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Gone with the wind: The life and death of a wind turbine rotor blade

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Wind turbines, in the form of the tall, slender, two- or three-blade pinwheels, have been capturing the power of wind and producing renewable energy since the 1990s. However, if we do not find end-of-life solutions for the materials of their rotor blades, their profile may not remain as green and sustainable as currently viewed.

As the first generation of wind turbines are slowly decommissioned to waste treatment centers and disposal sites, thousands of tons of blades, 15- to 20-m long, are awaiting incineration or perhaps a second chance through reuse or recycle. The next generation of blades, which already needs dismantling, measure up to 60 m in length. For this army of Quixotic giants, no established recycling solution exists.

The materials that make up a wind turbine are generally considered as recyclable: valuable rare-earth metals, for example, found in the magnets of some wind turbines generators or metals, such as steel, which make up almost 90% of a wind turbine's mass and is mainly concentrated in its tower. The blades, however, with many composites in their complex structures built from different designs and with varying lengths, are a discontinuous and inhomogeneous source of material and very challenging to recycle.

Of all the components of a wind turbine blade, the most complicated and difficult to manage are the glass and carbon fiber-reinforced polymer composites (GFRPs and CFRPs), which, as their names suggest, are glass and carbon fibers surrounded by a polymer matrix, such as an epoxy resin. These hybrid materials, which represent the biggest fraction of a blade's composition, have been chosen for light and robust blades, which rotate easily, thus harvesting more energy from the wind.

GFRPs have a high strength-to-weight ratio that allows the blades to withstand large mechanical loads and to contribute to their overall aerodynamic performance; they are resistant to fatigue and corrosion, characteristics that ensure a long lifetime. They can also be easily affixed with add-on components, such as lightning protectors or leading-edge protectors and heating systems, to improve performance. The requirements for higher power output and the scarcity of sites suitable to host windmills encouraged engineers to design larger rotors with longer blades, in which GFRPs alone could not bear the loads and achieve the stiffness required. CFRP composites, which are much stronger and stiffer per unit of weight than GFRPs, were used more frequently to support the blades at critical spots.

Early enthusiasm for wind turbines pushed the technology beyond full life-cycle analysis, leaving end-of-life considerations for today. "Fiber-reinforced composites are mechanically optimized, very expensive systems (each blade costs several hundred thousand Euros). After being manufactured, they represent especially highly integrated multi-hybrid material systems. It is generally difficult to recycle them—on a material and on a component level—both partly or completely," said Tobias Melz, director of the Fraunhofer Institute for Structural Durability and System Reliability LBF.

In Germany, "the mass of the rotor blade material that is expected to arrive in waste reception centers will increase dramatically in the next few years, due to the approaching end of life of the plants built in the last two decades," said Petra Weißhaupt, from the German Environment Agency, who is leading a research project dedicated to answering the question of what is going to happen with the old blades. Their dismantling and recycling is expected to pose a "huge problem" in the national waste management system, news agency dpa reported. Weißhaupt and her team are putting together a strategic plan that aims to solve the problem, preferably before the first plants that contain CFRP composites arrive at waste treatment centers around the end of 2020.

"The best, most efficient way to recycle the blades would be to reuse the whole plant or to reuse the blades in other plants of the same type, but the length of the blades makes their transportation for refurbishment somewhere else in the world a very difficult task," said Anke Weidenkaff, head of Fraunhofer IWKS in Hanau and Alzenau, who works on making recycling processes for complex materials more efficient.

Blades can get second-life use as building elements for noise protection, flood control, or as bridge material, but the problem of transportation remains. A blade cut in pieces could also be used for construction purposes, but this creates a new challenge: how to cut the blade while retaining its mechanical properties (fibers and the matrix remaining intact), usually lost during dismantling. The use of methods such as hot wires, rotor blade cutting, or lasers needs a solution for the finishing of the newly formed blade's surface. There are only a few suitable mobile cutting tools for complex materials of that size, and currently the blades are mostly shredded or blown up on-site.

Decomposition of the blades' composite materials and reuse of the separated fibers is another desired recycling path that is full of challenges. Chemical recycling by dissolving the polymer matrix

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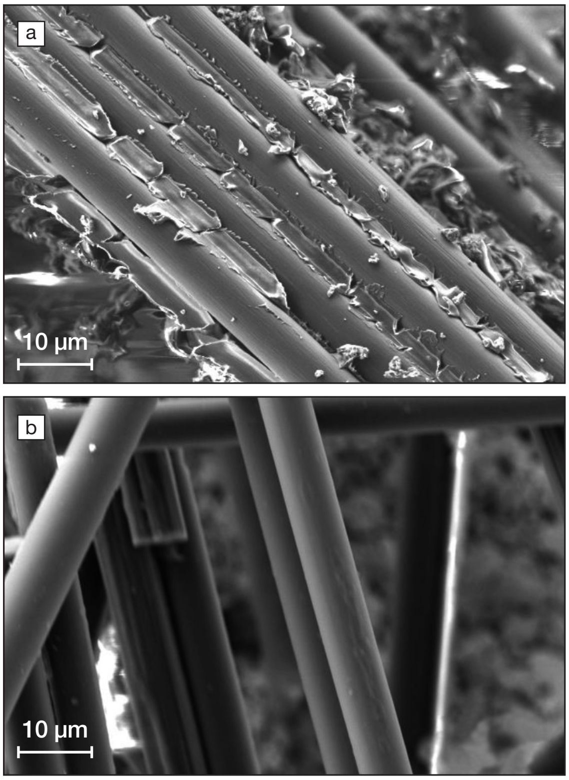
https://doi.org/10.1557/mrs.2020.71 Published online by Cambridge University Press

has been used for CFRP, but requires harsh solvents and leaves large parts of the polymer on the fibers' surface. Mechanical recovery of carbon or glass fibers, to thermally reform them into new products, is only suitable for thermoplastic matrices, while most of them are thermoset: when they are cured, the polymers become cross-linked and undergo an irreversible process that makes recycling difficult.

Currently, electrohydraulic fragmentation (EHF) of CFRPs is the only nonthermal process to separate the carbon fibers from the polymer matrix, known to give back high-quality fibers ready to be reused. It is based on strong pulses of sound waves, which separate the fibers from the resin when they hit the material. Katrin Bokelmann and her team at Fraunhofer IWKS were the first to apply the EHF on rotor blades. Bokelmann, head of the Department of Urban Mining, is responsible for the development of new technologies for the recycling of mineral byproducts and composite materials.

"We focused on carbon fibers recycling, since they are more valuable than glass fibers. After several reports in publications, the news came to our attention about the rising amount of fiber-reinforced plastics. We noticed that our EHF process fits perfectly with the selective fragmentation of these composite materials," said Bokelmann. The method works so well, that a big percentage of the carbon fibers becomes completely free of plastic, as electron microscopy studies revealed. According to Bokelmann, the method is still not economically satisfying to become a commercially recycling process. Another challenge is the general shortening of fibers in every process step and the resins left behind, which are very toxic with currently no way to treat them.



Scanning electron microscope images. (a) CFRP after processing with a cutting mill. (b) Carbon fibers separated from the polymer matrix via electrohydraulic defragmentation. Almost no polymer is left on the fibers' surface. Credit: Fraunhofer IWKS.

In Germany, the blades are mostly exported or, since 2015, treated by Neowa, a company based near the port of Bremen. Its subsidiary, neocomp GmbH, gives GRFPs a new life through cement coprocessing. The glass fiber-containing components are shredded into small pieces and handed over to the cement industry. The combustion of the organic fraction of the material delivers heat for the process, replacing coal as a fuel, and the glass fibers take the place of the aggregates in the cement clinker, replacing quartz sand.

"We have been keen on identifying a sustainable way to recycle GRFP," said Frank Kroll, CEO of Neowa. "We suggest replacing the raw sand with silicate from the rotor blades. This makes economic and environmental sense to cement manufacturers, since raw sand in good quality is getting more and more scarce and expensive. It is proof they can produce green cement, in a spiral process, in which fibers are used to produce cement and then concrete, and the concrete is used to produce the foundation of a wind turbine," he said. The side benefit of this method is that the CO_2 output of the cement manufacturing process can be significantly reduced: up to 16% reduction is possible if composites represent 75% of cement raw material.

Pyrolysis and energy recovery by incineration are two adddiditional ways to treat blades at the end of their operational life. In pyrolysis, the decomposition of the polymer matrix takes place at approximately 500–600°C, without oxygen, to ensure that the toxic resins are eliminated. Furthermore, thousands of tons of materials that come from the blades are incinerated. Glass fibers are incinerated and mixed with other wastes. The incomplete combustion is a huge problem; 60% of the material forms ashes and chokes the filters. In the case of carbon fibers containing composites, the electrical conductivity of the fibers poses a huge problem for the facilities; while respirable, potentially carcinogenic particles are presumably exhausted.

A sustainable process is needed for dealing with the blades at the end of the service life of wind turbines to maximize the environmental benefits of wind power. For Weißhaupt, all scenarios are open. "Even if we come to the conclusion that the most appropriate treatment is incineration, then we need a better process and tools with which the blades will [need to] be cut in pieces, as this mechanical treatment in itself is a challenge," she said.

Melz believes that the development of energy-efficient recycling concepts is an important but difficult challenge. What he finds even more challenging is the realization of circular processes for components or materials to realize a green technology. For future blades, formulations with appropriate additives and multimaterial concepts should be developed, including raw materials based on natural resources and reformulated and upgraded recyclates used carefully. "Moreover, it is worth it to rethink the blades' design concepts (e.g., when we think of repowering systems). Today's rotor blades are designed for its [their] operational lifetime. It might be a good approach to think about 'design for recycling' or 'design to reuse' concepts for the next generation of rotor blades," he said. □

https://doi.org/10.1557/mrs.2020.71 Published online by Cambridge University Press