End-of-life Options for Composite Material Wind Turbine Blades: Recover, Repurpose or Reuse?

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ABSTRACT

The technical and commercial success of wind energy has resulted in c. 650 GW of capacity being deployed around the world. Wind turbines have a typical operational lifetime of 20-25 years, therefore a large number of wind turbines will be decommissioned in the next two decades. This will lead to a large volume of composite material waste from end-of-life blades. In this paper, an overview of the technical, environmental, social and economic aspects of various end-of-life solutions is given, and repurposing is proposed as an optimal and sustainable end-of-life option for glass fibre reinforced polymer blade material. Repurposing is preferable to materials recovery, waste-to-energy or landfilling within the circular economy paradigm, and may offer additional social benefits over these other options. A method is proposed to assess the environmental, social and economic sustainability of repurposing solutions for end-of-life wind turbine blades.

KEYWORDS

Circular economy; glass fibre reinforced polymer; sustainable decommissioning; waste hierarchy; life cycle analysis.

INTRODUCTION

Wind energy contributes a significant proportion of electricity demand in many countries. For example, in Ireland, wind contributed 30% of electricity demand in 2018 (1). In Denmark, over 4,000 wind turbines supplied over 40% of total electricity demand in 2017 and 2018 (2). The total installed wind power capacity in the world grew from c. 14 GW to 159 GW in the decade 1999-2009 (3). In the following decade the aggregate capacity increased to c. 600 GW.

Most wind farms have a design lifetime of 20 years, therefore, many of the wind farms in countries such as Germany, Denmark, Spain and Ireland will soon be reaching the end of their originally-planned operational lifespan. A wind farm operator may decide to end the actual operational life due to one or more of the following factors: end of the original design life of the wind farm; expiration of permission to operate on the site; electricity market reforms reducing the economic benefit of the power generated; expiration of subsidies; increases in operating costs due to mechanical wear, fatigue, component failures, frequency and cost of repairs, turbine obsolescence and difficulty in obtaining spare parts. At this point, operators may seek to extend the operational life of the wind farm, repower the wind farm by replacing the turbines with newer models, or decommissioning the site completely. The decision will be driven by local factors which may depend on the consenting regime and subsidy schemes, leading to different outcomes. For example, the typical operational lifetime of a wind farm in Spain is over 20 years, whereas in Germany it is *c*. 16 years (4).

During the past three decades, the diameter and mass of wind turbine rotors have also increased steadily, with approximately a fivefold increase in blade length, a twentyfold increase in mass and a fortyfold increase in rated power. The rotor blades make up at least half of the turbine mass (excluding tower and foundations) and are generally constructed from composite materials such as GFRP (glass fibre reinforced polymer) along with other materials. Historically, the relationship of rotor power to total blade mass has been observed to follow the so-called 'square-cube' relationship, whereby the total blade mass increases with the cube of the blade length, and the rotor power only increases with the square of the blade length (Figure 1). Therefore, blade mass can be expected to grow faster than the rated power output as the rotor size increases (5). However, due to improvements in blade materials, construction and design, the 'square-cube' relationship has been improved upon in recent designs. Nonetheless, a large mass of waste GFRP is predicted to enter waste streams in coming years as turbines are decommissioned. Figure 2 shows an estimate of the projected number of turbines to be decommissioned on the island of Ireland to 2038. The total includes turbines from wind farms, but does not included single wind turbines. At the global scale, the cumulative total blade waste is expected to reach 2.9 Mt by 2050 (6).

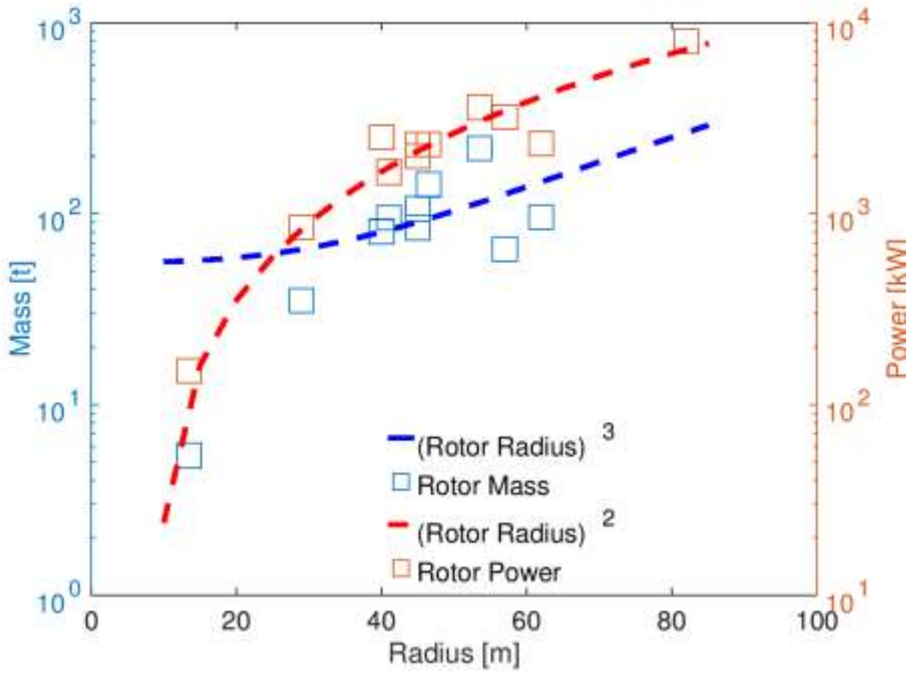

Figure 1. Total rotor mass and rotor power versus rotor radius for a number of turbine designs. The dashed lines show the cubic relationship (mass-to-radius) and the squared relationship (power-to-radius). Data taken from thewindpower.net and (7).

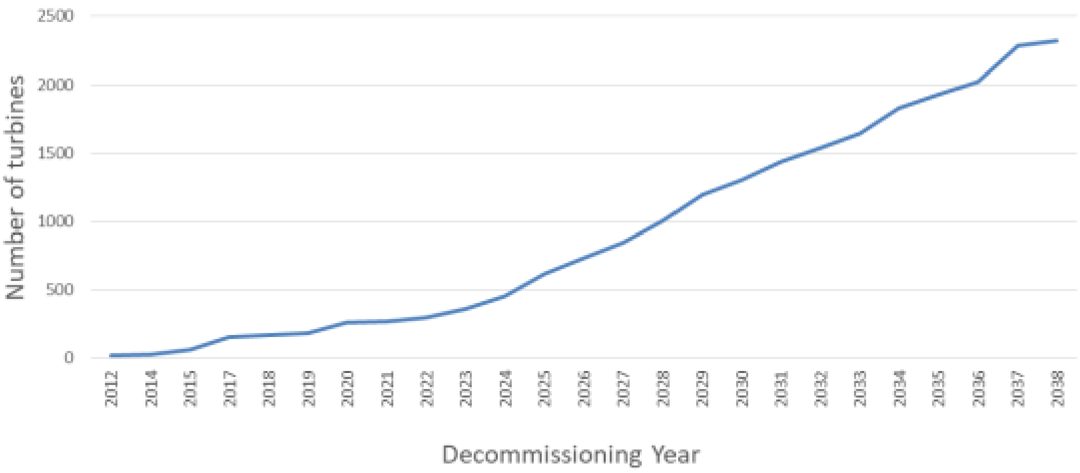

Figure 2. Estimated growth of cumulative total number of turbines to be decommissioned on the island of Ireland to 2038 (data: Emma Delaney, Queens University of Belfast).

When wind turbines are decommissioned due to a site being repowered or completely decommissioned, the turbines must be dismantled and removed. A secondhand market exists for many older turbine types (8), but many turbines end up in waste streams due to reasons such as obsolescence or lack of availability of spare parts. Current solutions for end-of-life composite GFRP wind turbine waste include incineration (with or without energy recovery), stockpiling, landfilling, grinding for aggregates or solid recovered fuel (SRF), or co-processing in cement kilns. Other materials recovery techniques such as pyrolysis and solvolysis are currently being investigated. The relative position of the different end-of-life options on the US Environmental Protection Agency's Waste Hierarchy is illustrated in Figure 3.

Lifetime Extension
Resale on secondhand market
Repurposing

Solvolysis; Pyrolysis; Aggregates

Waste-to-Energy
Cement Kiln Co-Processing

Incineration
Landfill

Figure 3. End-of-life blade options in the context of the Waste Hierarchy (US Environmental Protection Agency)

Repurposing end-of-life wind blades, i.e. transforming them into new products, is attracting increased attention. Repurposing, as opposed to recycling, offers the advantage of exploiting the valuable engineered properties of the blades, instead of reducing blades to relatively low-value component materials for use as fillers or solid recovered fuel (SRF) products. Previous research projects have investigated the creation of products such as urban play structures, street furniture and signage (9).

Repurposing of blades prevents or significantly delays GFRP material from entering conventional waste streams such as landfilling or incineration. Landfill is subject to tariffs and its use is restricted in many jurisdictions. Although incineration of waste is widely used in many European countries, it is subject to strong public opposition in Ireland (10). Products generated from decommissioned end-of-life blades also may substitute for equivalent products manufactured from newly-extracted resources and therefore repurposing can be placed at the most-preferred top level of the waste hierarchy (Fig. 2). Within the framework of the Waste Hierarchy, repurposing, together with lifetime extension, can be seen as preferable options to either waste-to-energy or materials recovery for dealing with end-of-life wind turbine blades, as they sit at higher levels in the diagram.

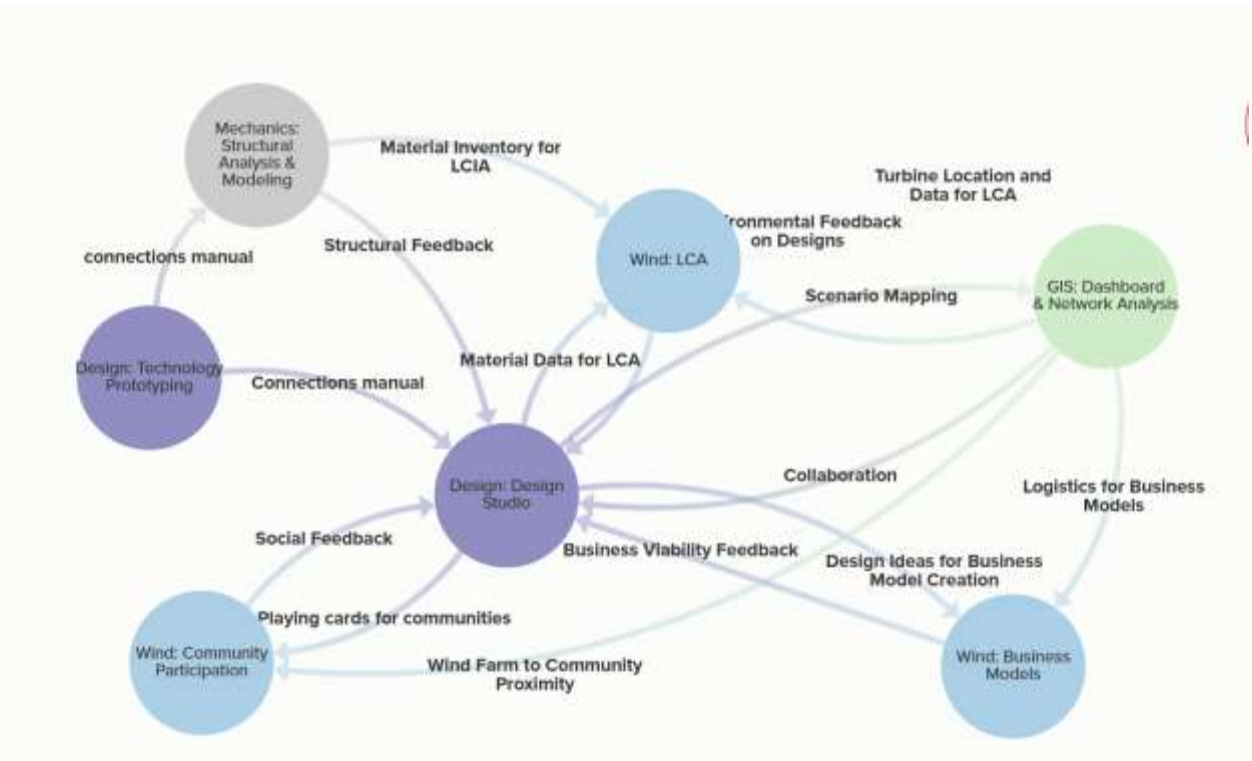

Figure 4. Re-Wind project GFRP blade repurposing method and information flows

METHODS

Finding new applications for end-of-life wind turbine blades is a complex problem, as it is subject to multiple constraints, many of which are highly location-dependent. For this research study, repurposing solutions are considered from multiple interlinked perspectives: the technical perspective, the spatial perspective, the environmental perspective, the social perspective and the business model perspective. Any proposal for blade repurposing must firstly be technically and practically realisable. As an example, transportation of entire blades is costly and may result in significant CO_2 emissions if distances are long. Cutting or processing of blades on site leads to dust and potential noise disturbances. Therefore, local repurposing options are preferable. Social dimensions must be taken into consideration, as any proposed new structure made from repurposed wind turbine blades placed in the public realm must be acceptable to the local community. Finally, the business model underlying wind turbine blade repurposing must be economically sustainable, in comparison to alternative disposal means such as waste-to-energy or cement kiln co-processing.

The method adopted by the Re-Wind project combines several approaches to capture the different perspectives on repurposing:

- An architectural Design Office to generate, refine and develop repurposing ideas
- Structural Mechanics analysis to analyse residual properties of end-of-life blades and proposed new products which will be used in structures or subject to structural loads
- A Geographical Information System to identify locations and store metadata on existing wind turbine blades, including expected dates of decommissioning
- Life Cycle Analysis to identify environmental impacts on air, water and land
- Stakeholder consultations where communities discuss repurposing scenarios in order to gather information on potential social impacts
- Business model development and analysis in order to determine the economic sustainability of repurposing

The flow of information between these processes is illustrated in Figure 4.

The test case for the study is the island of Ireland. With a total installed wind capacity of over 5.5 GW (June 2020), a significant volume of turbines is expected to be decommissioned in coming decades (Figure 2). End-of-life options on the island are constrained by the issue of scale. For example, large volumes of waste are required to make some recycling processes such as cement kiln co-processing economically viable. Transportation to processing facilities on continental Europe or Great Britain adds extra costs and environmental impacts (11). Currently, most decommissioned blades are cut and exported for further processing in continental Europe.

Data has been gathered on all of the installed turbines on the island of Ireland, which has led to the creation of a turbine geodatabase and geographical information system (GIS). Life cycle analysis (LCA) has been carried out on conventional disposal options including landfill, incineration and cement kiln co-processing abroad. The initial appraisal of technical, environmental, social and economic feasibility of several end-of-life options is presented in Table 1. In many cases, detailed blade designs are not available from the original manufacturers, therefore blades have been scanned by 3-D Light Detection and Ranging (LiDAR) scans in order to determine their geometry.

RESULTS AND DISCUSSION

Decommissioned blades have been procured in order to test cutting methods and fastening techniques. The Design Office exercise has generated c. 50 repurposing ideas One example is temporary emergency housing partially constructed from wind turbine blades (Figure 5). Of these, three, including a short-span pedestrian bridge, have been down-selected and developed in greater detail. Life Cycle Analysis of conventional end-of-life blade GFRP disposal solutions (landfill, cement kiln co-processing) has been completed in order to provide a baseline for comparison with blade repurposing.

Table 1. Overview of technical, environmental, social and economic feasibility of end-of-life scenarios for GFRP blade waste, with particular application to Ireland.

	Technical Feasibility	**Environmental Feasibility**	**Social Feasibility**	**Economic Feasibility**
Reduction & Reuse				
Lifetime extension	Feasible in many cases subject to turbine condition	High. Minimal new resources required. Component failures, outages may increase	No change to current operations. Dependent on current local attitudes	Depends on local incentives, subsidy regimes, and planning regimes
Decommission and resale	Feasible in many cases subject to turbine condition	High. CO_2 emissions from transport to new location and reinstallation.	Unknown, but likely to be high.	Proven secondhand market, successful decommissioning business models in operation
Repurposing	Site- and purpose-specific	Expected to be high, dependent on repurposing application.	Expected to be high, dependent on repurposing application.	To be determined
Recycling				
Solvolysis	Under active development	Concerns regarding use of solvents and energy inputs	Likely to be low	Processing costs currently high, value of recovered materials is low.
Energy Recovery				
Waste-to-Energy	Mature	Medium (emissions to air; transport; residues to landfill)	Widespread public opposition in Ireland.	Successful commercial operations
Cement kiln co-processing	Operational	Medium (emissions to air; transportation). Some substitution of source materials.	Unknown	Successful commercial operations (Holcim/Neocomp)
Treatment and Disposal				
Incineration (without energy recovery)	Operational	Medium/high. (emissions to air; transportation).	Widespread public in Ireland.	Successful commercial operations
Landfill	Feasible	Medium. (land use, transportation)	Highly regulated, likely to become less acceptable in future	Successful commercial operations (dependent on local regulations)

Figure 5. Emergency housing concept incorporating blade sections in roofs (reproduced from (12)).

Lifetime Extension

Lifetime extension is a technically, socially and economically viable option for wind farms nearing the end of their originally-planned service lifetimes, subject to suitable planning regimes, turbine serviceability and market and planning regimes. Widespread adoption of lifetime extension will simply delay the decommissioning of GFRP blades, and the overall quantity ultimately entering waste streams will be unchanged.

Reuse (at a different location)

In many cases, particularly when wind farm sites are repowered before the end of their design lifetime, the turbines may be sold on the secondhand market and reinstalled at another location. This end-of-life option will incur environmental impacts due to the energy required for dismantling the turbines and transportation to the new location. However, this option lies at the top of the waste hierarchy (Fig. 3) therefore the overall impact is expected to be low.

Repurposing

Creating new structures incorporating large blade parts is technically feasible (13), but further work is needed in order to create detailed estimates of costs and to gauge community acceptability of new structures created from repurposed wind turbine blades.

Materials Recovery

When dealing with decommissioned end-of-life GFRP wind turbine blades, the costs associated with somematerial recovery methods (e.g. solvolysis) are too currently too high for commercial viability. This is exacerbated by the low quality and value of recovered glass fibres from solvolysis or pyrolysis. Such approaches are far more promising for carbon fibre reinforced polymer blades, but these will not enter waste streams in large volumes for at least another decade. Use of blade GFRP in aggregates for concrete production requires grinding which is energy-intensive.

Energy Recovery / Co-processing

Incineration of GFRP blades with energy recovery (i.e. waste-to-energy) has lower environmental impacts than landfill or incineration without energy recovery. Cement kiln co-processing is costly relative to landfill but has lower environmental impacts than either landfilling or incineration with energy recovery. The additional environmental benefits arise due to the partial substitution of cement raw materials with e-glass from the blade GFRP material.

Incineration and Landfill

Incineration and landfill lie at the bottom of the waste hierarchy. Neither of these options offer any opportunities for substitution of raw materials or resources, unlike waste-to-energy or cement kiln co-processing. Incineration without energy recovery results in emissions to air as well as the requirement to dispose of incineration residues which are usually landfilled.

CONCLUSIONS

The transdisciplinary research project "Re-Wind" has developed a method to compare the social, economic and environmental performance of repurposing solutions for end-of-life blades. Current and future solutions for dealing with end-of-life wind turbine blades include landfill, incineration without energy recovery, waste-to-energy, co-processing in cement kilns, materials recovery or recycling, materials substation in cement kilns or other processes or products, repurposing, reuse and lifetime extension.

End-of-life options which lie near the top of the US EPA's Waste Hierarchy generally have the lowest environmental impacts. However, it is necessary to consider geographical location and social acceptability implicitly when analysing the impacts of end-of-life blade options. Options which may be attractive in one country may be less attractive in another country, due to regulatory differences (e.g. rules on materials which may be landfilled), social aspects such as public tolerance of incineration or waste-to-energy facilities, and economic factors such as the projected scale of the waste stream which would determine future investment in local processing facilities. In this context, local repurposing GFRP wind turbine blades for new applications may prove to be a socially, environmentally, and technically attractive solution to dealing with end-of-life wind turbine blades.

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NOMENCLATURE

CO_2	Carbon Dioxide
EPA	Environmental Protection Agency (USA)
GIS	Geographical Information System
GFRP	Glass Fibre Reinforced Polymer
LCA	Life Cycle Analysis
SRF	Solid Recovered Fuel

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