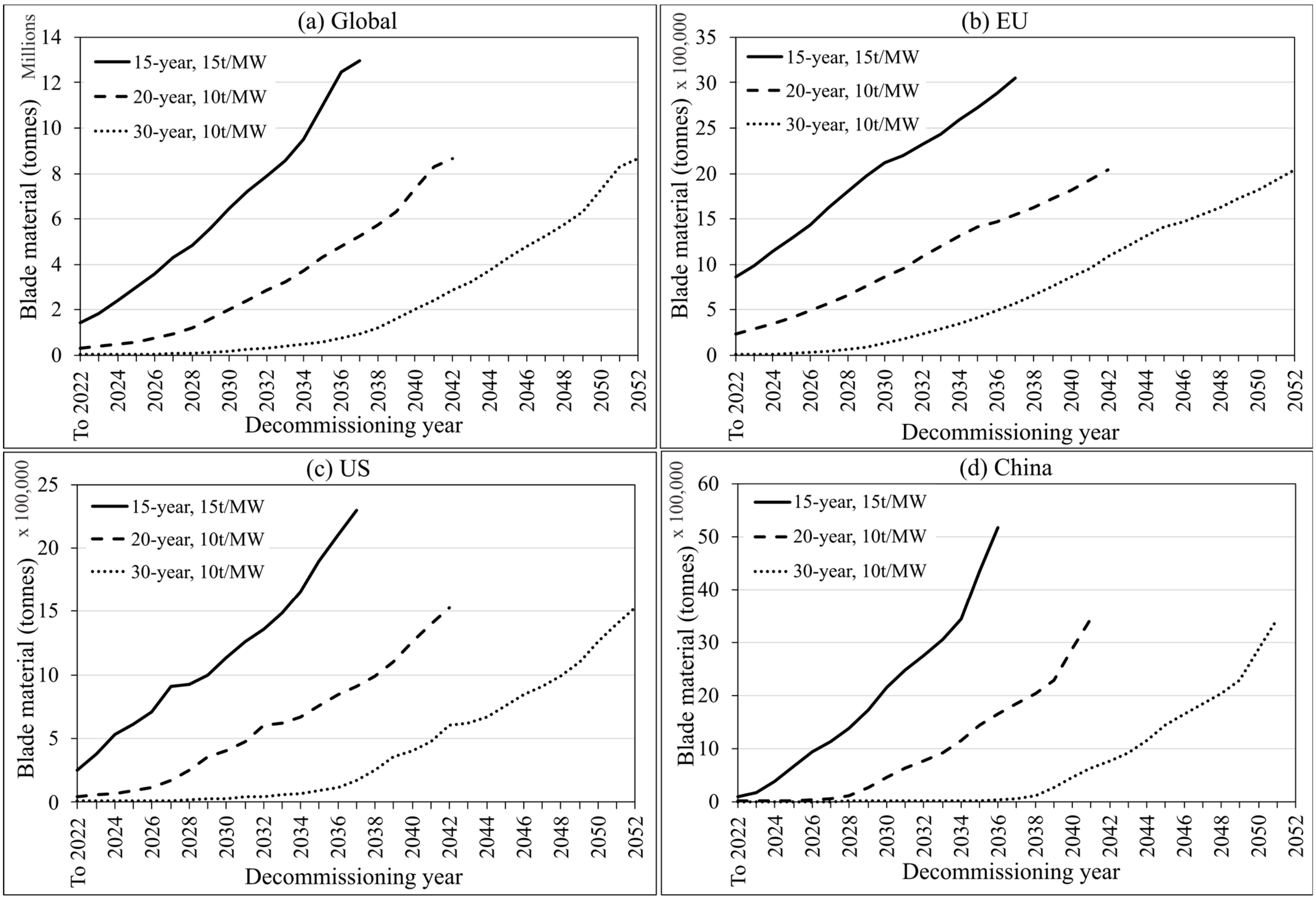

Figure 4. Sensitivities of EOL blade material predictions for the high, common and low scenario for (**a**) global, (**b**) EU, (**c**) US and (**d**) China based on blades installed up to the end of 2022 (Data source: Wood Mackenzie [74]).

Table 2. Cumulative number of blades that would be decommissioned for each service life with breakdowns for global and sub-regions (EU, US and China) (Data source: Wood Mackenzie [74]). (Based on the assumption that turbines have three blades).

Decommissioning Year	Lifespan				Known to Have Been Decommissioned by 2022
	15	20	25	30	
Global (Inc. EU, US and China)					
Up to 2022	310,907	167,793	80,340	42,939	55,765
2027	660,222	310,907	167,793	80,340	
2032	975,656	660,222	310,907	167,793	
2037	1,285,668	975,656	660,222	310,907	
2042		1,285,668	975,656	660,222	
2047			1,285,668	975,656	
2052				1,285,668	

Table 2. *Cont.*

Decommissioning Year	Lifespan				Known to Have Been Decommissioned by 2022
	15	20	25	30	
EU (inc. UK)					
Up to 2022	166,370	98,055	35,616	13,311	23,755
2027	241,518	166,370	98,055	35,616	
2032	297,247	241,518	166,370	98,055	
2037	332,371	297,247	241,518	166,370	
2042		332,371	297,247	241,518	
2047			332,371	297,247	
2052				332,371	
US					
Up to 2022	67,293	43,533	31,671	29,352	29,637
2027	139,824	67,293	43,533	31,671	
2032	182,340	139,824	67,293	43,533	
2037	246,755	182,340	139,824	67,293	
2042		246,755	182,340	139,824	
2047			246,755	182,340	
2052				246,755	
China					
Up to 2022	18,441	2484	990	93	1062
2027	160,890	18,441	2484	990	
2032	295,383	160,890	18,441	2484	
2037	442,918	295,383	160,890	18,441	
2042		442,918	295,383	160,890	
2047			442,918	295,383	
2052				442,918	

By the end of 2022, around 55,765 blades are known to have been decommissioned as reported in the Wood Mackenzie database, which is significantly less than expected based on the common scenario. Based on the data reported it appears that blades that have already been decommissioned (up to 2022) have been in service between 25 and 30 years. The accuracy of this prediction, however, is still unclear due the lack of detailed data on decommissioning and other cases resulting from some wind farms being run-to-fail and others being abandoned. No data is available on the breakdown in quantities (up to 2022) sent either for disposal (landfill or incineration) or to the different recycling categories shown in Figure 5, and therefore, no comparisons with predictions can be made.

Additional uncertainties may also impact EOL material forecasting. CFRP has been used to a limited extent in blades with the aim to reduce weight while maintaining the strength [77]. Carbon fibre has a higher commercial value compared to glass fibre and, therefore, recycling strategies which separate the fibres from the matrix are preferred for carbon fibre [78].

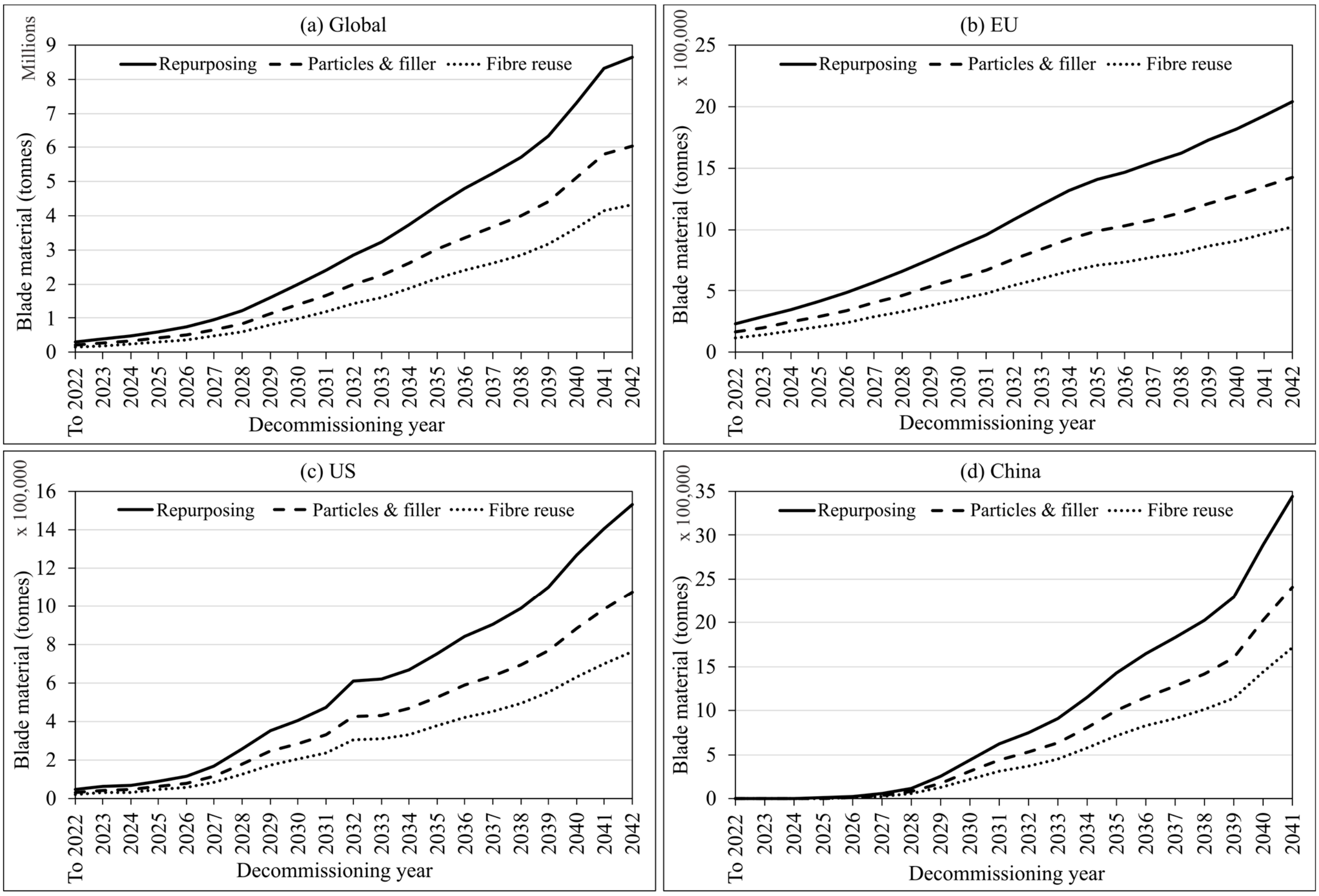

Figure 5. The quantities of blade material that can be diverted from landfill through repurposing and recycling scenarios based on the common scenario for (**a**) global, (**b**) EU (including UK), (**c**) US and (**d**) China. Global values include the EU, US and China (Data source: Wood Mackenzie [74]).

It has been found in previous research studies that when comparing and cross-referencing different data sources, there are often discrepancies between some of the data [37]. Any uncertainties caused by inaccurately entered data will therefore propagate into the results of the analysis. Better quality data will support good decisions for end-of-life wind turbine blades. There is a clear need for the sharing of data in a controlled way to enable better EOL predictions to be made for the planning and development of EOL management strategies. As mentioned previously, each country will face different laws, regulations, costs and incentives which will impact the EOL blade predictions and management practices. This study has demonstrated how the different methods highlighted in the literature contribute to uncertainties in blade waste predictions. Moving forward, the authors suggest that 'method 2' provides a good indication for estimating future EOL blade material. The authors believe that this method should be modified to only include EOL blade waste material rather than manufacturing and in-service waste. To gain a more accurate understanding of the EOL blade landscape, it is also necessary to develop an up-to-date accurate country-level Geographical Information Systems (GIS)-based model. This would enable a more detailed local level decommissioning plan to be established, accounting for the different parameters that impact each country or region. There is a need to develop a parameterised life cycle model considering technical, temporal and geographical factors, which can be tailored for project specific wind turbine characteristics for the assessment of environmental performance and carbon footprints [79].

Overall, the sustained development in wind energy over the last few decades has largely been driven by the need to reduce greenhouse gas emissions to help achieve climate targets. This global growth in wind farms is continuing to contribute towards the United Nations (UN) Sustainable Development Goal (SDG) 7, which encourages access to sustainable energy for all as well as SDG 13 which aims to address climate change and its impacts [80]. As many of the wind farms from the first installations proceed towards their EOL stage, the wind industry is faced with a major challenge regarding blade decommissioning and waste disposal. There is a clear need to develop circular management practices for blades to ensure wind energy remains as sustainable as possible. Circular practices such as reuse and recycling provide an opportunity to reduce waste as well as the demand for raw materials. The development of these strategies for EOL blades also contributes toward SDG 12, which encourages responsible consumption and production. Management plans will need to be in place by the time a farm reaches its EOL to ensure blade removal is not delayed, particularly in cases where farms are being repowered. The repowering of a site at the EOL provides an opportunity to not only maximise energy production through the installation of more efficient turbines but also prevents the loss of installed capacity from the decommissioning process. Understanding the EOL blade landscape can help policy makers, local governments and the wind industry to develop plans accordingly.

7. Conclusions

Gaining an accurate depiction of the EOL blade landscape is a critical aspect for policy makers, local governments, the wind industry and the waste processing industry for planning and preparing waste management strategies. This paper identifies and discusses the factors that contribute to significant uncertainty when forecasting EOL blade waste material. First, an understanding of what is meant by "end-of-life" is presented with different scenarios impacting the wind turbine lifespan (e.g., lifetime extension, blade damage or breakage, relocation through the second-hand market, early repowering, stockpiling or abandoning). While a typical wind turbine lifespan is assumed to be around 20 years, these factors result in sensitivities ranging from 15 to 30 years.

Various methods for estimating current and future quantities of EOL blade material are then discussed, including the timeframes for which blade material predictions are made, the mass conversion factors, the geographical location in which the turbine reaches its EOL and the lack of data on how many blades have actually been decommissioned. A review of the existing literature suggests that there is no clear agreement on the best approach to take. Some studies determine future material quantities based on the current wind farm installations and a set lifespan. Other studies account for EOL blade material based on current installations as well as predictions based on future installations up to 2050 and/or the consideration of additional waste material from blade manufacturing and in-services activities. Typically, blade material quantities are calculated based on a mass-to-capacity conversion factor; however, estimates vary from around 10 t/MW to 15 t/MW. The variations between the different lifespans, timeframes and conversation models all contribute to levels of uncertainty in blade material predictions.

There are a lack of data and publications on how many wind blades have actually been decommissioned, with little known about what has happened to them. Evidence from the media suggests that many have been sent to landfill sites or are stockpiled in the US; this, however, is unlikely to remain a viable pathway in the future. The strong reuse potential and the increasing emphasis of circular economy strategies are all likely to encourage alternative management practices.

The different EOL management strategies such as repurposing, recycling, recovery and landfill are all discussed in terms of how much material can be "reused" and according to their position in the waste hierarchy. Using the Wood Mackenzie (2023) database of wind farm installations up to the end of 2022, this paper provides an analysis of the global blade material with breakdowns for the key wind energy markets including the EU, US and China. The sensitivities of the blade material predictions to the different blade models (10 t/MW and 15 t/MW) and the different blade lifespans (15, 20 and 30) are compared to demonstrate the wide range of uncertainty. The amount of material that can be diverted from landfill and reused through repurposing (100%) or recycling applications such as particles and filler (70%) and fibre reuse (50%) are also analysed. The results reveal a wide range of uncertainty between all scenarios and highlights the need for more accurate models to be developed. Under the common scenario, it is expected that nearly 168 thousand blades should have been decommissioned by the end of 2022, contributing to just over 313 thousand tonnes of FRP material. The reality of this, however, is unknown. This research highlights the lack of standards across the industry for recording and preparing for EOL blade management.

Overall, it is clear that there is a high level of uncertainty when predicting EOL blade material. Understanding the EOL blade landscape will become a critical part for the development of management plans, highlighting the need to track, understand and accurately predict EOL blade material. To do this, a country-wide, high-resolution Geographical Information System (GIS)-based standardised model could be developed, incorporating local plans for blade decommissioning.

Author Contributions: Conceptualisation, L.C.B., P.G.L., E.L.D., J.M.M. and T.R.G.; methodology, L.C.B.; formal analysis, E.L.D.; data curation, J.E. and E.L.D.; writing—original draft preparation, E.L.D.; writing—review and editing, L.C.B., P.G.L., J.M.M., T.R.G., J.E. and A.J.N.; supervision, L.C.B. and J.M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by the Department for the Economy (DfE), Grant USI-116; by the Science Foundation Ireland, Grant 16/US/3334; and by the U.S. National Science Foundation, Grants 1701413 and 1701694, under the project "Re-Wind".

Data Availability Statement: No new data were created in this research.

Acknowledgments: The authors thank the Re-Wind Network for the support in this research (www.re-wind.info).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. *Accelerating Wind Turbine Blade Circularity*; WindEurope: Brussels, Belgium, 2020. Available online: https://windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Accelerating-wind-turbine-blade-circularity.pdf (accessed on 24 June 2023).
2. Fingersh, L.; Hand, M.; Laxson, A. *Wind Turbine Design Cost and Scaling Model: Report No. NREL/TP-500-40566*; National Renewable Energy Laboratory (NREL), US Department of Energy: Golden, CO, USA, 2006.
3. Nagle, A.J.; Delaney, E.L.; Bank, L.C.; Leahy, P.G. A Comparative Life Cycle Assessment between landfilling and Co-Processing of waste from decommissioned Irish wind turbine blades. *J. Clean. Prod.* **2020**, *277*, 123321. [CrossRef]
4. Geiger, R.; Hannan, Y.; Travia, W.; Naboni, R.; Schlette, C. Composite wind turbine blade recycling—Value creation through Industry 4.0 to enable circularity in repurposing of composites. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *942*, 012016. [CrossRef]
5. Coughlin, D.; Stevenson, P.; Zimmerman, L.B. *Wind Turbine Blade Recycling: Preliminary Assessment*; Electric Power Research Institute (EPRI): Palo Alto, CA, USA, 2020; p. 3002017711. Available online: https://www.epri.com/research/products/000000003002017711 (accessed on 3 January 2023).
6. Ortegon, K.; Nies, L.F.; Sutherland, J.W. Preparing for end of service life of wind turbines. *J. Clean. Prod.* **2013**, *39*, 191–199. [CrossRef]
7. Sakellariou, N. Current and potential decommissioning scenarios for end-of-life composite wind blades. *Energy Syst.* **2018**, *9*, 981–1023. [CrossRef]
8. Martin, C. Wind Turbine Blades Can't Be Recycled, so They're Piling up in Landfill. Bloomberg. Available online: https://www.bloomberg.com/news/features/2020-02-05/wind-turbine-blades-can-t-be-recycled-so-they-re-piling-up-in-landfills (accessed on 27 December 2022).
9. Diez-Cañamero, B.; Manuel, F.; Mendoza, J. Circular economy performance and carbon footprint of wind turbine blade waste management alternatives. *Waste Manag.* **2023**, *164*, 94–105. [CrossRef] [PubMed]
10. Larsen, K. Recycling wind turbine blades. *Renew. Energy Focus* **2009**, *9*, 70–73. [CrossRef]
11. Beauson, J.; Laurent, A.; Rudolph, D.P.; Pagh Jensen, J. The complex end-of-life of wind turbine blades: A review of the European context. *Renew. Sustain. Energy Rev.* **2022**, *155*, 111847. [CrossRef]
12. Bank, L.C.; Delaney, E.L.; McKinley, J.M.; Gentry, R.; Leahy, P.G. Defining the landscape for wind blades at the end of service life. *Compos. World* **2021**, *7*, 6–9.
13. Ziegler, L.; Gonzalez, E.; Rubert, T.; Smolka, U.; Melero, J.J. Lifetime extension of onshore wind turbines: A review covering Germany, Spain, Denmark, and the UK. *Renew. Sustain. Energy Rev.* **2018**, *82*, 1261–1271. [CrossRef]

14. Siemens Gamesa Renewable Energy (SGRE). *Life Extension*; SGRE: Zamudio, Spain, 2018. Available online: https://www.siemensgamesa.com/products-and-services/service-wind/life-extension (accessed on 24 June 2023).
15. General Electric (GE). TÜV NORD and GE Renewable Energy Announce first Design Conformity Statement for Wind Turbines with a Lifetime of 40 Years | GE News. Available online: https://www.ge.com/news/press-releases/t%C3%BCv-nord-and-ge-renewable-energy-announce-first-design-conformity-statement-wind (accessed on 19 August 2022).
16. Rosemeier, M.; Saathoff, M. Assessment of a rotor blade extension retrofit as a supplement to the lifetime extension of wind turbines. *Wind Energy Sci.* **2020**, *5*, 897–909. [CrossRef]
17. Windemer, R. Considering time in land use planning: An assessment of end-of-life decision making for commercially managed onshore wind schemes. *Land Use Policy* **2019**, *87*, 104024. [CrossRef]
18. Liu, P.; Barlow, C.Y. Wind turbine blade waste in 2050. *Waste Manag.* **2017**, *62*, 229–240. [CrossRef] [PubMed]
19. Du, Y.; Zhou, S.; Jing, X.; Peng, Y.; Wu, H.; Kwok, N. Damage detection techniques for wind turbine blades: A review. *Mech. Syst. Signal Process.* **2020**, *141*, 106445. [CrossRef]
20. Mishnaevsky, L.; Thomsen, K. Costs of repair of wind turbine blades: Influence of technology aspects. *Wind. Energy* **2020**, *23*, 2247–2255. [CrossRef]
21. Cinar, S. Sustainable reverse logistic network design for end-of-life use-case study. *RAIRO Oper. Res.* **2021**, *55*, S503–S521. [CrossRef]
22. Beauson, J.; Brøndsted, P. Wind turbine blades: An end of life perspective. In *MARE-WINT: New Materials and Reliability in Offshore Wind Turbine Technology*; Ostachowicz, W., McGugan, M., Schröder-Hinrichs, J.-U., Luczak, M., Eds.; Springer International Publishing: Berlin, Germany, 2016; pp. 421–432. [CrossRef]
23. Albers, H.; Germer, F.; Wulf, K. Status Quo and Current Challenges in Recycling and Dismantling Wind Turbines. In *Breaking & Sifting—Expert Exchange on the End-of-Life of Wind Turbines*; Bönisch, B., Ed.; Onshore Wind Energy Agency: Berlin, Germany, 2018; pp. 3–7. Available online: https://www.fachagentur-windenergie.de/fileadmin/files/Veroeffentlichungen/FA-Wind_Breaking_Sifting_englisch.pdf (accessed on 24 June 2023).
24. Tota-Maharaj, K.; McMahon, A. Resource and waste quantification scenarios for wind turbine decommissioning in the United Kingdom. *Waste Dispos. Sustain. Energy* **2020**, *3*, 117–144. [CrossRef]
25. Sommer, V.; Stockschläder, J.; Walther, G. Estimation of glass and carbon fiber reinforced plastic waste from end-of-life rotor blades of wind power plants within the European Union. *Waste Manag.* **2020**, *115*, 83–94. [CrossRef]
26. Martínez, E.; Latorre-Biel, J.I.; Jiménez, E.; Sanz, F.; Blanco, J. Life cycle assessment of a wind farm repowering process. *Renew. Sustain. Energy Rev.* **2018**, *93*, 260–271. [CrossRef]
27. Staffell, I.; Green, R. How does wind farm performance decline with age? *Renew. Energy* **2014**, *66*, 775–786. [CrossRef]
28. Lantz, E.; Leventhal, M.; Baring-Gould, I. *Wind Power Project Repowering: Financial Feasibility, Decision Drivers, and Supply Chain Effects (NREL/TP-6A20-60535)*; National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2013. [CrossRef]
29. Himpler, S.; Madlener, R. *Repowering of Wind Turbines: Economics and Optimal Timing*; FCN Working Paper No. 19/2011; Elsevier: Rochester, MN, USA, 2012. [CrossRef]
30. Colmenar-Santos, A.; Campíñez-Romero, S.; Pérez-Molina, C.; Mur-Pérez, F. Repowering: An actual possibility for wind energy in Spain in a new scenario without feed-in-tariffs. *Renew. Sustain. Energy Rev.* **2015**, *41*, 319–337. [CrossRef]
31. de Bona, J.C.; Ferreira, J.C.E.; Ordoñez Duran, J.F. Analysis of scenarios for repowering wind farms in Brazil. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110197. [CrossRef]
32. Lacal-Arántegui, R.; Uihlein, A.; Yusta, J.M. Technology effects in repowering wind turbines. *Wind. Energy* **2020**, *23*, 660–675. [CrossRef]
33. Simpson, K. Most Used Wind Turbine Blades End up in Landfills. Colorado Is Part of the Push to Make the Industry Greener. The Colorado Sun. Available online: https://coloradosun.com/2020/02/26/wind-turbine-blades-colorado-landfills/ (accessed on 24 June 2023).
34. Stripling, W. Wind Energy's Dirty Word: Decommissioning. *Tex. Law. Rev.* **2016**, *95*, 123–151.
35. Conaway, J. Be Aggressive with Wind Energy: Blow Away the Decommissioning Fears. *Oil Gas Nat. Resour. Energy J.* **2017**, *2*, 621.
36. Madlener, R.; Glensk, B.; Gläsel, L. Optimal Timing of Onshore Wind Repowering in Germany under Policy Regime Changes: A Real Options Analysis. *Energies* **2019**, *12*, 4703. [CrossRef]
37. Delaney, E.L.; McKinley, J.M.; Megarry, W.; Graham, C.; Leahy, P.G.; Bank, L.C.; Gentry, R. An integrated geospatial approach for repurposing wind turbine blades. *Resour. Conserv. Recycl.* **2021**, *170*, 105601. [CrossRef]
38. Andersen, P.D.; Bonou, A.; Beauson, J.; Brøndsted, P. *Recycling of wind turbines, In DTU International Energy Report 2014: Wind Energy—Drivers and Barriers for Higher Shares of Wind in the Global Power Generation Mix*; Larsen, H.H., Sønderberg Petersen, L., Eds.; Technical University of Denmark (DTU): Lyngby, Denmark, 2014; pp. 91–97.
39. Lichtenegger, G.; Rentizelas, A.A.; Trivyza, N.; Siegl, S. Offshore and onshore wind turbine blade waste material forecast at a regional level in Europe until 2050. *Waste Manag.* **2020**, *106*, 120–131. [CrossRef]
40. Cooperman, A.; Eberle, A.; Lantz, E. Wind turbine blade material in the United States: Quantities, costs, and end-of-life options. *Resour. Conserv. Recycl.* **2021**, *168*, 105439. [CrossRef]
41. Bank, L.; Arias, F.; Yazdanbakhsh, A.; Gentry, T.; Al-Haddad, T.; Chen, J.-F.; Morrow, R. Concepts for Reusing Composite Materials from Decommissioned Wind Turbine Blades in Affordable Housing. *Recycling* **2018**, *3*, 3. [CrossRef]

42. Albers, H.; Greiner, S.; Seifert, H.; Kuehne, U. Recycling of wind turbine rotor blades. Fact or fiction? *DEWI-Magazin* **2009**, *34*, 32–41.
43. GWEC (Global Wind Energy Council). Global Wind Energy Outlook 2016. Available online: https://gwec.net/wp-content/uploads/2020/12/GWEO_2016.pdf (accessed on 14 August 2023).
44. Jensen, J.P.; Skelton, K. Wind turbine blade recycling: Experiences, challenges and possibilities in a circular economy. *Renew. Sustain. Energy Rev.* **2018**, *97*, 165–176. [CrossRef]
45. Andersen, N.; Eriksson, O.; Hillman, K.; Wallhagen, M. Wind Turbines' End-of-Life: Quantification and Characterisation of Future Waste Materials on a National Level. *Energies* **2016**, *9*, 999. [CrossRef]
46. Arias, F. Assessment of Present/Future Decommissioned Wind Blade Fiber-Reinforced Composite Material in the United States. Masters Thesis, City College of New York, New York, NY, USA, 2016.
47. *End-of-Life Disposal and Recycling Options for Wind Turbine Blades*; Electric Power Research Institute (EPRI): Palo Alto, CA, USA, 2018. Available online: https://www.epri.com/research/products/000000003002012240 (accessed on 24 June 2023).
48. Volk, R.; Stallkamp, C.; Herbst, M.; Schultmann, F. Regional rotor blade waste quantification in Germany until 2040. *Resour. Conserv. Recycl.* **2021**, *172*, 105667. [CrossRef]
49. Lefeuvre, A.; Garnier, S.; Jacquemin, L.; Pillain, B.; Sonnemann, G. Anticipating in-use stocks of carbon fibre reinforced polymers and related waste generated by the wind power sector until 2050. *Resour. Conserv. Recycl.* **2019**, *141*, 30–39. [CrossRef]
50. Correia, J.R.; Almeida, N.M.; Figueira, J.R. Recycling of FRP composites: Reusing fine GFRP waste in concrete mixtures. *J. Clean. Prod.* **2011**, *19*, 1745–1753. [CrossRef]
51. *End-of-Life Management of Fibre Reinforced Plastic Vessels: Alternatives to at Sea Disposal*; Office for the London Convention/Protocol and Ocean Affairs, International Maritime Organization (IMO): London, UK, 2019. Available online: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fibre%20Reinforced%20Plastics%20final%20report.pdf (accessed on 24 June 2023).
52. Job, S.; Leeke, G.; Mativenga, P.T.; Oliveux, G.; Pickering, S.; Shuaib, N.A. *Composite Recycling: Where Are We Now?* Composites UK: Berkhamsted, UK, 2016.
53. Shafiee, M.; Adedipe, T. Offshore wind decommissioning: An assessment of the risk of operations. *Int. J. Sustain. Energy* **2022**, *41*, 1057–1083. [CrossRef]
54. Ruane, K.; Zhang, Z.; Nagle, A.; Huynh, A.; Alshannaq, A.; McDonald, A.; Leahy, P.; Soutsos, M.; McKinley, J.; Gentry, R.; et al. Material and Structural Characterization of a Wind Turbine Blade for Use as a Bridge Girder. *Transp. Res. Rec. J. Transp. Res. Board* **2022**, *2676*, 354–362. [CrossRef]
55. Ruane, K.; Soutsos, M.; Huynh, A.; Zhang, Z.; Nagle, A.; McDonald, K.; Gentry, T.R.; Leahy, P.; Bank, L.C. Construction and Cost Analysis of BladeBridges Made from Decommissioned FRP Wind Turbine Blades. *Sustainability* **2023**, *15*, 3366. [CrossRef]
56. Alshannaq, A.A.; Bank, L.C.; Scott, D.W.; Gentry, R. A Decommissioned Wind Blade as a Second-Life Construction Material for a Transmission Pole. *Constr. Mater.* **2021**, *1*, 95–104. [CrossRef]
57. *Blade Made Playgrounds*; Superuse Studios: Rotterdam, The Netherlands, 2009. Available online: https://www.superuse-studios.com/projectplus/blade-made/ (accessed on 24 June 2023).
58. Eilers, H. Wind Turbine Wing Gets New Life at the Port of Aalborg. Energy Supply. Available online: https://www.energy-supply.dk/article/view/699757/vindmollevinge_far_nyt_liv_pa_aalborg_havn (accessed on 20 July 2022).
59. Bank, L.; McDonald, A.; Kiernicki, C.; Bermek, M.; Zhang, Z.; Poff, A.; Kakkad, S.; Lau, E.; Arias, F.; Gentry, R. *Re-Wind Design Catalog 2nd Edition Fall/Autumn 2022*; Re-Wind Network: Atlanta, GA, USA; Cork, Ireland; Belfast, UK, 2022.
60. Nagle, A.J.; Mullally, G.; Leahy, P.G.; Dunphy, N.P. Life cycle assessment of the use of decommissioned wind blades in second life applications. *J. Environ. Manag.* **2022**, *302*, 113994. [CrossRef]
61. Yazdanbakhsh, A.; Bank, L.C. A Critical Review of Research on Reuse of Mechanically Recycled FRP Production and End-of-Life Waste for Construction. *Polymers* **2014**, *6*, 1810–1826. [CrossRef]
62. Yazdanbakhsh, A.; Bank, L.C.; Rieder, K.A.; Tian, Y.; Chen, C. Concrete with discrete slender elements from mechanically recycled wind turbine blades. *Resour. Conserv. Recycl.* **2018**, *128*, 11–21. [CrossRef]
63. Beauson, J.; Madsen, B.; Toncelli, C.; Brøndsted, P.; Bech, J.I. Recycling of shredded composites from wind turbine blades in new thermoset polymer composites. *Compos. Part A Appl. Sci. Manuf.* **2016**, *90*, 290–299. [CrossRef]
64. *How Wind Is Going Circular: Blade Recycling*; ETIPWind: Brussels, Belgium, 2019. Available online: https://etipwind.eu/files/reports/ETIPWind-How-wind-is-going-circular-blade-recycling.pdf (accessed on 24 June 2023).
65. *Discussion Paper on Managing Composite Blade Waste*; WindEurope: Brussels, Belgium, 2017. Available online: https://windeurope.org/wp-content/uploads/files/policy/topics/sustainability/Discussion-paper-on-blade-waste-treatment-20170418.pdf (accessed on 24 June 2023).
66. *Decommissioning of Onshore Wind Turbines*; WindEurope: Brussels, Belgium, 2020. Available online: https://windeurope.org/intelligence-platform/product/decommissioning-of-onshore-wind-turbines/ (accessed on 24 June 2023).
67. *Joint Contribution of CEMBUREAU and EuCIA to the JRC "Recycling" Definition Project with Regard to Co-Processing of Composite End of Life/Use Material Specific to the Cement Industry*; Position Paper; European Composites Industry Association (EuCIA): Brussels, Belgium, 2022. Available online: https://eucia.eu/wp-content/uploads/2023/05/Position-paper-co-processing-of-composites-CEMbureau-EuCIA-for-JRC-study-final.pdf (accessed on 24 June 2023).

68. WindEurope CEO Visits German Cement Plant That's Running on Blade Waste. WindEurope, Brussells, Belguim. Available online: https://windeurope.org/newsroom/news/windeurope-ceo-visits-german-cement-plant-thats-running-on-blade-waste/ (accessed on 8 March 2023).
69. Gray, B. What to Do with Old Wind Turbine Blades? Mississippi River Facility Recycles Them. Available online: https://www.stltoday.com/business/local/what-to-do-with-old-wind-turbine-blades-mississippi-river-facility-recycles-them/article_e0342ece-185e-5de9-a405-a6b34c0c2aca.html (accessed on 8 March 2023).
70. Job, S. Recycling glass fibre reinforced composites—History and progress. *Reinf. Plast.* **2013**, *57*, 19–23. [CrossRef]
71. Qureshi, J. A Review of Recycling Methods for Fibre Reinforced Polymer Composites. *Sustainability* **2022**, *14*, 16855. [CrossRef]
72. Fitzgerald, A.; Forsyth, M.; Job, S.; Keen, N. *The Sustainability of Fibre-Reinforced Polymer Composites: A Good Practice Guide*; Composites UK: Berkhamsted, UK, 2022.
73. DecomBlades. Results & Resources. Available online: https://decomblades.dk/ (accessed on 3 March 2023).
74. Wood Mackenzie. Global Wind Power Asset Ownership Report and Database 2023 (Q1). Available online: https://www.woodmac.com/reports/power-markets-global-wind-power-asset-ownership-report-and-database-2019-355658/ (accessed on 3 March 2023).
75. Burton, T.; Jenkins, N.; Sharpe, D.; Bossanyi, E. *Wind Energy Handbook*, 2nd ed.; John Wiley & Sons, Ltd.: Chichester, UK, 2011. [CrossRef]
76. GWEC (Global Wind Energy Council). *Global Wind Report Annual Market Update 2013*; GWEC: Belgium, Brussels, 2014.
77. Jamieson, P. *Innovation in Wind Turbine Design*, 1st ed.; John Wiley & Sons, Ltd.: Chichester, UK, 2011. [CrossRef]
78. Oliveux, G.; Dandy, L.O.; Leeke, G.A. Current status of recycling of fibre reinforced polymers: Review of technologies, reuse and resulting properties. *Prog. Mater. Sci.* **2015**, *72*, 61–99. [CrossRef]
79. Sacchi, R.; Besseau, R.; Pérez-López, P.; Blanc, I. Exploring technologically, temporally and geographically-sensitive life cycle inventories for wind turbines: A parameterized model for Denmark. *Renew. Energy* **2019**, *132*, 1238–1250. [CrossRef]
80. United Nations. Sustainable Development Goals. Available online: https://www.un.org/sustainabledevelopment/ (accessed on 21 July 2023).