Rotor blade cut into cross sections © Fraunhofer IWES

Challenges and approaches when recycling wind turbine rotor blades

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The recycling of wind turbine rotor blades represents a major challenge within the energy transition. The recycling of other turbine components, such as towers made of steel and concrete, foundations and nacelles with integrated electronic components, is generally relatively uncomplicated. The complex material composition and structure of rotor blades mean that recycling them requires considerable technical and economic effort. For this reason, work is underway in a variety of research projects at the Fraunhofer Institute for Wind Energy Systems IWES to develop systematic approaches to address this challenge.

Material complexity of rotor blades

Rotor blades are predominantly composed of glass fiber-reinforced and carbon fiber-reinforced plastics (GFRP and CFRP), which, in combination with other materials, produce a robust and functional overall design. These specific materials are preferred in the wind energy sector because of their excellent mechanical properties, such as high strength while still being lightweight.

Rotor blades are typically designed as a sandwich construction or full-laminate structure, using fibers, balsa wood and PET or PVC foam embedded in a thermoset matrix. This diversity of materials increases the requirements for effective separation, which is necessary for the recycling of the individual components to guarantee a high-quality recycling solution.

The recycling process is particularly complex as the glass and carbon fibers need to be extracted from their matrix, which is a prerequisite for retrieving the fibers as a high-quality raw material that can be reused. As such, the recycling process must be designed to be both environmentally and economically sustainable, so as to maximize its efficiency and minimize the associated CO_2 emissions.

Recycling and downcycling

Despite the existence of a variety of recycling methods, only a small share of rotor blades is recycled at present. There are multiple reasons for this:

1. **Extension of the life cycle:** A significant percentage of wind turbines, approximately 13% in Germany, continue to be used beyond their calculated life span and the guaranteed feed-in tariff period, or are sold for further use after dismantling. In many cases, the rotor blades are still in good working order and can be employed in other wind energy projects or used for replacement parts, reducing the necessity for immediate disposal.
2. **Economic aspects:** The process of separating materials is energy-intensive and therefore expensive. For example, it is often more cost-efficient to produce new glass fibers than to recycle the existing ones. These economic considerations contradict the environmental goals of a sustainable circular economy.
3. **Quantitative challenges:** Although the estimated volume of rotor blades reaching the end of their life span by 2037 in Germany might seem substantial at around 83,000 tons, it is relatively low in comparison with the total waste volumes. According to a recent press release issued by Destatis (the Federal Statistical Office of Germany), 380.1 million tonnes of waste were produced in Germany in 2023. Consequently, the establishment of sorting and recycling facilities for rotor blades will only be economically viable if the processes are both energy efficient and automated.

Legal framework

It has been illegal to dispose of rotor blades at landfill sites in Germany since 2009. This regulation has also already been introduced or is in the process of being implemented in other European countries. Such legal measures aim to optimize waste disposal practices and minimize the environmental pollution caused by materials either not recycled at all or disposed of improperly.

While some rotor blades are repurposed creatively, for example, as playground equipment or seating, the primary method of disposal at present is incineration with energy recovery in the cement industry. In this process, shredded rotor blades are burned to generate energy, while the ash from the glass fibers is used as a raw material in the cement.

However, there is still a long way to go before we achieve genuine material recycling, i.e., the use of materials for new products or as raw materials.

Technical approaches to recycling

The key to efficient material recycling is the separation of the individual materials used in rotor blades from one another. Balsa wood and foam materials can be mechanically separated with relative ease and then reused as building or insulation materials. This separation is of key importance in maximizing the recyclability of the materials and minimizing waste.

The number of decommissioned rotor blades is set to increase with the planned expansion of the wind energy industry. The high share of CFRP in modern rotor blades, especially those over 70 meters in length, is rendering new disposal methods necessary, as such materials cannot be recycled conventionally.

The separation of the CFRP and GFRP from each other requires more complex processes such as pyrolysis or chemical dissolution (solvolysis). At present, the available processes often result in downcycling, as the recycled materials do not display the same mechanical properties as the original fibers. This transformation can lead to the recovered materials being used in lower-quality applications, which reduces the overall efficiency of the recycling process.

Research at Fraunhofer IWES

Researchers at Fraunhofer IWES are working on solutions to allow high-quality recycling, preserving the positive material properties of the fibers. In the scope of a range of research

Following separation: the shredded PVC foam, GFRP and balsa wood from a rotor blade © Fraunhofer IWES

projects, a concept is being developed for an economic disposal strategy for rotor blades that will optimize the individual steps of the recycling process.

One key element of the KoReNaRo research project is the 'incoming goods inspection' of the rotor blades. This sees hot air blown into the blade to create thermographic images, providing an accurate picture of the material structure. This information is important for preparing the disassembly of the rotor blades based on the materials. The next step is mechanical disassembly, where the different components are separated for recycling using different methods.

To extract the foam and balsa wood from the sandwich materials, they are first coarsely shredded and then separated from one another using the sink-float method. This method utilizes the different densities of the materials to separate them efficiently.

Another option is the separation of the shredded materials using a conventional waste sorting system modified to suit the special characteristics of the materials. Initial testing has delivered very promising results.

The full-laminate structures can be separated into oil, gas and pure fibers as raw materials using batch pyrolysis, for example. In this process, the resin in the thick fiber-composite components is heated and broken down into oil and gaseous hydrocarbon compounds. This method enables more efficient recovery of valuable raw materials, which can then be employed in new applications.

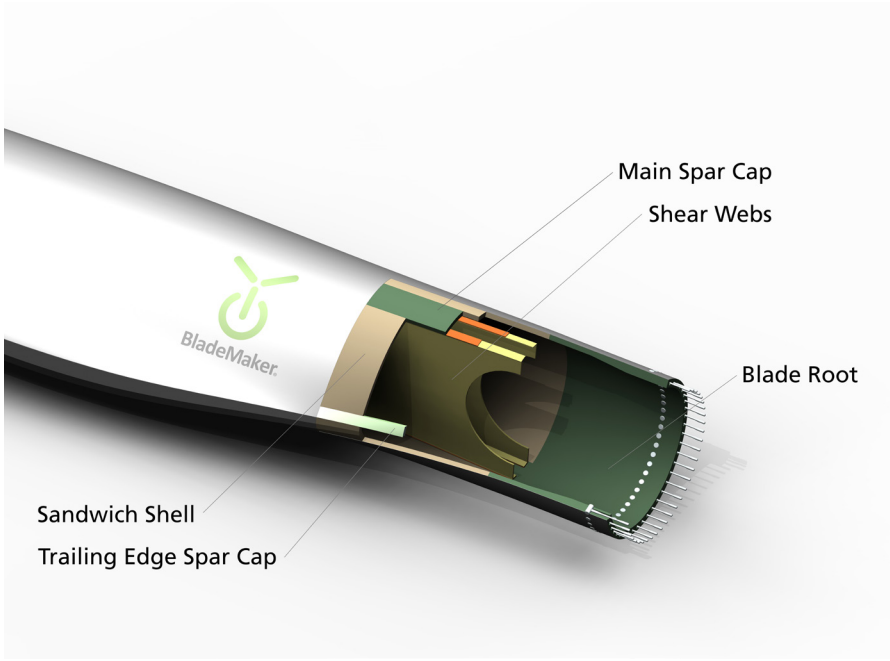
Innovative approaches

In the RE SORT project, scientists at Fraunhofer IWES are also investigating microwave pyrolysis alongside batch pyrolysis. In microwave pyrolysis, the energy is supplied by microwaves, which allows targeted and equal heating of the components to be pyrolyzed. Both pyrolysis processes aim to achieve an optimum balance between energy input and the quality of the recycled fibers. Fraunhofer IWES is responsible for the evaluation and testing of the recovered fibers.

In the ReusaBlade project, the institute is working in cooperation with a rotor blade manufacturer and other partners to investigate the use of solvolysis with 50% acetic acid as an alternative chemical process.

However, this method is only suitable for special resins basically designed to be dissolvable in acids. The focus is on the relationship between the speed of material degradation and the thickness and surface area of the test material. Initial testing on a laboratory scale has delivered very promising results, and the recovered fibers are then reprocessed and tested to determine their suitability for different applications.

In the international joint project EoLO-HUBs, Fraunhofer IWES is investigating the entire process chain from the disassembly of the rotor blades to the recovery of the fibers right up to the meaningful use of the recycled materials in cooperation with 20 partners from all over Europe.



Structure of a rotor blade © Fraunhofer IWES, rendering: © Siemens Industry Software GmbH

The focus is on three main areas: dismantling and pretreatment of the blades, sustainable fiber recovery and improving processes for refining the recovered fibers. By the end of the project in 2026, a demonstration recycling plant is to be set up in Spain and Germany, respectively, to test the entire process from blade to new fibers.

Conclusion: rotor blade recycling and the energy transition

From today's perspective, it is not yet possible to say for sure which process and which approach will ultimately prevail. There are still many steps needed for the development of an economically viable recycling solution. Nonetheless, current advances in research and the ongoing projects indicate that solutions for rotor blade recycling are not far out of reach.

However, it is important to emphasize that the disposal and recycling of rotor blades is not the central issue of the energy transition. Even if it should not prove possible to establish a completely circular economy for rotor blades, viable solutions will still be identified for overcoming the challenges and consolidating environmental responsibility within the wind energy industry.

The findings and technologies emerging from these research projects could not only revolutionize the recycling of rotor blades but also have an impact on other industries employing similar materials. In a time in which climate change and global warming are among the most pressing challenges facing humankind, it is essential to develop sustainable solutions that are both environmentally and economically viable.

Future research could focus on further improving the effectiveness of the existing processes and developing innovative technologies that significantly raise the recycling quota. Interdisciplinary cooperation between research institutes, industry and policymakers will be crucial for establishing the requisite political framework that promotes the development and implementation of innovative recycling technologies.

Overall, as one of the central pillars of renewable energy, wind energy is the focus of efforts to ensure a sustainable and environmentally friendly energy supply. Rotor blade recycling may represent a challenge at present, but the advanced research approaches and commitment of those involved show that solutions are in sight.

With the right measures and technologies, the wind energy sector can continue to make an important contribution to the energy transition while assuming responsibility for the environment at the same time.

As such, the future of rotor blade recycling is not only a technical challenge but also an opportunity to develop innovative solutions that contribute to the preservation of the environment and our planet.

Optimization of recycling processes and research into new materials can help to consolidate wind energy as a sustainable energy source while simultaneously reducing the industry's environmental footprint.

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