

Rotor blade recycling: the hidden challenge facing wind energy

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As a central element of a wind turbine, a rotor blade not only plays a decisive role in energy conversion but also makes a significant contribution to the cost efficiency and energy yield of the turbine overall. With sustainability and environmentally friendly solutions becoming increasingly important, the recycling of rotor blades is becoming increasingly relevant.

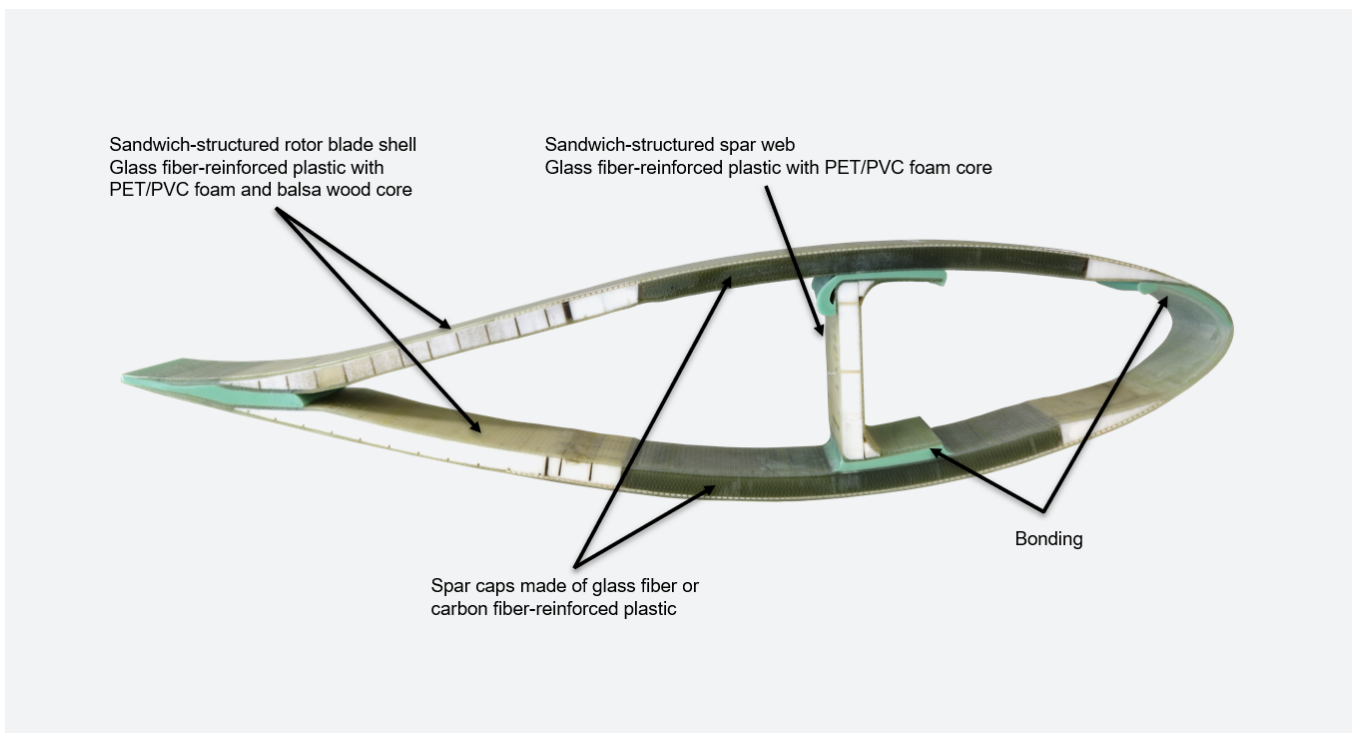


Fig. 1: Cross section of a rotor blade © Fraunhofer IWES

High-quality recycling requires a detailed understanding of the specific materials used in the construction of rotor blades.

A rotor blade is essentially made of fiber-reinforced composite materials such as glass fiber and carbon fiber, sandwich materials such as balsa wood and PET foam, and a thermoset matrix. The matrix, nowadays usually based on epoxy resin, permanently bonds the components together.

The smart combination of sandwich materials with spar caps made of glass fiber produces very light and highly buckling-resistant panels.

Balsa wood is usually employed as the sandwich material in the first third of the rotor blade. Further towards the blade tip, a lighter PET foam is used.

The main load of the rotor blade is borne by a spar-web system with a solid laminate spar on both sides and a web of sandwich materials. The flange, the connection to the rotor blade hub, is also made of solid glass fiber laminate.

Separation of materials by type

Comprehensive recycling demands the separation of the various materials used in

construction, as they are treated differently in the final recovery process. For the separation of the materials by type, it is important to know which material is located where in the rotor blade.

The resin, for example, can be separated from the fibers using pyrolysis, a thermal decomposition process in the near absence of oxygen, or solvolysis, a chemical dissolution process.

The glass fibers can then be returned to the material cycle by melting them down. Glass

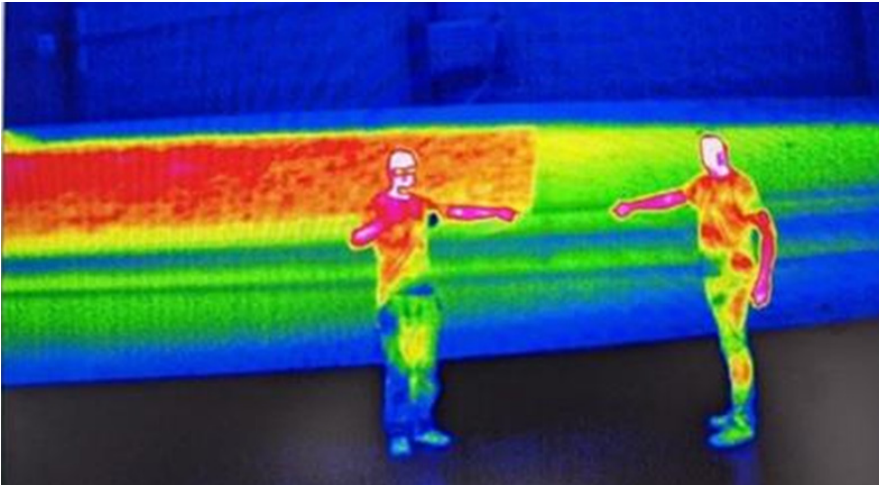


Fig. 2: Thermographic visualization of the boundaries between the balsa, foam, and spar caps © Fraunhofer IWES

fiber manufacturers have already developed suitable processes for this purpose and, in some cases, have introduced recycled glass rovings to the market.

The sandwich material can be separated from the glass fiber laminate using suitable shredding methods. The PET foam can be fully recovered by being broken down into its constituent parts using a suitable process called revolPET, patented by a German climate company.

Following further processing, the separated balsa wood can find a new use as an organic insulation material in the green building sector. This application was developed and brought to pre-production readiness within the scope of Fraunhofer WKI's ReRoBalsa research project.¹

Research needs for older rotor blades

As there is little or no documentation available concerning the construction of the rotor blades to be recycled that are 20 or more years old, the position and composition of the materials need to be determined using methods that still require further development, such as thermography and near-infrared spectroscopy.

The scientists at Fraunhofer IWES are working on adapting these methods for use in incoming inspection to identify the materials used and their positions in end-of-life (EoL) rotor blades. A new research project will construct a pilot facility for a disassembly center with subsequent recycling of the recovered materials.

In today's modern rotor blades, the spar cap is made of carbon fiber rather than glass fiber. Unlike glass fiber, carbon fiber cannot be melted down again, and the dust produced during shredding needs to be extracted using suitable filtering technology.

Once identified, the carbon-fiber spar caps must be removed and recycled separately. At present, the carbon-fiber spar caps are shredded and processed into a variety of carbon-fiber products such as short fibers and compounds made of recycled carbon fiber for thermoplastic materials.

For recycling solutions to be viable in practice, further information is required in addition to development of suitable processes: the decisive factor here being when, and in what quantities, rotor blades will actually be dismantled for recycling in the future.

Potential EoL rotor blade masses from onshore decommissioning

The real test for the circular economy begins when rotor blades reach the end of their service life: large quantities of fiber-reinforced composite materials must not only be disposed of but also ideally be transferred into new material flows as effectively as possible.

With the decommissioning of the first generation of wind turbines, end-of-life rotor blades are increasingly coming into focus. Forecasting the future end-of-life rotor blade masses is crucial to be able to develop suitable recycling and disposal strategies in good time, as well as securing the necessary capacity for managing future material volumes.

This is the only way to ensure that the increasing volume of decommissioned rotor blades can be processed in a way that is both environmentally friendly and saves resources.

Forward-looking planning allows the development of new recycling pathways and innovations in the circular economy sector, so that valuable materials such as glass fibers and resin can be returned to the production cycle and disposal bottlenecks can be avoided.

With this in mind, the Institute for Energy, Recycling and Environmental Protection (IEKrW) at Bremen University of Applied Sciences created a database within the scope of the RecycleWind 2.0 project which contains data on all wind turbines installed both onshore and offshore in Germany. This database is updated annually by Fraunhofer IWES, and also includes a forecasting tool.

In addition to detailed forecasts of total masses in the future, the database also allows material-specific evaluations of the EoL rotor blades. For example, the proportions of glass and carbon fiber, resin and core materials. This makes it possible to draw direct conclusions to aid the design of recycling processes.

Based on this data set, Figure 3 shows the estimated annual EoL rotor blade masses for the onshore sector in Germany from 2019 to 2042 in tons, as of December 2023. Figure 4 represents the corresponding forecast for

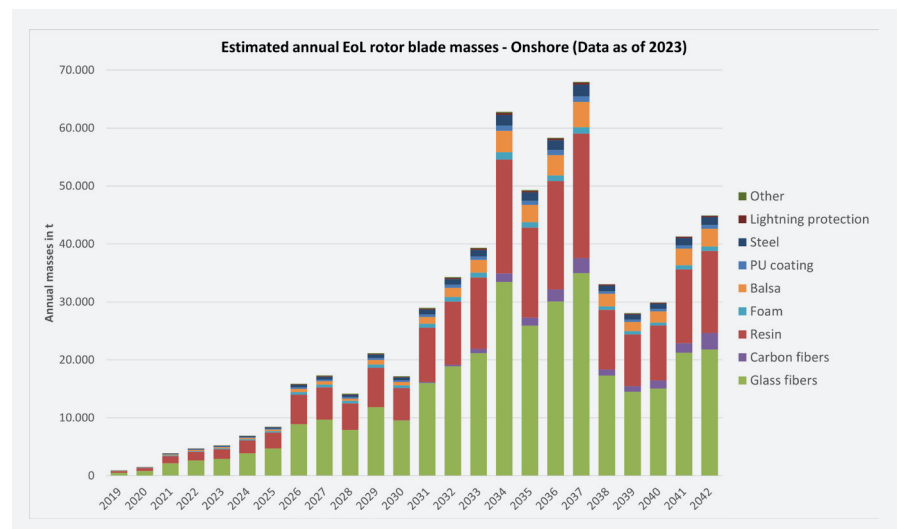


Fig. 3: Estimated annual EoL rotor blade masses in Germany for the onshore sector, based on installed turbines as of December 31, 2023 [Source: Fraunhofer IWES]

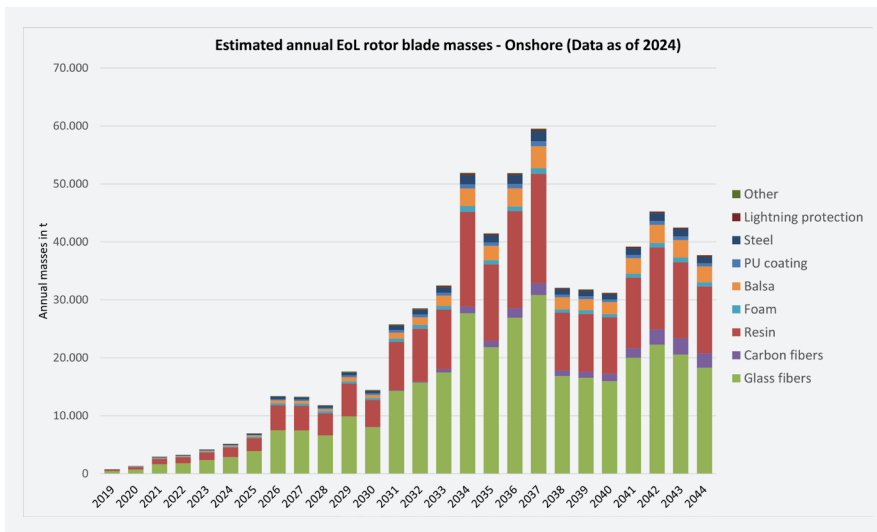


Fig. 4: Estimated annual EoL rotor blade masses in Germany for the onshore sector, based on installed turbines as of December 31, 2024 [Source: Fraunhofer IWES]

2019 to 2044 based on the updated data as of December 2024.

The rotor blade masses are broken down by material components into glass and carbon fiber, resin, foam, and further elements. Both diagrams clearly indicate that a considerable increase in the annual EoL rotor blade masses is expected in the coming years. The largest proportion of material will be glass fiber, followed by resin and core materials.

This direct comparison shows that the predicted rotor blade masses can vary significantly depending on the dataset used and assumptions applied. These fluctuations can be traced to the wide variety of challenges involved in forecasting EoL rotor blade masses.

For example, there are uncertainties regarding the actual lifespan of wind turbines, as factors such as maintenance, repowering and early decommissioning can significantly influence their effective lifespan.

In the past, a turbine lifespan of around 20 years was widely assumed, corresponding to the typical design and approval period, whereas current operational experience reveals that many turbines can be operated for 25 years or more, provided maintenance is correctly performed and site conditions are favorable.

Currently, modern wind turbines are usually designed for a service life of 25 to 30 years, and coordinated maintenance, retrofitting and technical improvements can enable continued operation in some cases even beyond this period. Incomplete or inconsistent data on installed turbines and the material composition of the rotor blades makes it difficult to estimate future volumes with precision. Therefore, it is all the more important to continuously collect up-to-date

data and to regularly adjust forecasting models so as to ensure reliable planning for recycling and disposal.

Potential EoL rotor blade masses from offshore decommissioning

A database was similarly created for offshore wind turbines. Figure 5 shows the estimated annual EoL rotor blade masses for the offshore sector in Germany from 2029 to 2044 in tons, as of December 2024. Glass fiber is also the main component of offshore rotor blades, followed by resin and core materials. However, as the first offshore wind turbines in Germany were not installed until 2010, an increase in decommissioning is not to be expected until 2030.

Due to the difficulty in estimating operating lifetimes of 25+ years for the offshore wind turbines installed to date, the expected

decommissioning volumes for individual years can only be estimated to a very limited extent.

In contrast to the onshore sector, future decommissioning scenarios play a key role here. Whereas the wind turbines are decommissioned individually or within a wind farm in the onshore sector and the surfaces then freed up for repowering, the situation at sea is completely different: as a standard capacity of 2,000 MW has been defined for future offshore grid connection systems (OGCS), new areas with a capacity of 1,000 or 2,000 MW have been designated according to the Site Development Plan 2025 for the German North and Baltic Sea.²

To achieve these capacities, it has been assumed that once existing, smaller wind farms within an area have been decommissioned, large, consolidated sites will be formed and developed in a single phase.

This means that individual wind farms are likely to operate for varying lengths of time beyond their approved operating period. For this reason, the estimated annual EoL rotor blade masses will likely become strongly concentrated in specific individual years because of evolving decommissioning scenarios. Figure 6 shows possible new offshore wind farm layouts, taking the DolWin cluster as an example.³

The Fraunhofer IWES study named above explored the possibility for the continued operation of existing offshore wind farms, taking the DolWin cluster as an example, and the associated offshore grid connection systems beyond their original operating period. The aim was to analyze the advantages and disadvantages of continued operation compared with decommissioning and new development from a scientific perspective.

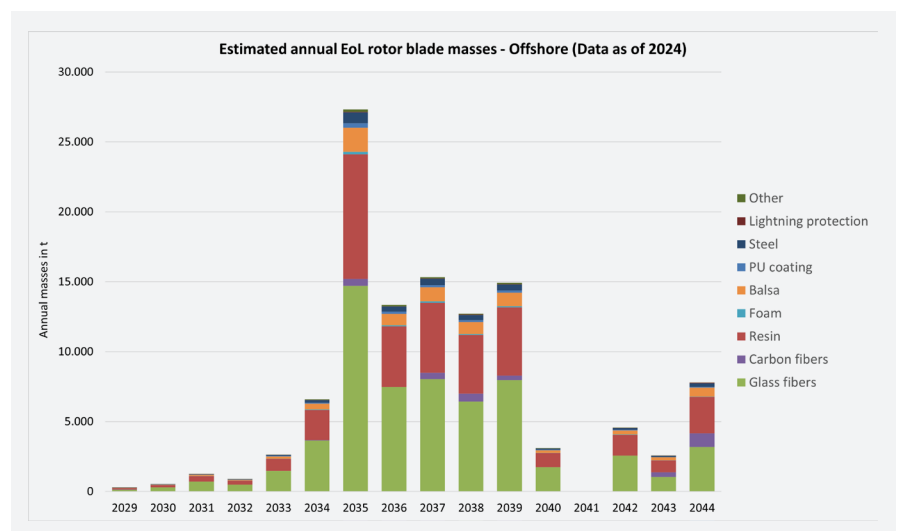


Fig. 5: Estimated annual EoL rotor blade masses for the offshore sector in Germany, based on installed turbines as of December 31, 2024 [Source: Fraunhofer IWES]

It is crucial to develop and make available innovative recycling pathways and sufficient capacities for the handling of these material flows, to master the challenges of the circular economy in the wind energy sector.

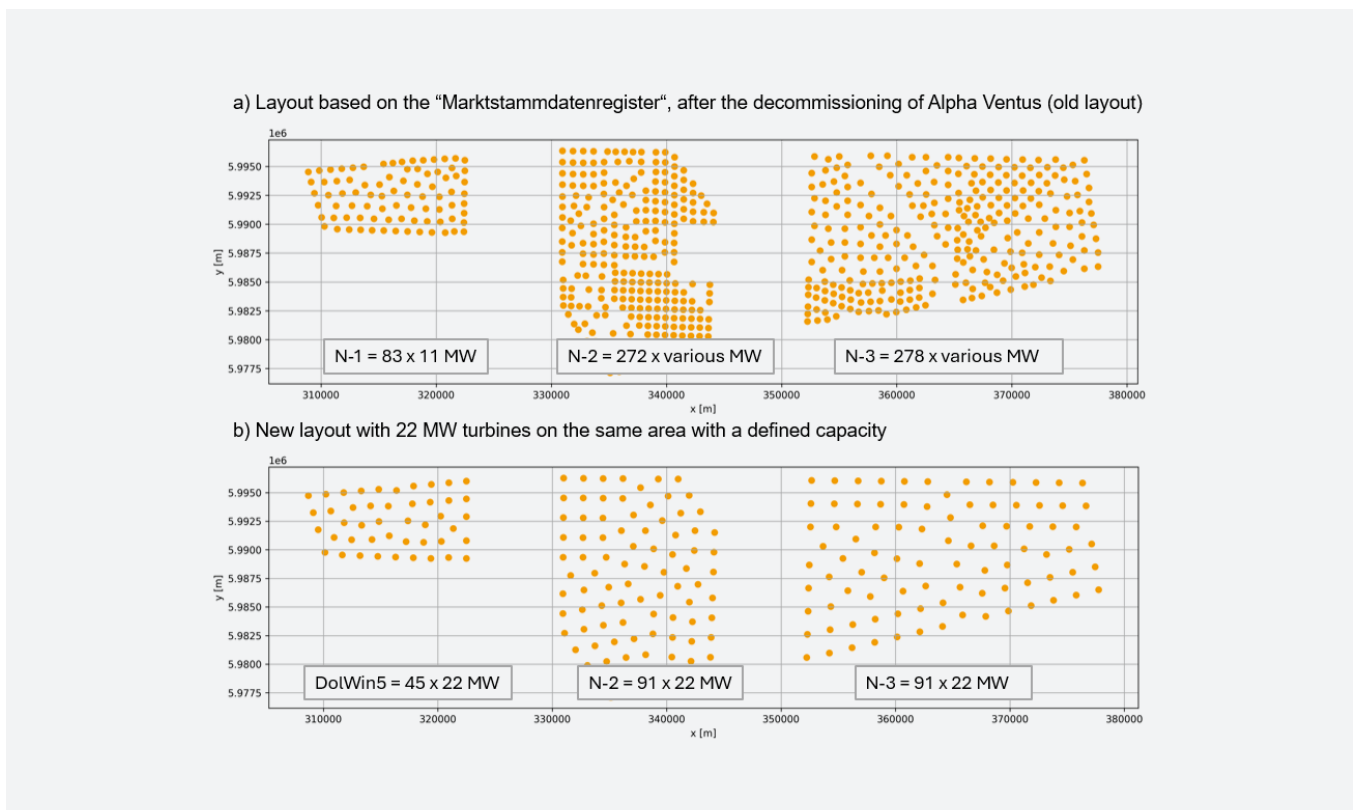


Fig. 6: Possible new offshore wind farm layouts at the DolWin cluster © Fraunhofer IWES

In addition to the considerations regarding supply chains, resources, capacities, and environmental aspects, a general finding of this study is that by continuing to operate the wind farms they can generate energy yields under economically favorable conditions, provided that sufficient offshore wind farms within a given area remain in operation to justify the operating costs of the grid connection.

Conclusion

Beyond the findings of the study, additional challenges arise for offshore decommissioning regarding the availability of special vessels required for this purpose, as well as port capacities for the storage and handling of the dismantled wind turbine components.

Furthermore, the further processing and recycling of other returned wind turbine components, such as the nacelles, towers including foundations, and especially the rotor blades, still need to be clarified.

The first onshore rotor blades are set to reach the end of their service life in the coming years and will thus be the first to accumulate in larger volumes for disposal and recycling. As such, it is crucial to develop and provide innovative recycling pathways with sufficient capacity to handle future material flows, in order to overcome the particular challenges of the circular economy of the wind energy sector.

iwes.fraunhofer.de/en.html

References

¹ Further information on the ReRoBalsa project: https://www.wki.fraunhofer.de/en/research-projects/2017/ReRoBalsa_rotor-blades-recycling-balsa-wood-plastic-foam-for-insulation-materials.html

² Site Development Plan: https://www.bsh.de/EN/TOPICS/Offshore/Sectoral_planning/Site_development_plan_2025/_Anlagen/Downloads_FEP2025/EN/Site-development-plan-2025-EN.pdf?__blob=publicationFile&v=3

³ See Fraunhofer IWES study "Evaluation verschiedener Weiterbetriebs- und Nachnutzungsszenarien von Offshore Windparks und Offshore-Netzanbindungssystemen in der Deutschen Bucht" commissioned by the BDEW, September 2025 (in German)