Review of the suitability of thermoplastic rotor blades in terms of the circular economy

Joshua Steinigeweg[*]

Münster University of Applied Sciences, Stegerwaldstraße 39, 48565 Steinfurt, Germany

Abstract

Wind energy has steadily gained importance in the generation of renewable energy over the last 25 years. A wind turbine has an average life expectancy of about 25 years. After that, thermoplastic composite materials from the rotors, among other things, accumulate and have to be recycled. Previous methods, such as landfilling, incineration and pyrolysis, have not yet proven to be effective in terms of the circular economy because the recycled material cannot be reused for equivalent products. The use of thermoplastic materials can be a sensible alternative, as thermoplastic resins can be recycled almost without loss of value due to their properties. Recycling of fibreglass is also possible with less loss of stiffness. In the future, it will be crucial to scale up thermoplastic rotor blades and create a market for the recycled material.

Keywords: Wind power, Recycling, Thermoplastic rotor, Solvolysis, Circular economy

1 Introduction

Wind power plants are of great importance for the energy turnaround and in the fight against climate change. After about 20 to 25 years they have to be shut down and dismantled because they have reached the end of their design life. Here, the experience with onshore plants is much greater than with off-shore plants [1].

In order to achieve the goal of closed material cycles, the materials must be recycled. Success can already be seen in the tower, hydraulics, generator and gearbox, while the neodymium (NdFeB) magnets, nacelle and rotors are still considered problematic. Especially the rotors are problematic because they are made of composite materials consisting of epoxy resin, fiberglass and balsa wood. For this reason, only incineration and subsequent landfilling of these components has so far been an economical method of exploitation, since alternatives such as pyrolysis, oxidation in fluidized bed and treatment with chemicals are very costly and only possible with a high energy input [2].

In the USA, recyclate is obtained from shredded rotor blades and then used as an aggregate for polyresin for the production of railway tracks, subway rails and masts. Since the rotor blades are additionally shredded in this process, recovery of the raw materials resin and fiberglass after use is almost impossible [3].

Therefore, this paper will first take a closer look at the current recycling of rotor blades and then discuss to what extent thermoplastics are suitable for the production of rotor blades and whether recycling without downcycling can be achieved through their use. The recycling of the other material flows is not considered in this review, because they are not as critical as the composite materials or already functioning recycling technologies.

2 Existing recycling methods for thermoset rotors

A wind farm consists mainly of different metals, such as iron, copper and aluminum. Composite materials made of wood, resin and fiberglass represent another large fraction. Other components are NdFeb magnets, various oils, electronic components and batteries. Recycling for these different material streams has been worse for some materials and better for others. For example, the tower, hydraulics, generator and gearbox are considered relatively easy to recycle, while the rotor blades, made of composite materials, are the most difficult to recycle. Table 1 gives an overview of the typical material composition of a 60 MW wind farm.

2.1 Recycling of composites

Composite materials are mainly found in the rotor blades and nacelles. The recycling of these materials is very difficult due to the complex material structure. In addition, the rotors will grow from a length of 15 to 20 m to a length of 75 to 80 m. It is crucial to have the right technology and a market for the recycled products [2].

---

[*] Corresponding author: j.steinigeweg@fh-muenster.de.

https://doi.org/10.25974/ren_rev_2021_06

Tab. 1: Material components of a 60 MW wind farm [2]

Type of Material	Mass [kg]
Ferrous metal	6 560 000
Aluminium	104 000
Composite Materials	660 000
Lubricating oil	30 000
Electronics	124 000
Batteries	36 000
Fluorescent lamps	3 800
NdFeB magnet	40 000
Copper	292 000
Balsa Wood	29 000
Polyethylene	32 000
Polypropylene	6 600
Polyvinylchloride	6 000
Miscellaneous	-
Total	7 923 400

2.1.1 Mechanical recycling and thermal utilization

The composite materials are shredded. However, it is almost impossible to separate the resin from the material. Therefore, it is only possible to use these materials as landfill materials. But this is prohibited in Germany, which is why incineration and subsequent disposal of the ashes is preferred [2].

In the USA the company Global Fiberglass Solutions Inc. cooperates with the Environmental Protection Agency (EPA) to jointly issue recycling certificates. Here the rotor blades are also processed to a recyclate by shredding. Poly resin is added to this recyclate and new products for infrastructure, such as railroad sleepers, subway sleepers and bollards are produced. This products did not show disadvantages compared to conventionally made products [3].

2.1.2 Pyrolysis

The pyrolysis process requires temperatures in a range of 450 °C to 700 °C. The process is divided into two sub-steps, each of which takes place in rotating ovens. An oxygen-free atmosphere is required in the first oven [2]. The resin becomes steam and can be used to generate electricity [3]. In the second rotating oven oxygen is present. This removes the remaining impurities on the surface of the fiberglass [2]. The company ReFiber from Denmark is well known for this process, but a commercial use is not yet being made [2, 3].

2.1.3 Chemical

By adding a solvent to the composite stopper, the glass fiber is released without mechanical damage. The resin can be partially recovered by chemical solvolysis [4].

2.2 Problems

High costs of the recycling processes, a lack of market for the recycled products and a general lack of business model are the main problems of current recycling in all processes [2].

2.2.1 Mechanical recycling and thermal utilization

The rotor blades are shredded into 15 mm to 25 mm long pieces [2], which makes reuse almost impossible, since the fiberglass has very poor mechanical properties [3]. In addition, only an incomplete separation of resin and fiberglass is possible, since a resin residue remains on the fiberglass [2, 3]. In addition, fiberglass dust can be released during the shredding process, which can lead to health problems for the workers[3].

After incineration, about 60 % remains as ashes [2], depending on anaorganic pollutants. Further treatment of the ashes may therefore become necessary [4]. Small glass fibre components in the flue gas can also cause clogging of the filter system. This can lead to the release of toxic flue gases [4]. Both mechanical crushing and combustion represent downcycling in the waste hierarchy, which is why these processes should not be the methods of choice [2].

2.2.2 Pyrolysis

The disadvantage of the pyrolysis process is that the glass fiber has a much lower strength after the process. Because the glass fiber cannot be reused for the production of new rotor blades, downcycling takes place. In addition, the resin cannot be recovered, but can only be burned as pyrolysis gas to generate electricity and heat [4]. However, the energy yield of this process is low [3].

2.2.3 Chemical

Problems with this process are the use of toxic and aggressive chemicals and the extremely high costs [3, 4].

3 Thermoplastic blades

As the results from chapter 2 demonstrate, no suitable process has yet been found that meets the requirements of a circular economy, since the conventional recycling processes for rotors made of composite materials are very costly and energy-intensive, in some cases toxic chemicals are required and in some cases materials are withdrawn from the material cycles. This chapter will therefore examine whether rotors made of thermoplastic composite material are suitable for replacing the rotors made of thermoset composite material used to date, since the thermoplastic composite material has significantly better recycling properties [5]. For this purpose, two rotor blades of identical shape, which differ in the use of thermoplastic composite material in one rotor blade and thermoset composite material in the other, are first compared in terms of their mechanical properties. Recycling techniques for the rotors with thermoplastic composite material are then presented.

3.1 Comparison between thermoset and thermoplastic rotor blades

In the following, two 13 m long test rotor blades, one made of a composite material with thermoplastic resin and the other made of a composite material with thermosetting resin, are compared with regard to their mechanical properties. The rotor blade was developed and validated for another National Rotor Testbed (NRT) project. The aerodynamic behavior is comparable to that of a rotor blade for 1.5 MW wind turbines [6].

Both rotors have the same shape and the same balsa wood core. Hexion epoxy resin was used for the thermoset composite rotor. The manufacturer of the fiberglass is Nippon Electric Glass, which is woven by Vectopryl in unidirectional and biaxial directions. For the rotor made of thermoplastic composite material, Elium thermoplastic resin was used. The fiberglass is from Johns Manville. Due to density and weight differences, different numbers of layers of fiberglass had to be used for the rotors. However, computer simulations showed that the effect on stiffness was not significant [6].

The molds for both rotors were produced using 3D-printing. The individual blade components were produced by vacuum assisted resin transfer (VARTM) and then glued together. Polymethyl metacrylate adhesive was used for the thermolastic components and a special epoxy adhesive for the thermoset composite rotor. It is necessary to limit the temperature to below 80 °C for the exothermic reaction during the production of the rotor components made of thermoplastic composite material, otherwise there will be negative effects on the material. A control agent must therefore be added. But this has no influence on the material properties. In the manufacture of the thermoset composite rotor, the resin was poured into a mold and then kept at a temperature of 70 °C for a period of 4 hours [6].

3.1.1 Measurement methodology

As Figure 1 shows, the static load is simulated at the positions 4.60 m, 7.55 m and 10.85. At the 4.60 m point, a static ballast weight is mounted and at the other two points, the force is applied by an overhead crane, with a force redirection performed by a turning plate on the floor and the two points connected by a stirrup. At all points, the forces are transmitted by stirrups attached to the rotor. The deflection is measured by string potentiometer at positions 4 m, 7 m and 11.25 m respectively. Load is applied at a rate of 45 N/s over a period of 30 s. The load is applied up to the design limit [6].

To simulate fatigue loads, the weights on the saddles are adjusted. Fatigue test moments are achieved Resonance Excitation actuators at damped natural frequency [6].

Fig. 1: 13 m thermoplastic blade at the test stand (c) Ryan Beach [7]

3.1.2 Results

In terms of static response, the thermoplastic rotor has a displacement at the 4 m measuring point that is 11 % greater than that of the thermoset rotor. At the 11 m measuring point, the deflection of the thermoplastic rotor is only 3 % greater. The small difference near the outer edge of the rotor indicates that there is only a small difference in stiffness between the two materials. The small differences can be attributed to the use of fibreglass from different manufacturers and the use of different adhesives, as the adhesive for the thermoplastic components has a higher elasticity [6].

The fatigue behaviour of the two different composites is good, with less than 0.5 % deviation in compliance after each of 1 000 000 cyclic runs compared to the first run [6].

The same test set-up as for the fatigue test was used to determine the structural damping. The results show that the thermoplastic rotor has 0.70 % of the critical damping and the thermoset rotor 0.13 % of the critical damping in the flatwise direction. In the edgewise direction, the thermoplastic rotor has 1.34 % of the critical damping and the thermoset rotor 0.21 % of the critical damping. In both directions, the values of the thermoplastic rotor exceed those of the thermoset rotor by at least five times. One possible reason for this is the use of different adhesives; however, this can be neglected as the proportion of adhesive is very small in relation to the total mass. The main cause can be seen in the different material matrix of thermoplastics and thermosets. Due to the higher damping, the reaction of the rotor to dynamic changes may be reduced, thus increasing stability. [6].

3.2 Recycling

The main recycling processes for thermoplastic rotor blades are thermal treatment by pyrolysis, mechanical shredding, thermal forming and chemical solvolysis. As the pyrolysis and mechanical treatment processes do not differ significantly from the processes for the treatment of thermoset rotor blades presented in chapters 2.1.1 and 2.1.2, only thermal reshaping and chemical solvolysis are discussed below [7].

3.2.1 Thermoforming

The thermoforming process for thermoplastics has meanwhile matured. First, the material must be heated to the glass transition of the respective polymer. Then it can be formed into other shapes. Even after cooling, the material remains dimensionally stable. However, this process has so far only been established for granulated material. For composite materials, there is little experience available so far. One possible procedure could be the division of large rotors into smaller segments, which are then heated and shaped into new shapes. For example, building boards or skateboards could be produced in this way [7].

3.2.2 Chemical

The chemical process used is solvolysis. In this process, the covalent bonds of the polymer matrix are broken by a reactive solvent. This process requires high temperatures and pressures, which results in a high energy input. However, there have been recent developments that have shown promising results in a low energy process. In the solvolysis process, both the polymer and the glass fibre can be reused, as the stiffness of the fibre has only been reduced by 12 %. So far, however, there is also limited experience with composite materials [7].

4 Evaluation

The discussion of existing recycling processes for thermoplastic rotors has shown that there is currently no technology available that can be used to recycle the rotor blades in the sense of closed cycles. Therefore, a comparison between a 13 m long rotor blade made of thermoplastic composite material and a rotor made of thermoset composite material was presented. In the static test the results only differ slightly. The deflection of the rotor blade made out of thermoplastic composite material is slightly higher in comparison to the one made out of thermoset composite material. The more than 5 times higher damping can have the effect of increasing the stability of the system, as it reacts less to dynamic changes. In addition, after solvolysis almost complete recycling of the thermoplastic composite material is possible. The reduction in the stiffness of the fibreglass is low at 12 %, which means that further use is possible.

This clearly shows that a thermoplastic rotor can be a promising replacement for the existing thermoset rotors; also in the sense of the increasingly important closed raw material cycles.

5 Outlook

In the future, it will be important to gain more experience with thermoplastic rotors. Especially the scale-up will be crucial. Then it will be necessary to check whether cost reductions can be realised through technology on a large scale, because currently this is still more expensive for the rotors used in chapter 3. It will also have to be checked whether a cost advantage can be realised through self-heating due to the exothermic reaction [6]. In addition, a further development of the existing recycling methods is necessary to reduce the costs. It is important that markets are created for recycled materials, because only then it will be possible for them to displace raw materials [7].

References

[1] M. M. Luengo and A. Kolios. “Failure Mode Identification and End of Life Scenarios of Offshore Wind Turbines: A Review”. *Energies* 8.8 (2015-08-01), pp. 8339–8354. ISSN: 1996-1073. DOI: 10.3390/en8088339.

[2] J. P. Jensen. “The path towards sustainable energy”. *Wind Energy* 22.2 (2019), pp. 316–326. ISSN: 1095-4244. DOI: 10.1002/we.2287.

[3] N. Sakellariou. “Current and potential decommissioning scenarios for end-of-life composite wind blades”. *Energy Systems* 9.4 (2018), pp. 981–1023. ISSN: 1868-3967. DOI: 10.1007/s12667-017-0245-9.

[4] K. Larsen. “Recycling wind turbine blades”. *Reinforced Plastics* 53.1 (2009), pp. 20–25. ISSN: 0034-3617. DOI: 10.1016/S0034-3617(09)70043-8.

[5] J. Garate, S. Solovitz, and D. Kim. “Fabrication and Performance of Segmented Thermoplastic Composite Wind Turbine Blades”. *International Journal of Precision Engineering and Manufacturing - Green Technology* 5.2 (2018-04-01), pp. 271–277. ISSN: 2288-6206. DOI: 10.1007/s40684-018-0028-3.

[6] R. E. Murray, R. Beach, D. Barnes, D. Snowberg, D. Berry, S. Rooney, and et al. “Structural validation of a thermoplastic composite wind turbine blade with comparison to a thermoset composite blade”. *Renewable Energy* 164 (2021), pp. 1100–1107. ISSN: 0960-1481. DOI: 10.1016/j.renene.2020.10.040.

[7] D. S. Cousins, Y. Suzuki, R. E. Murray, J. R. Samaniuk, and A. P. Stebner. “Recycling glass fiber thermoplastic composites from wind turbine blades”. *Journal of Cleaner Production* 209 (2019), pp. 1252–1263. ISSN: 0959-6526. DOI: 10.1016/j.jclepro.2018.10.286.