End-of-Life phase and three circularity concepts for Wind Turbine Blades

DECOM TOOLS **2022**

Interreg
North Sea Region
Decom Tools
European Regional Development Fund

EUROPEAN UNION

Project Partners:

Publication: 12 / 2022

Coordinator and Editor: PreZero Metaal

Layout: Energy Cluster Denmark

Main Authors: Nina Vielen-Kallio, Olivier Amersfoort

Project Title: DecomTools

Reference Number: Interreg North Sea Region – Project Number: 20180305091606

Abbreviations

CF	Carbon fibre
CFRP	Carbon fibre reinforced plastic
EoL	End-of-Life
EPD	Environmental product declaration
GF	Glass fibre
GFRP	Glass fibre reinforced plastic
IEA	International Energy Agency
PDS	Product Disposal Specifications
PET	Polyethylene terephthalate
PUR	Polyurethane
REE	Rare Earth Elements
RTM	Resin Transfer Moulding
SCRIMP	Seemann Composite Resin Infusion Process
TRL	Technology Readiness Level
VARTM	Vacuum Assisted Resin Transfer Moulding
WTB	Wind Turbine Blade

Table of Contents

1. Introduction

The general public and policy makers took large scale interest in wind turbine blade waste after Bloomberg released an article in February 2020 with title "*Wind turbine Blades can't be recycled, so they're piling up in landfills*", companioned with, by now infamous, picture of cut wind turbine blades been covered with dirt by a landfill compactor [1]. However, the challenges regarding circularity in wind industry is not different from any other industries as our society is working on to meet the targets of Paris Agreement, EU's Circular Economy Action Plan and many others. The challenge of the ongoing system change from linear economy to circular economy is multidisciplinary one and requires horizontal and vertical action from industry, policy, and academia.

In order to bring this "End-of-Life phase and three circularity concepts for wind turbine blades" into a larger context, this document presents the general overview about wind turbines, the materials used in them and how the industry has evolved over the years. This is done with motivation to provide the reader an understanding about (some of) the complexity related to this topic. It is crucial to understand that the evolution of the materials, waste volumes, geographical location of the wind farm, wind farm permit conditions, definitions used in policy papers and many other variables have a direct impact on the feasible End-of-Life options for WTBs.

As DecomTools project started in 2018 and has a focus on decommissioning phase of offshore wind farms, this report provides three circular concepts for decommissioned blades: cement-kiln route, pyrolysis, and repurposing, which all have their special pros and cons. The common factor between these is their focus on EoL solutions. This is important in the context of finding solutions for the currently operating (onshore and offshore) wind farms, from which thousands of tons of WTB waste are expected. Before the blades end up in any of these three EoL solutions, several other decisions related to economics, technical feasibility, legislation and environmental impacts needs to made by the wind farm owners[2], which make the role of EoL solution providers highly uncertain regarding business development. Without regulative push, the EoL solution providers often have to compete with the low landfilling and incineration prices. When the volume of feedstock material (WTBs) is uncertain and processes never get optimized, the service price stays high, hindering the progress toward more circular solutions.

As our society needs to shift towards circular economy, the focus also needs to change from EoL to total lifetime circular strategies – all the way from design phase. Major research and projects have been conducted about circular strategies in wind industry with a focus of the total lifetime of offshore windfarms by A.Velenturf[3] and in in general at the Circular Wind Hub[4],

---

[1] https://www.bloomberg.com/news/features/2020-02-05/wind-turbine-blades-can-t-be-recycled-so-they-re-piling-up-in-landfills
[2] J. Beauson et al. "The complex end-of-life of wind turbine blades: A review of the European context", 2022
[3] A. Velenturf, "A Framework and Baseline for the Integration of a Sustainable Circular Economy in Offshore Wind", 2021
[4] N. Vielen-Kallio et al. "How to support wind industry to become circular", 2022

to mention a few. However, the innovations and new circular strategies for EoL blades are often provided by SMEs or developed as part of publicly funded research project, making it challenging for those concepts to become mainstream without strong industrial partner.

Some frontrunners have been seen at the policy side, where circularity has been implemented as part of tenders for new wind farms. First in France, where recyclability of blades provided more points in the bid and then in the Netherlands where circularity will be implemented as part of the tender criteria in the 4 GW Dutch offshore windfarm, Ijmuiden Ver[5]. Hopefully, this will set a much-needed larger scale trend, where policy makers highlight the circular strategies as an obligatory focus point already at the design and project development phase of wind farms, instead focusing only on the EoL phase strategies.

Currently, in Europe, the cement kiln route for wind turbine blades is the only large-scale solution for recycling blades. However, the industry, policy makers and academia (and the collaboration between these three) are looking for other circular strategies and how to strengthen their implementation. Assessments, initiatives and research are done for example in projects and consortiums such as IEA Wind Task #45, EoLO-HUBs, Lichenblades and Re-Wind. However, the main challenge for implementing circularity to the wind industry is not anymore, a technical one, but related to policies and market conditions, which still facilitate mainly short-term price-based approaches.

[5] https://www.rijksoverheid.nl/documenten/kamerstukken/2022/11/04/vergunningverlening-windenergie-op-zee-ijmuiden-ver-4-gw

2. Wind turbine materials

Since the early 2000s, wind turbines have grown in size (in both height and blade lengths) and generate more energy. These wind turbines contain a large quantity and mixture of various materials. The main materials used in a wind turbine are cast-iron, steel, copper, aluminium, fibreglass, epoxy and neodymium and dysprosium magnets. Steel mainly used in the foundations and the tower sections of the wind turbine form the bulk of the material obtained. Steel and cast-iron recycling industry has been established for many years thus these materials are easily recycled. Similarly, copper and aluminium are mainly recycled as they have a large monetary value. The fibreglass and epoxy resin used in the blades and the hub are of primary discussion in the industry. Proper disposal of fibreglass is one of the most challenging aspects due to the size of components, recycling complexity and low market value. The composites in the blades consist of various materials with different properties. NdFeB (neodymium-iron-boron) magnets are mostly used due to their superior performance. These magnets contain about 30% of Rare Earth Elements (REE) like Neodymium[6].

2.1 Onshore vs offshore wind turbine materials

There are only a few published studies specifying the mass of materials used in an offshore wind turbine. For sake of simplicity, offshore and onshore windfarm materials analysed by DecomTools were considered to be the same. Also, as the turbine components (rotor, tower, nacelle) in both the turbine types onshore and offshore, have similar materials and quantities this further makes it a valid assumption. The main difference between onshore and offshore wind turbines, is the foundation, which also has a major influence on the material balance[6].

Offshore wind production is much more complicated than onshore in terms of the design of the wind turbine system and construction of the wind farm. Offshore wind turbines must be located above the crest level of the highest waves and have strong support structures connected to the seabed by foundations. Existing installed offshore wind turbines mostly comprise wind turbines with fixed foundations, such as gravity base, monopile, tripod and jacket foundations (Figure 1), installed in water depths of less than 50 m. Except for the gravity-based foundation made from reinforced concrete, these offshore foundations typically are composed of single steel[7].

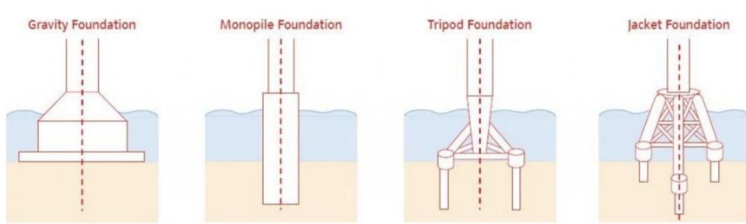

Figure 1: Four types of fixed foundations[7]

[6] DecomTools, "Decom offshore wind farms, recycling, reusing and selling of components/materials", 2020

[7] X. Wu et al. "Foundations of offshore wind turbines: a review", 2019

The foundation methods for onshore wind turbines can be divided into two subgroups; spread foundations and piled foundations. A spread foundation (or a slab foundation) is a foundation which consists of a big plate that makes use of the big area for spreading the loads to the ground. The construction material for spread foundations is almost exclusively reinforced concrete (concrete with steel beams that support the structure). If the soil properties are not sufficient to foot the foundation on the ground, it can be a good solution to install piles to conduct load to better soil at a greater depth in the ground. Even a piled foundation consists of a concrete plate, but here it serves as a connection between the piles and the tower, and the size of the plate can therefore be reduced. A pile is a long cylinder or prism of reinforced concrete or a tube of steel that is placed in the ground[8].

2.2 Recycling rates for wind turbine materials

The recycling rate of the materials varies according to the quality of the material, concentration in a component and available infrastructure. In the case of wind turbines, due to large quantities of materials in their components, the recycling rates are high compared to the global averages[6].

Table 1 shows the recycling rates of materials in an OWF based on the analysis done in DecomTools project[6] where ranks from 1 to 5 are given, where 1 signifies highly relevant or important while 5 indicates the material not so important under that parameter. Copper, cast iron and aluminium are highly recycled as the recycling industries have been well established, securing the 1st rank. Similarly, the recycling rate of the steel used in turbines is 92%, however during decommissioning offshore wind turbines, the monopile foundation below the seabed is kept in situ, thus a 50% recycling rate of steel in foundations is assumed indicating partial removal.

At present, most of the blades are disposed to cement kilns for incineration, this approach is considered as a recovery and was not included as recycling in the analysis. Thus, 15% of fibreglass and epoxy is assumed to be recycled back into similar fibre material. The recycling of magnets back into its raw material is not yet well established thus they have the lowest rank with a 5% recycling rate. The recycling potential of the wind turbine is 84%. This indicates the fraction of the wind turbine being recycled. With an increase in the recycling of fibreglass and epoxy, higher recyclability can be achieved. There is still research ongoing to develop a commercial process to recycle the glass fibres and epoxy back into the raw materials as the process of recycling is still difficult. In the next chapter wind turbine blades and its materials are further discussed[6].

[8] H. Svensson, "Design of foundation for wind turbines", 2010

Table 1: recycling rates of materials in an OWF[6]

Materials	Recycling rate	Rank
Copper	98%	1
Cast Iron	98%	1
Aluminium	95%	1
Steel	92%	2
Cables	90%	2
Foundations	50%	3
Fibre glass	15%	4
Epoxy	15%	4
Magnet	5%	5

3. Wind turbine blade materials

In 1941, electricity production from wind was made using turbines with steel blades. One of the blades failed after only a few hundred hours of intermittent operation. Thus, the importance of the proper choice of materials and inherent limitations of metals as a wind blade material was demonstrated early in the history of wind energy development. The next, quite successful example of the use of the wind turbine for energy generation is the so-called "Gedser" wind turbine, with three composite blades built from steel spars, with aluminium shells supported by wooden ribs, installed in Denmark in 1956–1957. After the 1970s, wind turbines were mainly produced with composite blades[9].

Nowadays, the most widely used technology to produce wind turbine blades, especially longer blades, is the resin infusion technology. In the resin infusion technology, fibres are placed in closed and sealed mould (see Figure 2), and resin is injected into the mould cavity under pressure. After the resin fills all the volume between fibres, the component is cured with heat. The resin infusion technologies can be divided into two groups: Resin Transfer Moulding (RTM) (resin injection under pressure higher than atmospheric one) and Vacuum Assisted Resin Transfer Moulding (VARTM) (or Vacuum Infusion Process) (when resin is injected under vacuum or pressure lower than atmospheric, typically, under a vacuum bag). A variation of VARTM called SCRIMP™ (i.e., Seemann Composite Resin Infusion Process) was developed in late 1980s and is quite efficient for producing large and thick parts. Currently, vacuum-assisted resin transfer moulding (VARTM) is the most common manufacturing method for manufacturing of wind turbine rotor blades. With his method, layers of fabrics of dry fibres, with nearly all unidirectional fibres (Figure 3), aligned in the direction along the length of the blade, are position on mould parts along with polymer foams or balsa wood for sandwich structures (for the aeroshells)[9].

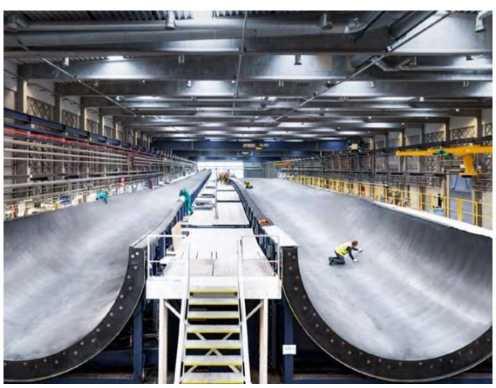

Figure 2: Mould for 115.5-meter offshore wind blade[10]

[9] L. Mishnaevsky et al. "Materials for Wind Turbine Blades: An Overview", 2017
[10] https://www.offshorewind.biz/2022/02/10/vestas-installs-mould-for-worlds-longest-wind-turbine-blades/

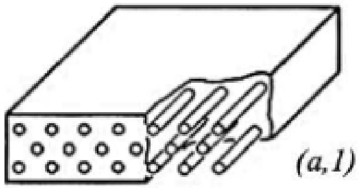

Figure 3: Unidirectional fibres[9]

3.1 Glass fibre reinforced plastics (GFRP) vs carbon fibre reinforced plastics (CFRP)

The stiffness of composites is determined by the stiffness of fibres and their volume content. Typically, E-glass fibres are used as the main reinforcement in the composites. With increasing the volume content of fibres in unidirectional composites, the stiffness, tensile and compression strength increase proportionally, yet, at high volume content of fibres (after 65%), there might be dry areas without resin between fibres and the fatigue strength of the composite reduces. Typically, the glass/epoxy composites for wind blades contain up to 75 weights % glass[9].

Many investigations toward the development of fibres, which are stronger than the usual E-glass fibres, have been carried out. The high-strength fibres (which are still used seldom in practice but represent a promising source of the improvement of the composite material) include glass fibres with modified compositions (S-glass, R-glass, etc.), carbon fibres, basalt and aramid fibres. S-glass (i.e., high strength glass, S means “Strength” here) developed in the 1960s, shows 40% higher tensile and flexural strengths, and 10–20% higher compressive strength and flexural modulus, as compared to E-glass. Carbon fibres are considered to be a very promising alternative to glass fibres. They show much higher stiffness and lower density than the glass fibres, thus, allowing the thinner, stiffer and lighter blades. However, they have relatively low damage tolerance, compressive strength, and ultimate strain, and are much more expensive than the E glass fibres. Carbon fibre-reinforced composites are sensitive to fibre misalignment and waviness: even small misalignments lead to a strong reduction of compressive and fatigue strength. Carbon fibre composites are used by the companies Vestas (Aarhus, Denmark) and Siemens Gamesa (Zamudio, Spain), often in structural spar caps of large blades[9].

3.2 Balsa wood and its substitutes

Balsa wood is a fast-growing hardwood that thrives in the climates found in parts of South America and as a core material for wind turbine blades known for its strength and lightweight[11].

Based on the application, the wind energy segment holds the largest share of more than 30% in the balsa core materials market in 2019. Low weight, cost-effectiveness and high strength of balsa core materials make it suitable to use in wind turbine blades. Increased global demand for wind power generation has propelled the growth of the balsa core materials market. According to International Energy Agency (IEA), global onshore wind electricity generation increased by 12% in 2018 and is expected to grow in future, which in turn boosts the increased growth of balsa core materials. Balsa has a natural honeycomb-like cell structure and is extensively used in sandwich composites due to its unique properties.

Currently, there is a worldwide shortage of balsa wood, which can cause worldwide delays of new wind power projects[11]. The use of PET (Polyethylene terephthalate) plastic as a substitute for balsa wood has been progressively adopted in recent years in the manufacture of blades. To provide greater supply chain flexibility in blade production, LM Wind Power has been working with its suppliers during the last number of years to replace balsa as a core material, with PET which is a plastic polymer commonly found in food and drink packaging. It can also be recycled (known as R-PET) and while its material properties differ from balsa wood, the infusion process during blade manufacturing strengthens the foam sheets even further[12]. In 2014, LM Wind Power started using PET foam in the shear webs of blades and its use has been steadily gaining momentum ever since.

As the materials used in the WTBs are currently changing, it is challenging to keep up and design optimized solutions for their EoL processing. This is the case especially if the materials need chemistry-based processing. Even though diversifying the supply chain brings flexibility and security to the manufacturing industry of WTBs, it also brings additional complexity to material processing at EoL.

3.3 Other substituting materials

The global installed capacity of onshore wind power should increase three-fold by 2030 (to 1.787 GW) and ten-fold by 2050 (to 5044 GW) to meet the net zero targets. Global cumulative offshore wind capacity would increase almost ten-fold by 2030 (to 228 GW) and even more

---

[11] ttps://www.linkedin.com/pulse/remarkably-strong-lightweight-paulownia-wood-wind-victor-garlington/

[12] https://www.lmwindpower.com/en/stories-and-press/stories/sustainability/from-a-plastic-bottle-to-a-wind-turbine-blade

towards 2050, with total offshore installation nearing 1.000 GW by 2050[13]. Therefore, it is critical to quickly introduce also circular solutions.

Besides companies developing more durable and cost-efficient wind turbine blades they are now also developing recyclable blades as those have been the most challenging component when it comes to circularity.

The ZEBRA (Zero wastE Blade ReseArch) consortium has produced the first prototype of its 100 per cent recyclable wind turbine blade. Within the project, LM Wind Power, a GE Renewable Energy Business, has designed and built the world's largest thermoplastic blade. According to LM Wind Power, the 62-metre blade was made using Arkema's Elium® resin, which is a thermoplastic resin known for its recyclable properties together with the new high-performance Glass Fabrics from Owens Corning[14]

Siemens Gamesa pioneers wind circularity and launched world's first recyclable 81-meter-long wind turbine blade for commercial use offshore. With this technology, separation of the materials in the blade is possible at the end of its lifetime, enabling recycling into new applications and thereby defining the next milestone in sustainability. Siemens Gamesa RecyclableBlades are made from a combination of materials cast together with resin to form a strong and flexible lightweight structure. The chemical structure of this new resin type makes it possible to efficiently separate the resin from the other components at end of the blade's working life[15]. However, a market for the extracted fibres still needs to be developed. Additionally, the recycling of these blades requires a process, which uses mild acid for the resin to be extracted, meaning that at the EoL phase of these blades they require tailor-made processing plant.

The company Covestro partnered with the Chinese wind turbine giant Goldwind and the wind blade manufacturer LZ Blades to develop the world's very first 64.2m wind turbine blade entirely made of polyurethane (PUR) resin, demonstrating the material's suitability as a cost-effective solution for wind turbines. The 64.2-meter blade, from spar cap to the shear web and the shell, was constructed entirely of polyurethane infusion resin, making it the first of its kind for the wind power industry. Covestro in planning a small-scale production to start soon[16].

ACT Blade Ltd has also responded on the need for new type of blades with an innovative design. Incorporating the same technology used to create the fastest boat in the world, this innovative blade boasts the potential to cut the costs of energy production by 9%. The increased length of the blade in comparison to its conventional counterparts is made possible by a light textile body. Unlike conventional fibreglass blades, the ACT Blade has been designed to be partly recyclable and to use recycled material, reducing landfill waste and in line with

---

[13] IRENA, "Future of wind: Deployment, investment, technology, grid integration and socio-economic aspects", 2019

[14] https://www.offshorewind.biz/2022/03/17/first-fully-recyclable-wind-turbine-blade-rolls-out/

[15] https://www.siemensgamesa.com/newsroom/2021/09/launch-world-first-recyclable-wind-turbine-blade

[16] https://solutions.covestro.com/en/highlights/articles/cases/2020/goldwind-lz-blades-wind-turbine-blade-success

responsible energy production[17]. Additionally, a modular approach could provide major cost and CO2 footprint improvements in the logistics.

ExoTechnologies is a next-generation solution and investment company that developed a pioneering composite material, which according to the company has exceptional strength capable of being recovered, recycled, and reused repeatedly. This technology called DANUTM can accelerate the green transition to circularity for composite material used in among other things wind turbine blades. On top of that, ExoTechnologies argue that the composite is free of toxins and considerably stronger than fibreglass[18]. The material has been tested in boats and the company is looking for opportunities to test the composite materials also in wind industry.

The examples given in this chapter provide only some of the industrial innovations related to material science. At the same time, it is an admirable proof of the innovativeness of wind industry, but it also provides a typical example of industrial partners acting independently, which might cause additional challenges on scaling-up EoL solutions due to diversity of materials used in the WTBs. The challenge remains between supporting innovativeness in the industry and; harmonising material content, which has potential to accelerate circular economy.

[17] http://actblade.com/act-blade-the-next-generation/
[18] https://exo-tech.com/index.php/danu/

4. Current situation

While most of the turbine components can be recycled, the EoL management and recycling of wind turbine blades have been frequently presented in the media as impossible and blamed for resulting in a huge environmental impact. Due to the nature of the materials used in wind turbine blades, namely GFRP, wind turbine blades are technically difficult to re-process and convert into new valuable materials[2]. Wind turbine blade waste is becoming an increasing problem as the first generation of turbines is now being decommissioned and the blades are ending up mainly in landfill, incineration, and the cement industry[19].

WindEurope called for a Europe-wide landfill ban on decommissioned wind turbine blades by 2025. Europe's wind industry actively commits to re-use, recycling, or recovering 100% of decommissioned blades. This comes after several industry-leading companies announced ambitious plans for blade recycling and recovery. A landfill ban would further accelerate the development of sustainable recycling technologies for composite materials. WindEurope expects around 25.000 tonnes of blades to reach the end of their operational life annually by 2025[20]. The impending ban on dumping wind turbine blades into landfills in the EU means that incineration will soon become the only option[21]. For wind turbine blade waste, incineration is however not so interesting as the materials have a high glass fibre content, which does not have a high calorific value and leaves a lot of ashes to be further treated[2].

The recovery potential for such a complex composite product as a blade, can be improved by relatively simple interventions such as documenting product specifications, enabling traceability through identification, and sharing information along the product value chain[22]. The DecomBlades project developed Product Disposal Specifications (PDS) by mapping out the composition of the blades of three major blade manufacturers: Siemens Gamesa, LM Wind Power, and Vestas. The data has formed the base for a standardised recommendation for blade disposal specifications, which includes what materials are used in the blades and where they are situated. This makes it is easier for recycling companies to separate the blades and recycle the parts[23]. The PDS can be seen as type of Material Passport (MP), which often includes weights and material contents of a component or a product.

Vestas also already works with a "material brochure" in which they show the material breakdown of specific Vestas' turbines. Life Cycle Assessments are used to provide detailed knowledge regarding the material composition of the wind plant[24]. TPI Composites also works on this subject and partnered with RecycleWind, a publicly funded research consortium aimed at developing resilient recycling networks for wind turbines and blades. The project developed

---

[19] https://northsearegion.eu/decomtools/news/bending-wind-turbine-blades-circular/
[20] WindEurope, "Wind industry calls for Europe-wide ban on landfilling turbine blades", 2021
[21] https://www.tno.nl/en/sustainable/renewable-electricity/offshore-wind-farms/designing-sustainable-wind-turbines/
[22] J. Joustra et al., "Structural reuse of wind turbine blades through segmentation", 2021
[23] https://decomblades.dk
[24] https://www.vestas.com/content/dam/vestas-com/global/en/sustainability/environment/2022_09_Material-Use-Brochure_Vestas.pdf.coredownload.inline.pdf

an Environmental Product Declarations (EPD) for blades, a Type III Environmental product label in accordance with ISO 14025, to share specific product information[25].

In the context of long-life products, such as rotor blades of wind turbines, structured information on the used materials and designs is of enormous importance for circular strategies at the end of the product's service life. However, due to the long service life, information on materials, personnel as know-how carriers, or even manufacturers themselves might not be available anymore[26]. In the case of dismantling projects for wind turbines, there are clear gaps in the documentation on the specification of the materials used and on the necessary technical data, such as weights. This makes dismantling planning and reliable cost calculation difficult[26].

For these reasons, EPDs should be required for the main components of a wind turbine for an efficient recycling management system. An EDP is a comprehensive and externally verified description of the environmental impact, including environmentally relevant properties of a specific product, presented in the form of neutral and objective data. However, such EPD's are currently not widely used[26].

Data sharing options related to MPs, LCAs, EDPs and PDSs provide interesting opportunity to facilitate circular strategies without major investments on technical R&D. This approach is not yet implemented on larger scale across stakeholders. However, it has potential to support knowledge sharing across the value chain, accelerate new innovations based on reliable data and support policy makers in decision making.

---

[25] https://www.tpicomposites.com/industries-services/wind/research-development/
[26] https://www.iekrw.de/recyclewind/

5. Circular Strategies

A circular Economy aims to keep products, components, and materials at their highest utility and value, at all times. The way to do this is to focus on the principals of the model, commonly known as the Circular Strategies (or R-strategies) of the circular economy namely, rethink, reduce, re-use, repair, refurbish, recover and recycle[27].

This report focuses on the solutions for the blades of currently operating (onshore and offshore) wind farms. Therefore, higher level circular strategies are not further discussed.

The European Waste Framework Directive (2008/98/EC) defines basic concepts related to waste management. It emphasizes the need for increased recycling and highlights the reduced availability of landfill. It also establishes the waste hierarchy shown in Figure 4.

The wind industry is committed to sustainable waste management in line with the waste hierarchy. The first step is the prevention of blade waste through reduction and substitution efforts in design. Then, the blade should be used and reused for as long as possible. Repurposing is the next step in the waste hierarchy. This means re-using an existing part of the blade for a different application, usually of lower value than the original. Where repurposing is not possible, recycling and recovery are the next options. Recycling means the blade becomes a new product or material with the same or different functional use. Disposing of blades via landfill or incineration without energy recovery are the least favoured waste treatment methods because there is no material or energy recovery.

Figure 4: The waste hierarchy for sustainable blade waste management

[27] https://medium.com/@beta__i/the-7-rs-of-the-circular-economy-11d27e933f01

Figure 5 shows a framework and baseline for a circular economy in offshore wind designed by Anne Velenturf. In this framework, circular economy strategies are organised by their application to materials, components and whole infrastructure (columns), the narrowing, slowing and closing of resource flows and their integration into the environment (rows, left side), throughout the offshore wind infrastructure lifecycle, from design to the end-of-use and beyond (rows, right side). Arrows indicate that one strategy enables another, for example, disassembly enables remanufacturing, and maintenance and repair enable lifetime extension[3].

The first row ties in with the previous discussed newcomers such as Siemens Gamesa, Covestro, RecyclableBlade, ACT Blade, ExoTechnologies. The second column comprises among other things, such as PDS developed by the DecomBlade project, and the repurposing strategy as described by The European Waste Framework Directive. The third and fourth row adhere to the different circular strategies for wind turbine blade disposal.

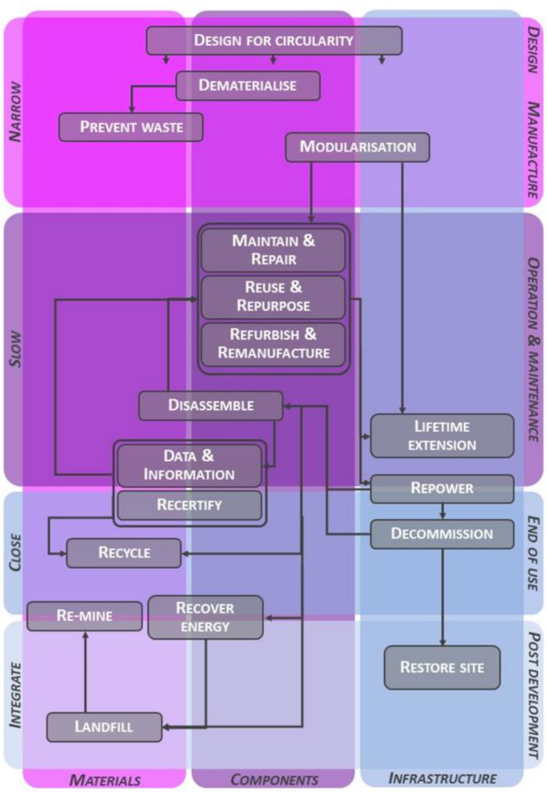

Figure 5: Circular Economy Framework for Offshore Wind[3].

Several examples can be given for companies and initiatives focused on EoL solutions. One example is Continuum, an organization registered in Copenhagen, Denmark with subsidiaries in Esbjerg and the UK, that developed a high-performance panel made from 92% recycled material that can be used in construction, for example as facades, doors, water-exposed interior walls like bathrooms, or even as sound barriers along motorways. See Figure 6 for the recycling process. This all translates into a huge potential environmental impact: The company's goal is to eliminate all industrial composite waste by 2050, thereby reducing emissions by at least 100M tons of CO2 per year[28].

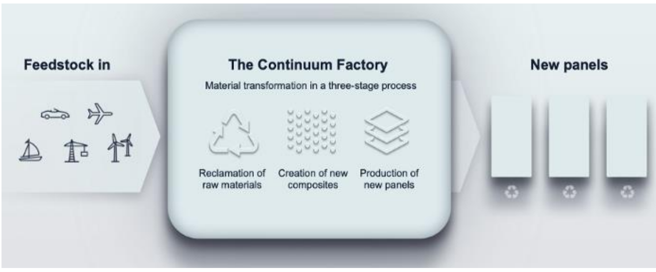

Figure 6: Continuum recycling process[28]

Circular recycling company (CRC) offers another solution for WTBs. The system developed for collecting, sorting, and mechanically and chemically processing these materials creates various recycling flows. CRC separates the material to different compositions. A coarse and a fine recyclate of glass and carbon fiber is created by means of a mechanical action[29].

Due to unclarity in communication between different recycling strategies many stakeholders involved in the composites supply chain refer to the concept of "recycling". To increase the understanding of different circular strategies in the wind industry, a circular wind guide has been recommended to translate valuable academic findings related to circular business models into an industry-friendly information package. By introducing the strategies systematically and giving practical examples of already utilized strategies, it is possible to increase the circular opportunity recognition of stakeholders in the industry and in the policy domains[4]. This shifts the general narrative from "recycling" to wider options of circular strategies.

[28] https://medium.com/@climentum/our-investment-in-continuum-a-startup-pioneering-zero-emissions-wind-blade-and-composite-materials-6443e56cba8
[29] https://c-r-c.nl

6. Circular concepts for wind turbine blades

Despite the developments in full circular solutions for wind turbine blades still, a large number of already produced blades will eventually reach their end of life. An estimated 10.000 to 20.000 blades annually are expected to be at the end of their lifespan between 2025 and 2040[30].

Today, the main technology for recycling composite waste is through cement co-processing, also known as the cement kiln route. Composite materials can also be recycled or recovered through mechanical grinding, thermal (pyrolysis, fluidised bed), thermo-chemical (solvolysis), or electro-mechanical (high voltage pulse fragmentation) processes or combinations of these. These alternative technologies are available at different maturity levels, and not all are available at the industrial scale, as shown by the technology readiness levels (TRL) presented in the table 2 below for each existing treatment method[31].

The processing methods also vary in their effects on the fibre quality (length, strength, stiffness properties), thereby influencing how the recycled fibres can be applied. The wind industry is pushing for the development and industrialisation of alternative technologies to provide all composite-using sectors with additional solutions for EoL[31].

The two recycling methods with the highest TRL ranking are the cement kiln route (in use) and pyrolysis (high promising) method. Therefore, this report focuses on these two concepts but also on the repurposing of wind turbine blades. Repurposing of wind turbine blades is already applied in various forms and as it is a higher circular strategy it should be considered before recycling[31].

Table 2: Recycling methods and their TRL[31]

Recycling method	TRL	
Cement kiln route	9	
Mechanical grinding	9 (Glass fibre)	6/7 (Carbon fibre)
Pyrolysis	9	4/5 microwave pyrolysis
High voltage pulse fragmentation	6	
Solvolysis	5/6	
Fluidised bed	5/6	

[30] https://www.nrel.gov/news/program/2022/nrel-researchers-point-to-path-for-improved-wind-blade-recycling-rates.html
[31] Wind Europe, "Accelerating Wind Turbine Blade Circularity", 2020

6.1 Cement kiln route

The largest commercially available technology for recycling composite waste today is through cement co-processing. This technology has a Technology Readiness Level (TRL) of 9. In cement co-processing the glass fibre is recycled as a component of cement mixes (cement clinker), substituting sand. The polymer matrix is burned as fuel for the process (also called refuse-derived fuel), which reduces the carbon footprint of cement production. Cement co-processing offers a robust and scalable route for treatment of composite waste. It also has a simple supply chain. Wind turbine blades can be broken down close to the place of disassembly thus facilitating transport to the processing facility. Although it is very promising in terms of cost-effectiveness and efficiency, in this process the fibre shape of the glass disappears and therefore cannot be used in other composites applications. Figure 7 gives an overview of the input and output in a cement kiln reactor[31].

Strengths of cement co-processing are the advantage that the process is highly efficient, fast, scalable and has no left-over ash. Large quantities can be processed which is still a challenge for other alternatives. This technology is also capable to reduce CO2 emissions of cement manufacturing by up to 16% and increases energy efficiency of cement manufacturing. The disadvantage is that there is a loss of the original fibre's physical shape. Also, this application is only suitable for glass-reinforced composites[31].

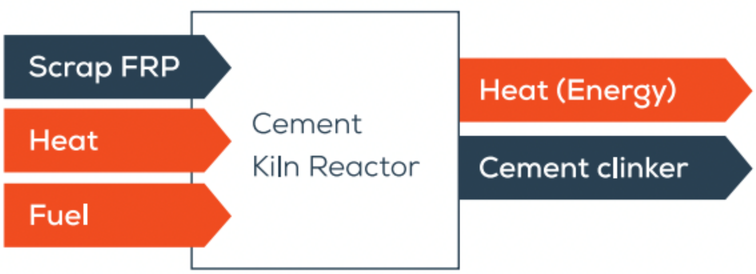

Figure 7: Flowchart Cement kiln process[32]

According to DecomBlades[23] project, the main requirements for the use of blades as alternative fuel in the cement industry are:

- Moisture content, high moisture less calorific value
- Particle size: high specific surface area improves the calorific value of the fuel
- Calorific value
- Amount of volatiles: volatiles as chlorine and sulphur leads to build-ups in the calciner and kiln systems impacting negatively the pyro process. Also clinker quality can be affected inducing to low late strength and rheology problems.
- Homogeneity: chemical and physical aspects can impact calorific value of the fuel and they will also impact the clinker quality

[32] Wind Europe, "Wind industry calls for Europe-wide ban on landfilling turbine blades", 2021

Four archetypes of blades were selected in the project, ground and a full characterization of the blades were carried out in order to ensure that they full fill all parameters required for a fuel. The results are intended to show the feasibility of the use of wind turbines blades in the cement industry, encouraging blades recycling and new materials development, by relating fundamental research to the normalisation process[23].

The company Neowa that started operations in 2015 now sustainably recycles fibre composites such as rotor blades. They have been exploiting their process technology know-how to process selected material flows in such a way as to allow these materials to be utilised in a range of different industries as a substitute for raw materials which are now becoming increasingly scarce. Now the material and thermal recycling of fibre composite waste resulting from the dismantling of wind turbines can be applied as a substitute in the cement-processing industry. Neowa is prepared to continue to face up to their responsibility and are gradually developing expertise as a solution provider and waste management plant operator[33].

Despite cement kiln route being viable solution for the WTBs and is getting implemented in larger scale also outside Europe[34] for example by Veolia, this strategy can only be considered circular if there is a viable solution also for the concrete. Additionally, the position of cement kiln route is not fully clear in the waste hierarchy, because only part of the WTBs (fibres) is substituting material in the process and large part (resin) is getting incinerated. This questions the definition of “recycling” in this context. However, the cement-kiln route is still partly substituting material use and therefore can be considered more valuable option than landfilling, which still takes place in many countries.

For GF based WTBs the cement kiln route is technically viable option, but the newer blades contain also CFs, which cannot be accepted to the processing. Therefore, a removal of CF-based parts is required. This would make sense also from economic perspective as recycled CFs have higher market value than GFs.

Unfortunately, due to lack of transparency in material transportations, it is not fully clear what are the current volumes of WTBs ending up in different EoL options. Here data sharing options related to traceability could provide solutions.

---

[33] https://www.neowa.de/en/about-neowa

[34] https://www.veolianorthamerica.com/media/newsroom/veolias-pioneering-wind-turbine-blade-recycling-program-supports-economic-growth-and

6.2 Pyrolysis

Pyrolysis is a thermal recycling process which allows the recovery of fibre in the form of ash and of polymer matrix in the form of hydrocarbon products. Pyrolysis technology in general has a TRL of 9 and the microwave variant TRL 4/5, but currently pyrolysis is not used in a commercial scale on WTBs. Although it allows for the lowest value loss from industrial-scale technologies, there is still a loss of value. Matrices are turned into powder or oil, potentially useable as additives and fillers. The fibre surface is often damaged due to the high temperatures, resulting in a decrease in mechanical properties. Pyrolysis requires high investment and running costs. Economic viability depends on the scale and reuse that the matrix-obtained chemicals can have. To date, this recycling technology is only economically viable for carbon fibres. It is, however, not currently implemented at large scale since the volumes of carbon fibre reinforced composites are low. However, for example CFK Valley Stade Recycling has been active developing a pyrolysis process with CF extraction in mind. Latest collaboration with Mitsubishi Chemical Advanced Materials show the potential of pyrolysis to become next level circular strategy for WTBs. However, for GFs the economic viability continues to be a challenge.

With the next generation of mega-turbines, the required weight reduction and mechanical properties will enhance the preferred use of carbon fibre composites and the market volume might grow accordingly. Figure 8 gives an overview of the input and output of the pyrolysis process[31].

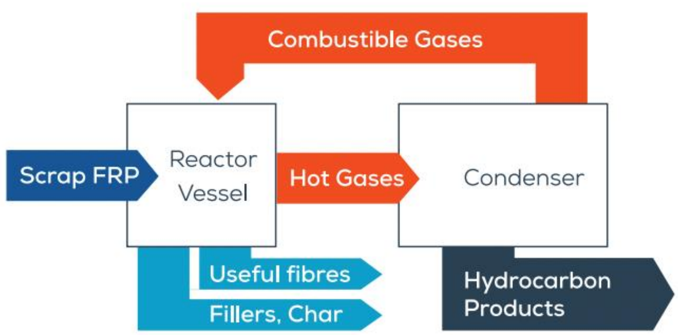

Figure 8: Flowchart Pyrolysis process[31]

Strengths of pyrolysis are the advantage that it is relatively easy to be scaled-up and the by-products (syngas and oil) can be used as energy source or as base chemicals/ building blocks. The technology is already used at commercial scale for recycling carbon fibre composites. Microwave pyrolysis is easier to control and causes lower damage to the fibres but is still in a lower TRL level[31].

The disadvantages are the loss of strength of fibres due to high temperatures, the fibre product may retain oxidation residue or char, and a decreased quality of the recovered fibres from original material. Though, it still has the lowest value loss in comparison to other mature recycling technologies. To date this technology is economically sound for carbon fibre recovery.

In DecomTools project pyrolysis process was used in pilot scale for processing approximately 70 kg of WTB pieces. In Figure 9 the different phases of the testing can be seen: WTB pieces before the pyrolysis, WTBs after the pyrolysis, extracted pyrolysis oil, GFs after heat treatment and CFs after heat treatment.

Figure 9: Pilot scale testing of pyrolysis in DecomTools project

The DecomBlades project also focusses on pyrolysis technology. The project has carried out several controlled small-scale tests which, combined with their knowledge from Plastcon (a plastic recycling plant), have enabled them to design a pilot plant. The primary output of their pyrolysis process is liquid (e.g. used as fuel or in the chemical industry), gas (e.g. used for heating or electricity) and solid materials (glass fibres, carbon fibres, ash). They have carried out initial analysis of the outputs which are looking promising. At the end of DecomBlades project they will aim to have concept-designed a full-scale pyrolysis plant for composite materials which interested parties can order[23].

TNO also develops pyrolysis to an advanced stage. The experts at TNO and Brightlands Materials Center have focused on a thermochemical process involving pyrolysis, in which the material is heated to almost 500 degrees Celsius without oxygen, releasing the fibres. They can then be processed into thermoplastic composite to be used in recyclable products. This is an extension of a technology TNO developed previously to produce biochar, a soil improver that they make from biomass by means of pyrolysis. They are now making that process suitable for recycling wind turbine blades. TNO now has a pilot plant that can make biochar on a scale of a few tonnes. And they've successfully replicated that process for turbine blade recycling[35].

Pyrolysis as a process is energy consuming, which hinders its implementation from sustainability perspective. Some pyrolysis processes optimise the energy consumption by using the extracted pyrolysis oil in the heating. However, this approach can question the environmental sustainability because part of the WTB material is in that case incinerated. In

[35] https://www.tno.nl/en/newsroom/insights/2022/10/tno-innovation-offers-discarded-wind/

order to utilize higher level circular strategy, the energy source for the pyrolysis process should either come from renewable sources or the process should at least be optimised to use only minor part of the pyrolysis oil (and gasses) for heating. The highest circular value can be obtained, when the pyrolysis oil is processed to new materials and products, therefore locking the carbon for reuse. This would at least require a design for a continuous pyrolysis process in order to avoid the process being run up and down, causing inefficiencies in energy use. Additionally, the optimal particle size should be considered. Larger particle size requires less preliminary processing in sizing, but longer processing time at the pyrolysis phase. The best solution is also highly dependent on the end-use of fibres as in general longer fibres are considered more valuable, but it can be challenging to keep the fibres in their original form and order through the process.

6.3 Repurposing

Repurposing is the step in the waste hierarchy that comes before recycling. Repurposing means re-using an existing part of the blade for a different application, usually of lower value than the original. See Figure 10 for an example of a blade turned into a bike shed[31].

The environmental benefit of repurposing can be found especially from the raw material side. As an example, LM Wind Power reports that 76% of the blades CO2 footprint originates from mining and processing[36]. For any material, which includes extensive global subbly chain, starting from raw material mining, the share of CO2 footprint is in the same level of magnitude. Therefore, repurposing WTBs to new functions, saves large amounts of material extraction and carbon emissions.

Figure 10: Bike shed from a blade[31]

As a circular strategy, repurposing can provide an opportunity for product to have several life cycles as presented by Jelle Joustra[37]. After WTB has served in its original purpose, it can be repurposed for other larger products such as bridges or sound walls. This prevents virgin raw material extraction even though it can be expected that 100% of the material might not be effectively used. After the first repurposing cycle, the product can again be repurposed for smaller designs such as plank, preventing virgin raw material extraction for a second time. The cascading approach is presented in the Figure 11.

An approach like this requires higher level implementation of circular economy and a new way of thinking related to material use.

[36] J. Korsgaard presentation, “Powering a cleaner world with sustainable blades”, 21.11.2022, Riso

[37] J. Joustra presentation, “Structural reuse by design”, 22.11.2022, Riso

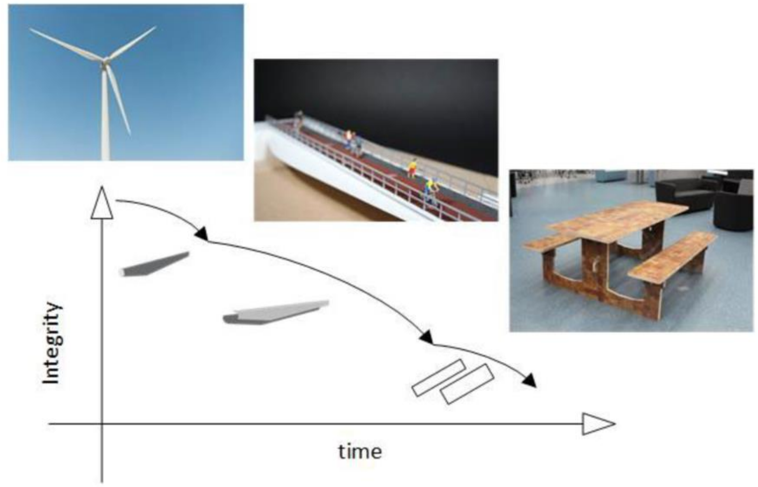

Figure 11: Cascading lifecycles[37]

A variety of companies and initiatives are now working on repurposing strategies for wind turbine blades. Dutch company, Blade-Made, started to bring the ideas of repurposed WTBs to the market. Blade-Made has a design strategy to (re)use EoL blades in large-scale design as a viable alternative to, or step prior to, blade recycling. With an appropriate design approach, EoL blades can add great social, environmental and economic value to design projects while storing blades in functional upcycled use until viable recycling or other disposal methods are fully developed[38]. Example of sound barrier concept is provided in Figure 12.

Figure 12: Blade-Made sound barrier concept as repurposing design

Also, other countries in Europe have come up with initiatives to repurpose wind turbine blades. In the UK the company ReBlade tackles the challenge of blade waste head-on by combining their technical understanding, operational experience, and understanding of the renewables industry, with an approach that is rooted in sustainable and circular values. They are

[38] https://blade-made.com/about/

pioneering processes and designs that make the most of the UK's first-generation turbine blades that will start coming down in large numbers in the near future[39].

Additionally, in Poland, the company Anmet provides solutions for owners and operators of wind farms in the field of cutting, transport and recycling of blades. They design architecture made from WTBs. They have engineered products such as bridges, recreational and fishing platforms, parking shelters, viewing towers, art installations and bike shelters. Smaller furniture products are also designed by Anmet as seen in Figure 13[40].

Figure 13: Furniture products from a blade by Anmet[40]

Gees recycling, an Italian company also transforms the environmental problem of fiberglass disposal into new high-performance products that are in turn recyclable. They transform industrial production waste and end-of-life products into new hand-finished design products such as bathroom furniture, panels, compound and designs on request[41].

The Re-Wind Network is a network of faculty, staff and students at five academic institutions (Georgia Institute of Technology, University College Cork, Queen's University Belfast, City University of New York and Munster Technological University) and industry affiliates. The Re-Wind project compares sustainable EoL repurposing and recycling strategies for composite material from wind turbine blades[42].

The Re-Wind Network provides architectural design, structural engineering analysis and design, and construction management and logistics services to those wishing to repurpose their EoL wind turbine blades. They now have designed and manufactured various types of blade bridges, blade boardwalks, blade poles, blade barriers (noise barriers), blade shelters, and more[43]. They also present Marine Structures such as floating PV platforms, jetties and buoys[44]. See Figure 14 for two innovative examples by the Re-Wind Network.

[39] https://www.reblade.co.uk/about-us
[40] https://www.anmet.com.pl/about-us/?lang=en
[41] https://www.geesrecycling.com
[42] https://www.re-wind.info
[43] Re-Wind Design catalogue, 2021
[44] Re-Wind Design catalogue, 2022

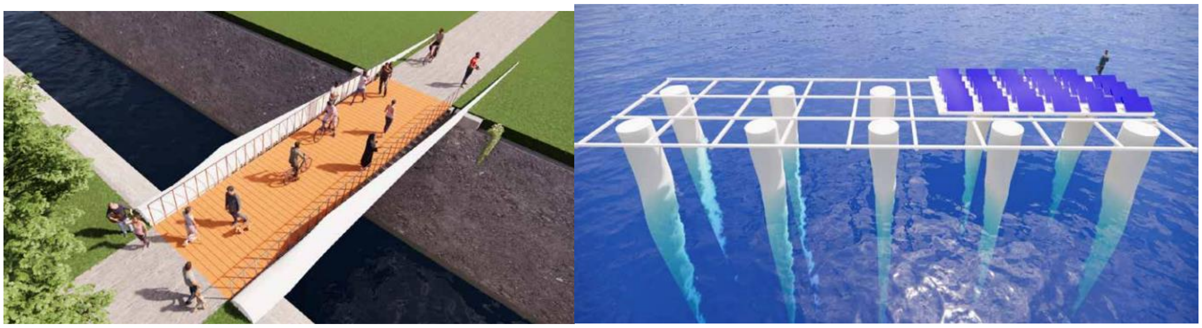

Figure 14: Examples from Re-wind catalogue[43, 44]

At the moment, the repurposing strategy has been used only in pilot projects, but for example in Re-Wind project the partners were able to cut costs by 40% for the second bridge made out of WTBs, compared to the 1st one[45]. This provides a promising preliminary result regarding the economic potential of repurposing.

The number of decommissioned wind turbine blades are rapidly increasing. In the United States alone, approximately 32.000 wind turbine blades will be retired by 2024. By 2040 in Germany, there will be 30.000 tons of EoL WTB waste produced every year. The disparity between the quantity of WTB waste and possible reuse options motivates the desire to facilitate repurposing-idea generation[46].

7. Conclusion and recommendations

To meet the targets of the Paris Agreement wind energy production as a renewable energy source is rapidly increasing. Besides this energy transition, society also needs to shift from a linear to a circular economy as the resources of our planet are limited. Most of the materials from wind turbines are recyclable, however, proper disposal of the blades is one of the most challenging aspects due to the size of components, recycling complexity and low market value. The composites in the blades consist of various materials with different properties. In the coming decades, a large number of blades will eventually reach their end of life and the composite waste volume will increase strongly.

The wind industry is committed to developing more durable, cost-efficient and (fully) circular wind turbine blades. The ZEBRA (Zero wastE Blade ReseArch) consortium has produced the first prototype of its 100 per cent recyclable wind turbine blade. Siemens Gamesa pioneers wind circularity and launched the world's first recyclable 81-meter-long wind turbine blade for commercial use offshore. ACT Blade Ltd has also developed a blade that, unlike conventional fibreglass blades, has been designed to be partly recyclable and to use recycled material. The focus needs to be on total lifetime circular strategies, all the way from the design phase.

---

[45] P. Leahy presentation, "Lessons learned from a wind turbine blade repurposing project", 23.11.2022, Riso

[46] Arabian & Shu, "Sustainable Creativity: Overcoming the Challenge of Scale When Repurposing Wind-Turbine Blades", 2022

Nevertheless, from the currently operating (onshore and offshore) wind farms, thousands of tons of composite wind turbine blades are expected. This calls for the need to apply circular strategies for the end-of-life phase of these blades. Today, the main technology for composite waste is through cement co-processing, also known as the cement kiln route. Although it is very promising in terms of cost-effectiveness and efficacy, in this process the fibre shape of the glass disappears and therefore cannot be used in other composite applications. This is not the most favourite circular strategy as there is a loss of the original fibre's physical shape. A promising alternative is pyrolysis, a thermal recycling process which allows the recovery of fibre in the form of ash and of polymer matrix in the form of hydrocarbon products. Pyrolysis is relatively easy to be scaled up and the by-products (syngas and oil) can be used as energy source or as base chemicals/ building blocks. Though, the technology also causes a loss of strength of fibres due to high temperatures and is only economically sound for carbon fibre recovery to date.

A third circular strategy is repurposing, which is the step in the waste hierarchy that comes before recycling. Various initiatives are working on repurposing strategies for wind turbine blades and have come up with applications in bridges, furniture, playgrounds, bike shelters and more. To date, the repurposing examples, represent demonstration projects that are unlikely to be a large-scale solution for future expected volumes. Repurposing will therefore not be the only solution but fulfil a part of the wind turbine blade circularity challenge.

The three most promising circular concepts have been discussed that have evolved over the years. However, some of these concepts are not yet competitive from a financial perspective compared to conventional methods such as incineration. A multi-sector approach is needed to have sufficient input of composite waste and to create a market with the highest possible retainment of the physical shape of fibres. To achieve this, competition should shift from price towards environmental impact and corporate social responsibility and collaboration in which transparency are crucial elements. On the other side, there is a fundamental need for standardization with regard to essential information on process and material flows during dismantling, disassembly and reprocessing after the end of the product's life, as well as on their supply to recycling or other recovery processes.

Sources

Interreg North Sea Region Decomtools. (2020). *Decom offshore wind farms, recycling, reusing and selling of components/materials.* Leer.

Wu, X., Hu, Y., Li, Y., Yang, J., Duan, L., Wang, T., . . . Liao, S. (2019, April). Foundations of offshore wind turbines: a review. *Renewable and Sustainable Energy Reviews, 104*, 379-393.

Svensson, H. (2010). *Design of foundation for wind turbines.* Lund, Sweden: Lund University.

Mishnaevsky, L., Branner, K., Petersen, H., Beauson, J., McGugan, M., & Sørensen, B. (2017, November). Materials for Wind Turbine Blades: An Overview. *Composites for Wind Energy Applications*, 11: 1285.

Garlington, V. (2021, March). *Remarkably Strong Lightweight Paulownia Wood Composite Wind Turbine Blades*. Retrieved from Linkedin.com: https://www.linkedin.com/pulse/remarkably-strong-lightweight-paulownia-wood-wind-victor-garlington/

LM Wind Power. (n.d.). *From a plastic bottle to a wind turbine blade*. Retrieved from lmwindpower.com: https://www.lmwindpower.com/en/stories-and-press/stories/sustainability/from-a-plastic-bottle-to-a-wind-turbine-blade

Covestro. (n.d.). *The world's first 64.2m full polyurethane resin wind turbine blade*. Retrieved from Solutions.covestro.com: https://solutions.covestro.com/en/highlights/articles/cases/2020/goldwind-lz-blades-wind-turbine-blade-success

IRENA. (2019). *Future of wind: Deployment, investment, technology, grid integration and socio-economic aspects.* Abu Dhabi: International Renewable Energy Agency.

Offshorewindbiz. (2022). *First Fully Recyclable Wind Turbine Blade Rolls Out*. Retrieved from offshorewindbiz.nl: https://www.offshorewind.biz/2022/03/17/first-fully-recyclable-wind-turbine-blade-rolls-out/

Siemensgamesa. (n.d.). *Siemens Gamesa pioneers wind circularity: launch of world's first recyclable wind turbine blade for commercial use offshore*. Retrieved from Siemensgamesa.nl: https://www.siemensgamesa.com/newsroom/2021/09/launch-world-first-recyclable-wind-turbine-blade

Actblade. (n.d.). *Act blade: The next generation*. Retrieved from actblade.com: http://actblade.com/act-blade-the-next-generation/

Exotechnologies. (n.d.). *Breakthrough composite material of exceptional strength capable of being recovered, recycled and reused repeatedly.* Retrieved from exo-tech.com: https://exo-tech.com/index.php/danu/

Beauson, J., Laurent, A., Rudolph, D., & Pagh Jensen, J. (2022, March). The complex end-of-life of wind turbine blades: A review of the European context. *Renewable and Sustainable Energy Reviews, 155*.

Interreg North Sea Region Decom Tools. (2020, September). *Bending Wind Turbine Blades Circular*. Retrieved from northsearegion.eu: https://northsearegion.eu/decomtools/news/bending-wind-turbine-blades-circular/

Windeurope. (2021, June 16). *Wind industry calls for Europe-wide ban on landfilling turbine blades*. Retrieved from windeurope.org: https://windeurope.org/newsroom/press-releases/wind-industry-calls-for-europe-wide-ban-on-landfilling-turbine-blades/

TNO. (n.d.). *Designing sustainable wind turbines for the circular economy*. Retrieved from tno.nl: https://www.tno.nl/en/sustainable/renewable-electricity/offshore-wind-farms/designing-sustainable-wind-turbines/

Joustra, J., Flipsen, B., & Balkenende, R. (2021, July). Structural reuse of wind turbine blades through segmentation. *Composites Part C: Open Access, 5*.

Vestas. (2022). *Material use in Vestas turbines.* Retrieved from Vestas.com: https://www.vestas.com/content/dam/vestas-com/global/en/sustainability/environment/2022_09_Material-Use-Brochure_Vestas.pdf.coredownload.inline.pdf

TPI. (n.d.). *Optimum Performance, Lowest Total Cost*. Retrieved from tpicomposites.nl: https://www.tpicomposites.com/industries-services/wind/research-development/

RecycleWind. (2021). *Environmental Product Declaration.* Recyclewind. Retrieved from https://www.iekrw.de/wp-content/uploads/2021/11/recyclewind-EPD_RecycleWind_TPI_LowRes.pdf

Beta-i. (2019). *The 7 R's Of The Circular Economy*. Retrieved from Medium.com: https://medium.com/@beta__i/the-7-rs-of-the-circular-economy-11d27e933f01

Circulaire maakindustrie. (2019). *Uitvoeringsprogramma circulaire maakindustrie 2019-2023.* Retrieved from circulairemaakindustrie.nl: https://circulairemaakindustrie.nl/app/uploads/2020/10/Werkwijze-UPCM-20201016b.pdf

Climentum Capital. (2020, September). *Our investment in Continuum: a startup pioneering zero-emissions wind-blade and composite materials recycling*. Retrieved from medium.com: https://medium.com/@climentum/our-investment-in-continuum-a-startup-pioneering-zero-emissions-wind-blade-and-composite-materials-6443e56cba8

CRC. (n.d.). *Circular recycling company*. Retrieved from c-r-c.nl: https://c-r-c.nl

Vielen-Kallio, N., van Diest, E., Room, J., & Knol, E. (2022). *The Circular Wind Hub- How to facilitate the wind industry to become circular.*

Hicks, W. (2022). *NREL Researchers Point to Path for Improved Wind Blade Recycling Rates*. Retrieved from NREL.gov: https://www.nrel.gov/news/program/2022/nrel-researchers-point-to-path-for-improved-wind-blade-recycling-rates.html

Windeurope. (2020). *Accelerating Wind Turbine Blade Circularity.*

Decomblades. (n.d.). *Recycling Technologies*. Retrieved from decomblades.dk: https://decomblades.dk/

TNO. (2022, October 17). *TNO innovation offers discarded wind turbine blades a circular future TNO innovation offers discarded wind turbine blades a circular future*. Retrieved from TNO.nl: https://www.tno.nl/en/newsroom/insights/2022/10/tno-innovation-offers-discarded-wind/

Neowa. (n.d.). *Innovations designed to protect the environment*. Retrieved from Neowa.de: https://www.neowa.de/en/about-neowa

Blade-Made. (n.d.). *About*. Retrieved from blade-made.com: https://blade-made.com/about/

Reblade. (n.d.). *About us*. Retrieved from reblade.co.uk: https://www.reblade.co.uk/about-us

Anmet. (n.d.). *About us*. Retrieved from anmet.com.pl: https://www.anmet.com.pl/about-us/?lang=en

Gees Recycling. (n.d.). *Fibre-reinforced plastic recycling: innovation, services, Eco Design*. Retrieved from Geesrecyling.com: https://www.geesrecycling.com

Rewind network. (n.d.). *Repurposing wind blades*. Retrieved from re-wind.info: https://www.re-wind.info

Re-wind. (2021). *Rewind design catalog fall 2021.* Retrieved from https://static1.squarespace.com/static/5b324c409772ae52fecb6698/t/61e95d5f4ef3ad0d5eddd595/1642683746379/Re-Wind+Design+Catalog+Fall+2021+Nov+12+2021+%28low+res%29.pdf

Re-wind. (2022). *Re-wind design catalog 2nd edition fall/autumn 2022.* Retrieved from https://static1.squarespace.com/static/5b324c409772ae52fecb6698/t/636bd07125aeb5312a8e320e/1668010099748/Re-Wind+Design+Catalog+Fall+2022+Nov+9+2022+%28low+res%29.pdf

Arabian, K., & Shu, L. (2022). Sustainable Creativity: Overcoming the Challenge of Scale When Repurposing Wind-Turbine Blades. *Journal of mechenical design, 144*(10), 144(10): 101402.

Durakovic, A. (2022). *Vestas Installs Mould for World's Longest Wind Turbine Blades*. Retrieved from Offshorewind.biz: https://www.offshorewind.biz/2022/02/10/vestas-installs-mould-for-worlds-longest-wind-turbine-blades/

DecomBlades. (n.d.). *Results & Resources*. Retrieved from decomblades.dk: https://decomblades.dk

Velenturf, A. (2021). A Framework and Baseline for the Integration of a Sustainable Circular Economy in Offshore Wind. *The Role of Energy in the Circular Economy*, 14(17), 5540.