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COMPOSITE RECYCLING: CHARACTERIZING END OF LIFE WIND TURBINE BLADE MATERIAL

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1. General Introduction

Glass fiber reinforced polymer (GFRP) using thermosetting resins are increasingly utilized for a wide range of applications, such as transportation, construction and energy. Indeed, the diversity in the manufacturing, possibilities from unidirectional laminates to randomly oriented fiber compound and attractive mechanical properties, make these materials very appealing. However, when these products come to end of life (EoL), they are rarely recycled. Consequently, increasing amount of composites wastes are produced and sent to landfill [1] .
In the wind energy sector, composite materials are mainly present in wind turbine (WT) blades. As the wind energy sector is growing, these blades represent a considerable challenge for the future. According to the European wind energy association (EWEA) scenarios, the share of energy coming from wind should increase to 15.7% by 2020, to 28.5% by 2030 and by 2050 the total electricity consumption coming from wind is expected to be 50% [2]. This represents millions of tons of blade to be produced globally over the coming decades, see Fig. 1 [1-3] resulting in considerable amount of waste to handle when these materials come to EoL. Estimations predict that the amount of EoL WT blade materials will account for 100 000 tons per year in Europe in 2030 [3-4]. The Danish Energy Agency has registered all wind turbines connected to the power grid since 1977. From 1977 up to 2012 7618 turbines were installed of which 2607 were decommissioned in the same period. The diagram in Fig. 2 shows the number of turbines installed each year for currently operating turbines.
The diagram in Fig. 3 shows the dimension of the rotor diameter of the turbine installed since 1978.
From these figures it is possible to notice that there are WT still running after 30 years. Furthermore, the diameter of the rotor has constantly increased since 30 years [5].

2. Wind turbine blade materials

WT blades are typically made from continuous GFRP. The fabrics used are mainly made of E-glass fibers, which is a low cost glass fiber grade combining high strength (2 GPa) and stiffness (76 GPa). The diameter varies from 8 to 30 µm. The resins used in WT blades are thermoset resins such as epoxy, polyester or vinylester resins. Part of the blade consists of sandwich laminates, see Fig. 4.
The sandwich is built as uniaxial or multiaxial glass fiber laminates with balsa wood or polyvinyl chloride (PVC) foam as core material. Surfaces are protected using gel coats, polyurethanes. Thermoplastic foils or special paints are used on leading edges [7]. In proportion, GFRP represents approximately two third of the total weight of the blade. As a benchmark for weight it is known that a 40m long blade weights approximately 8,4 t [8].
The trend goes towards more and more optimized blade designs where the low weight is a key issue. Reinforcement with the light and stiff carbon fibers helps to keep down the weight of some of the long blades, but also hybrid composites with a mix of glass fibers and carbon fibers will be more common in the future.

3. Current EoL solutions for WT blades

WT are designed for a lifetime of 20 years. During this period, the blades may be inspected and repaired several times due to leading edge erosion, impact or other damages. Some of the WT might be taken down and replaced by newer WT. Some other might already be damaged.
Depending on the reason for decommissioning, there are basically three EoL options for the WT blades. The schema in Fig. 5 describes these three choices. Two of them are gathered under the name of recycling, namely recovery and reuse. The third choice gathered all the non recycling solutions. This figure is based on the European waste framework [9], which defines recycling as “Any recovery

operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations".

From these three options, EoL WT blades have currently the choice between two of them.

The first one is to reuse them by extending their service life. Indeed, the turbine including the blades may still have residual capacity for several years of service. In Germany, a study [10] was carried out to investigate the effect of service life on WT blades by comparing the actual state and performance of blades after 20 years to the design properties of the blades. For that purpose, a WT operating for 18 years next to a weather station was demolished for evaluation. The blade visual inspection, the moisture content, the natural frequencies, the coupling joints and the full scale blade test run in that occasion conclude that no significant damage was found by visual inspection as well as no significant loss in blade stiffness.

Reusing WT and WT blades is technically possible and a number of companies operating in Europe and in the USA [11-15] offer refurbished or remanufactured WT typically in the range of 10 kW to 1 MW. The benefits listed are:

- Access to a wide range of proven small and medium size turbines;
- Short lead time;
- Low cost, about half the price per Mw [16].

Refurbishment procedures may involve visual inspection, ultrasonic inspection, and natural frequency measurements of the blades. The blades might be in addition repaired, repainted, weighed and balanced.

In the end, this solution seems technically affordable for blades with a rather small size, see Fig. 6. For 45 m long blades, which are commonly produced nowadays, the viability of that solution might be challenged; due to transport difficulties see Fig. 7.

If the blades are not reused, the alternative option is the non-recycling solution described in Fig. 5. It means that either the energy is recovered from the WT blades or they are sent to landfill.

In the first case, the German company Holcim claims to use shredded WT blade materials as a substitute for fuel in the calcination of cement raw material. Holcim also write that they incorporate the ashes into the clinker matrix up to a ratio of 50 % [18-20]. Energy recovery is however difficult with GFRP, as glass fibers are not combustible and hinder the incineration [21-23]. Moreover, it is noteworthy that glass fibers represent around 70% wt of the laminate used in WT blades. In the end, if EoL WT blades are not used in cement, they are sent to landfill, which is, from the Danish point of view, as expensive as to send them to Germany.

Considering all that and giving the challenging European target in terms of renewable energy and waste management, a fully recycling solution for EoL WT blades is needed as it might be the only solution accepted in the future.

Since reuse might not always be possible, other recycling solutions need to be available in order to handle blades that cannot be refurbished. The optimal EoL solution for WT blades is therefore a combination of recycling solutions covering all potential challenges such as blade dimension and shape, location and age.

4. Defining the optimal recycling solution

The scheme in Fig. 8 details the possible EoL recycling solutions for WT blades. In this figure, the solutions are ordered according to the amount of re-processing required. On the top of the figure are found the recycling solutions, which involve only few re-processing step, in contrary to the recycling solution shown in the lowest part of the figure. As a result, the first solution on the top is to reuse the whole blade as blade again and refers to the refurbishment solution mentioned earlier in this paper.

According to the same hierarchy, the following option is to reuse major pieces of WT blades in new applications. An example is shown in Fig. 9, where these pieces are reused in a playground for children.

Then, the next option is to cut large construction element out of the blade, like planks, beams, plates and curved elements. The geometries of these elements are restricted by the blade design and geometry. Regarding mass density and stiffness fibre reinforced polymer composites lies between woods and metals. This is illustrated in Fig. 10, showing density versus stiffness for various groups of materials. These pieces could be used in structural or semi structural applications, such as furniture, see the prototype in Fig. 11.

From these large pieces, the following possibilities are either to extract the glass fiber fabrics embedded in the composite, see Fig. 12, or to continue the size reduction by shredding the composite. Several companies implemented mechanical processes to

shred EoL composite products such as Phoenix Fibreglass Inc. in Canada (1990-1996) [28-29] and ERCOM in Germany (1990-2004), but none of them still exist today. This shredded composite can be reused as filler material in new composite manufacturing or as acoustic and thermal insulation material [30], see Fig. 13.
In the end, if the composite is shredded, fibers and resin can also be recovered from it, using thermal and/or chemical processes. This latter topic has been investigated for more than 20 years and techniques have been implemented [31] such as pyrolysis using microwave, subcritical water or fluidised bed. The products recovered from these techniques are glass fibers and sometimes chemicals from the resin. The recovered glass fibers have a decreased tensile strength [32-35]. The applications for these recovered fibers are diverse, for example they can be reused in new polymer composite manufacturing. However due to the glass fibers reduced tensile strength, the composite also shows reduced tensile properties compared to a composite only made with virgin glass fibers [32-37]. Moreover, none of these recycling techniques have been successfully implemented on a commercial scale. The company ReFiber in Denmark used pyrolysis to recover glass fiber from WT blades and transform it to insulation material [38] but stopped operating in 2007.
To sum up, the optimal recycling solution is a combination of the above mentioned solutions. To determine which of them are viable and how to implement them, the next part presents the objectives of the GenVind project, which is focusing on these challenges.

5. Implementing the optimal recycling solution

5.1. The GenVind Project

The GenVind consortium (2012-2016), supported by the Danish Council for Technology and Innovation has the ambition to find an optimal recycling solution for EoL WT blades [39]. All of the above mentioned solutions described in Fig. 8 will be investigated. For that the project is divided in work packages that cover all the phase of a recycling process, from the dismantling of the blade, to the transport, the reprocessing and the reuse of the recovered material.

5.1.1. Work packages

To determine the potential of the different recycling solutions, three types of working packages have been defined.

Research work packages lead by the universities will focus on the optimization of existing recovery processes, on the characterization of the recovered materials and on the implementation of a pilot scale study.

Technological work packages involving one or more partners will concentrate on developing and implementing the technology based on mechanical, thermal and/or chemical processes to recover resin and fibers from composite. Some of the technological work packages will focus on the reuse of the recovered materials. Finally, there is also a technological work package dedicated to the assessment of the environmental impact and energy consumption of the different composite recycling scenarios.

To validate the recycling solutions implemented in the precedent work packages, the project also includes **demonstration work packages**, to show examples of application for the recovered products.

5.1.2. Partners

To fulfill the work packages objectives, many partners specialist in one or more of the WT blade’s life cycle parts are involved, namely producers, maintainers, re-processer and re-users.

WT blades manufacturers:

- Vestas;
- Siemens Wind Power;
- LM WindPower;

Composite products manufacturers:

- Fiberline
- Velux
- Tunetanken
- TUCO
- Dyrup
- Comfil

Maintaining, dismantling and re-processing companies:

- Barsmarck
- Averhoff
- IF Nedbrydning
- Davai
- Ålsrode Smede og maskinfabrik
- Elcon

Potential re-users:

- Novopan
- Midform
- Contec

Authorized Technological Service Institutes (GTS:)

- Force Technology
- Teknologisk Institute

Universities:

- University of Aalborg – Department of Biotechnology, Chemistry and Environmental Engineering
- Technical University of Denmark – Department of Wind Energy
- University of Nottingham - Faculty of Engineering

One of the important questions for most of these partners is to know the properties of the material recovered from EoL WT blade in order to determine their viability in one or another application.
As explained in this paper, there are many potential recycling solutions for EoL WT blades and each of them have different recovered product (entire section, plate or shredded), see Fig. 8. Specific characterization procedures are therefore needed and the next part introduces the first tasks to achieve that work.

5.2. Characterizing EoL WT blade material

For the entire blade, that can be refurbished, full scale test on the blade structure will be of interest. Whereas, if we go down in the hierarchy to single glass fibers, then these full scale tests might not be relevant if the fibers are planned to be reused on their own. The following points detail the characterization work needed for each level.

Entire blade
The characterization of the full blade is meant to determine whether the blade can be reused or not. For that, the location and evaluation of the damages can be done using visual inspection and ultrasound scanning.

- Damage detection;
- Mechanical testing of blade;
- Mechanical testing of composite;
- Microscopy and porosity content.

Major pieces and construction elements
Major pieces of WT blade and construction elements are meant to be reused in structural or semi structural applications. For that purpose, besides the mechanical properties, the determination of which geometry can be cut out of the blades is important.

- Mechanical testing of composite;
- Microscopy and porosity content.

Shredded composite and recovered fabrics and fiber
Shredded composite can be reused as reinforcing material in new polymer composite, but also as insulation materials. For both of these applications, the analysis of the shape of the shredded component is of interest. Regarding recovered fibers, the surface properties are the main concern, the main challenge is to determine the nature of the surface degradation and how to improve it.

- Mechanical testing of fibers;
- Microscopy: shape analysis and fiber surface analysis.

These are the preliminary questions in building the different characterization procedures. From all these points, the literature only details information on full scale test of EoL WT blade. There are no results available regarding the mechanical testing neither the microstructure of composite from WT blades.

In the GenVind project, the Department of Wind Energy within the Technical University of Denmark will focus on defining these characterization procedures for the recovered materials from EoL WT blades. The focus will first be set on the top of the hierarchy presented in Fig. 8, meaning the full blades, major section of blade and construction element.

6. Conclusion

The difficulties to recycle thermoset polymer composites and the complex structure of WT blades make the recycling of EoL WT blades challenging. However, a recycling solution combining several techniques might solve this issue. Based on a description of WT blade materials and the available composite recycling techniques, this paper structures the potential opportunities.

Acknowledgements

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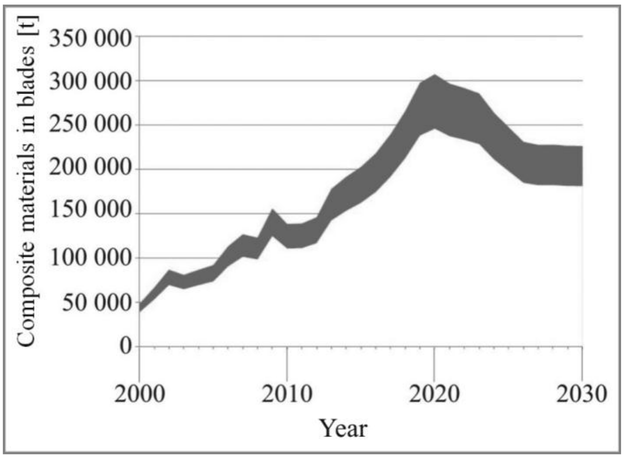

Fig. 1.Annual use of composite materials in blades [2]

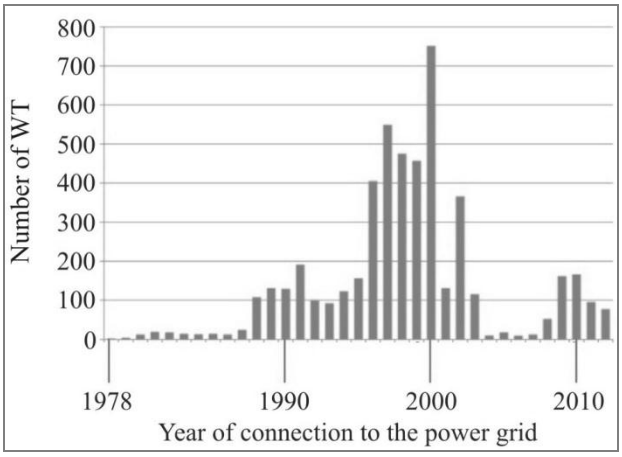

Fig. 2. Currently operating wind turbines and year of connection to the power grid [5]

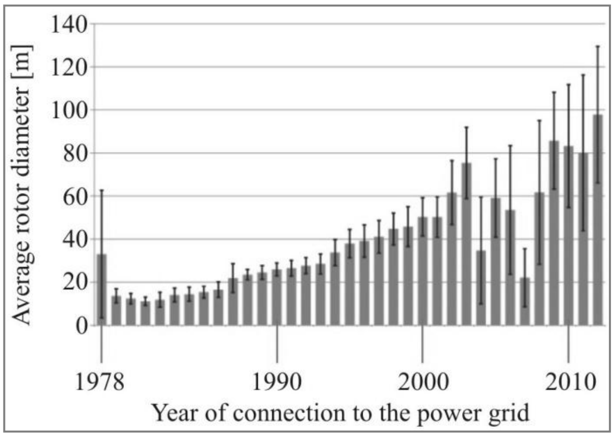

Fig. 3.Currently operating wind turbines, rotor diameter as a function of year of connection to the power grid [5]

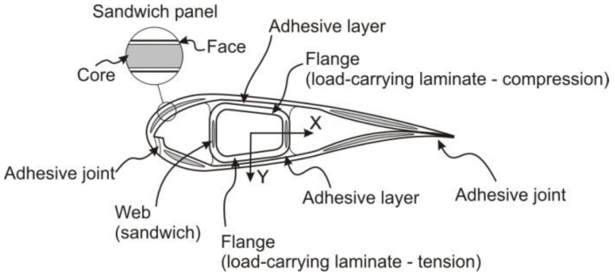

Fig. 4. Cross section of a blade [6]

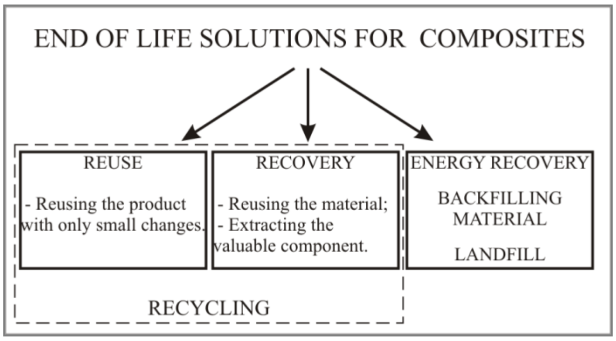

Fig. 5 End of life solutions for composites

Fig. 6 Transport of rather small EoL WT blades by Green-Ener-Tech Denmark [11]

Fig. 7 Transport of a 59 m long blade [17]

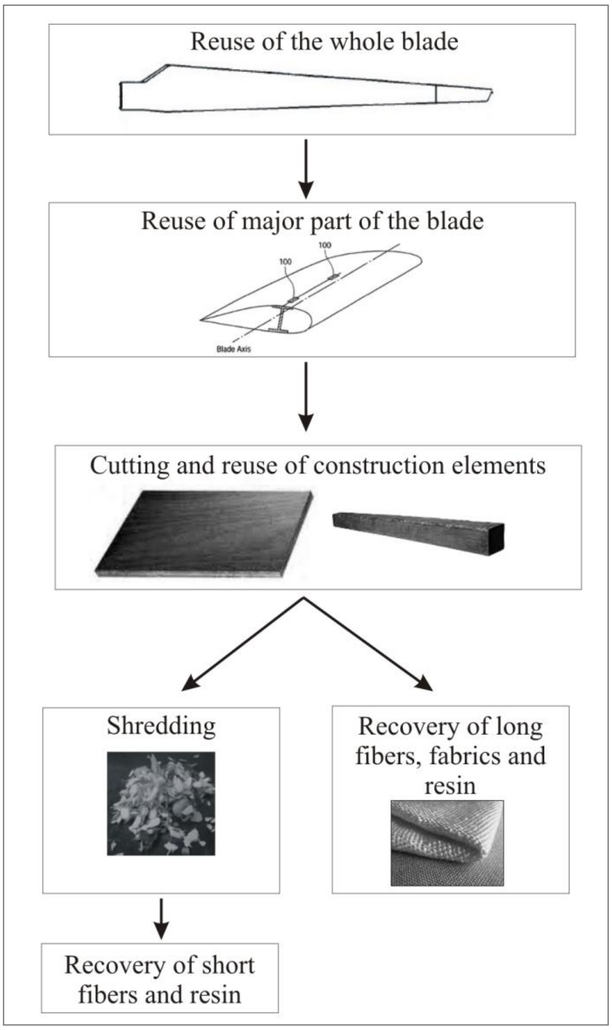

Fig. 8. Possible recycling solutions for EoL WT blades

Fig. 9. Wikado playground in The Netherlands by Architecten [24]

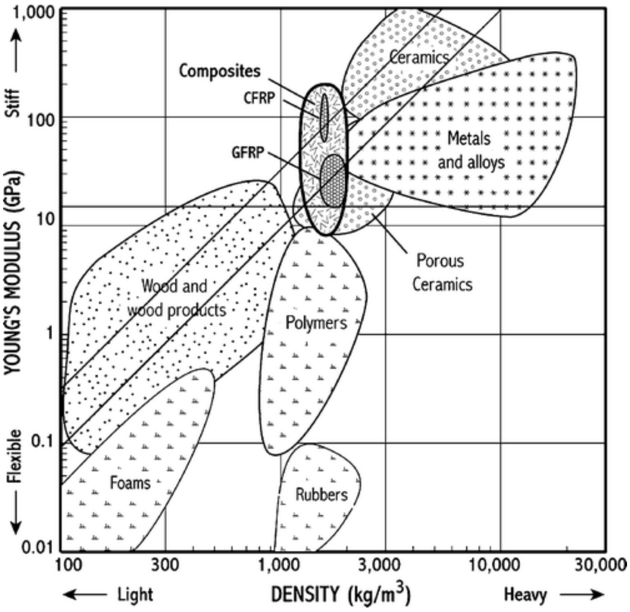

Fig. 10 Diagram showing stiffness versus mass density for different materials [25]

Fig. 11 Prototype of furnitures made out of EoL WT blades by Wigh Design [26]

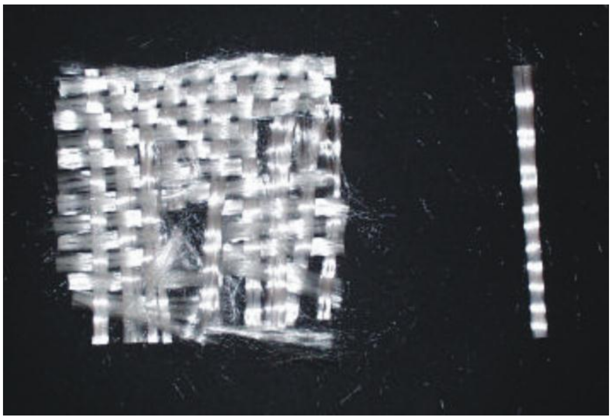

Fig. 12 Recovered glass fiber fabrics [27]

Fig. 13. Reuse of shredded composite [30]