Accelerating Wind Turbine Blade Circularity

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Wind EUROPE

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This report has been jointly prepared by WindEurope, Cefic and EuCIA through a collaborative cross-sector platform on wind turbine blade recycling. Notably, the report:

- describes wind turbine blade structure and material composition;
- highlights the expected volumes of composite waste, including wind turbine blade waste;
- maps the existing regulations governing composite waste in Europe;
- describes the existing recycling and recovery technologies for treating composite waste as well as innovative applications for using composite waste; and
- provides recommendations for research and innovation to further enhance the circularity of wind turbine blades and design for recycling.

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EXECUTIVE SUMMARY

As the wind industry continues to grow to provide renewable energy across the globe, we are committed to promoting a circular economy which reduces environmental impacts throughout product lifecycles. To this end, WindEurope (representing the wind energy industry), Cefic (representing the European Chemical Industry) and EuCIA (representing the European Composites Industry) have created a cross-sector platform to advance approaches for the recycling of wind turbine blades, including technologies, processes, waste flow management, re-integration in the value chain and logistics.

Today around 85 to 90% of wind turbines' total mass can be recycled [1], [2], [3]. Most components of a wind turbine – the foundation, tower and components in the nacelle – have established recycling practices. However, wind turbine blades are more challenging to recycle due to the composite materials used in their production. While various technologies exist to recycle blades, and an increasing number of companies offer composite recycling services, these solutions are not yet widely available and cost-competitive.

Wind turbine blades are made up of composite materials that boost the performance of wind energy by allowing lighter and longer blades with optimised aerodynamic shape. Today 2.5 million tonnes of composite material are in use in the wind energy sector globally [1]. WindEurope estimates around 14,000 blades could be decommissioned by 2023 [4], equivalent to between 40,000 and 60,000 tons. Recycling these old blades is a top priority for the wind industry. This requires logistical and technological solutions for disassembling, collection, transportation, waste management and reintegration in the value chain.

Composite recycling is not solely a challenge for the wind industry but rather a cross-sector challenge. Blade waste will represent only 10% of the total estimated thermoset composite waste by 2025. The relatively low volumes of composite blade waste make it challenging to build a recycling business based only on this waste stream. Active engagement from all the composite-using sectors and authorities will be required to develop cost-effective solutions and strong European value chains.

Existing European waste legislation emphasises the need to develop a circular economy and increase recycling rates to deal with unnecessary waste pollution and increase resource efficiency. At national level, Germany, Austria, Finland and the Netherlands forbid composites from being landfilled. France is considering introducing a recycling target for wind turbines in its regulatory framework due to be updated in 2020. Going forward there may be more harmonisation of guidelines and legislation, which would be more efficient for the development of a pan-European market for recycling blade waste. The wind industry is currently working on a proposal for an international guideline for the dismantling and decommissioning of wind turbines.

Today, the main technology for recycling composite waste is through cement co-processing. Cement co-processing is commercially available for processing large volumes of waste (albeit not in all geographies yet). In this process the mineral components are reused in the cement. However, the glass fibre shape is not maintained during the process, which from a waste hierarchy perspective may be less preferred. WindEurope, Cefic and EuCIA strongly support increasing and improving composite waste recycling through the development of alternative recycling technologies which produce higher value recyclates and enable production of new composites. Further development and industrialisation of alternative thermal or chemical recycling technologies may provide composite-using sectors, such as building & construction, transportation, marine and the wind industry, with additional solutions for end-of-life.

Europe needs to invest on more research and innovation to diversify and scale up composite recycling technologies, to develop new, high-performance materials with enhanced circularity, and to design methodologies to enhance circularity and recycling abilities of blades. At the same time existing treatment routes like cement co-processing must be deployed more widely to deal with the current waste streams. Finally, the scientific understanding of the environmental impacts associated with the choice of materials and with the different waste treatment methods should also be improved (life cycle assessment).

1. INTRODUCTION

1.1 CROSS-SECTOR PLATFORM

In 2019, WindEurope, Cefic (the European Chemical Industry Council) and EuCIA (the European Composites Industry Association) created a cross-sector platform to advance novel approaches to the recycling of wind turbine blades, including technologies, processes, waste flow management, reintegration in the value chain and logistics. In particular, this cross-sector platform aims to understand the potential of existing wind turbine blade recycling technologies and ensure recycling is factored in wind turbine blade design. This report supports this effort.

"Wind energy is an increasingly important part of Europe's energy mix. The first generation of wind turbines are now starting to come to the end of their operational life and be replaced by modern turbines. Recycling the old blades is a top priority for us, and teaming up with the chemical and composites industries will enable us to do it the most effective way."

- Giles Dickson, WindEurope CEO

"The chemical industry plays a decisive role in the transition to a circular economy by investing in the research and development of new materials, which make wind turbine blades more reliable, affordable and recyclable. Innovation is born from collaboration and we look forward to working together to advance wind turbine blade recycling."

- Marco Mensink, Cefic Director General

"The wind energy sector has always been at the forefront of using composites as they are instrumental to sustainable energy generation. With this collaboration we hope to set a great industry standard that ultimately will also help customers in other industries like marine and building & infrastructure."

- Roberto Frassine, EuCIA President

1.2 OBJECTIVES

The cross-sector platform conducted a series of workshops in 2019 during which new examples of blade repurposing and recycling were presented. Since WindEurope's 2017 publication on managing composite blade waste [5], some Member States have also started to consider legislation on decommissioning and on blade circularity.

The objective of this report is to present the state-of-play in the recycling of composites used in wind turbine blades. The report is based on the findings of those recent workshops. Notably, the report:

- describes wind turbine blade structure and material composition;
- highlights the expected volumes of composite waste, including wind turbine blade waste;
- maps the existing regulations governing composite waste in Europe;
- describes the existing recycling and recovery technologies for treating composite waste as well as innovative applications for using composite waste; and
- provides recommendations for research and innovation to further enhance the circularity of wind turbine blades, including new materials and design for recycling.

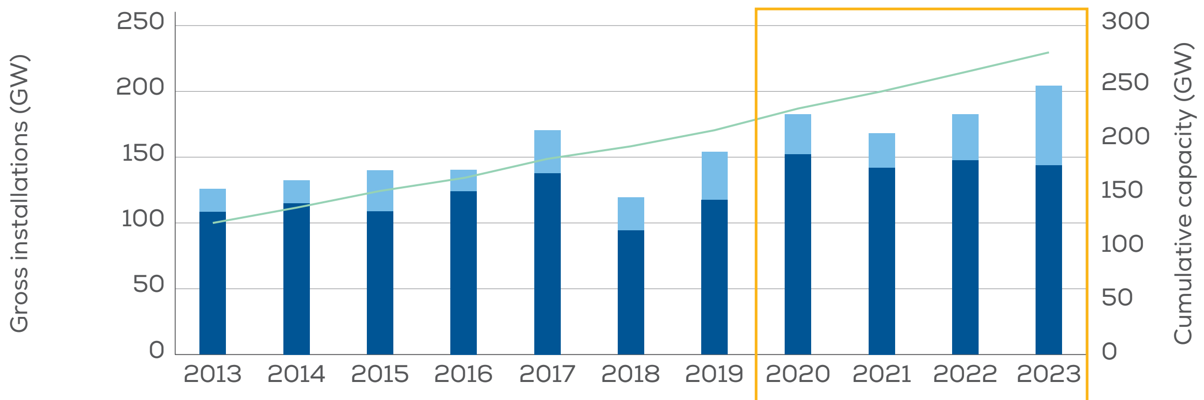
This report supplies relevant and practical information on the subject and promotes the sustainable management of composite blade waste. Research on the subject is ongoing and with this comes the challenge of keeping up to date with the state-of-the-art. If you have further input please notify us at Sustainability-Platform@windeurope.org.

1.3 CONTEXT

In 2019 wind energy supplied 15% of the EU's electricity [6]. This number will continue to grow in the coming years (Figure 1). The EU's binding target for increasing the renewable energy share to 32% by 2030, and its commitment to becoming carbon-neutral by 2050, emphasises wind power's important role in the future energy mix. The European Commission (EC), in their long-term decarbonisation strategy to 2050, estimates that wind alone could provide 50% of the EU's electricity demand by 2050. And importantly, this demand will be significantly higher than today's level, as society increases the electrification of energy uses.

FIGURE 1

Gross annual installations in Europe



	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Offshore	1.5	1.5	3.0	1.6	3.2	2.7	3.6	2.9	2.7	3.4	5.9
Onshore	11.0	11.6	10.9	12.3	13.9	9.4	11.7	15.2	14.2	14.7	14.5
Cumulative	**122**	**135**	**148**	**162**	**178**	**190**	**205**	**222**	**238**	**255**	**275**

Source: WindEurope

In the future, a growing amount of wind turbines will start to be decommissioned, considering that:

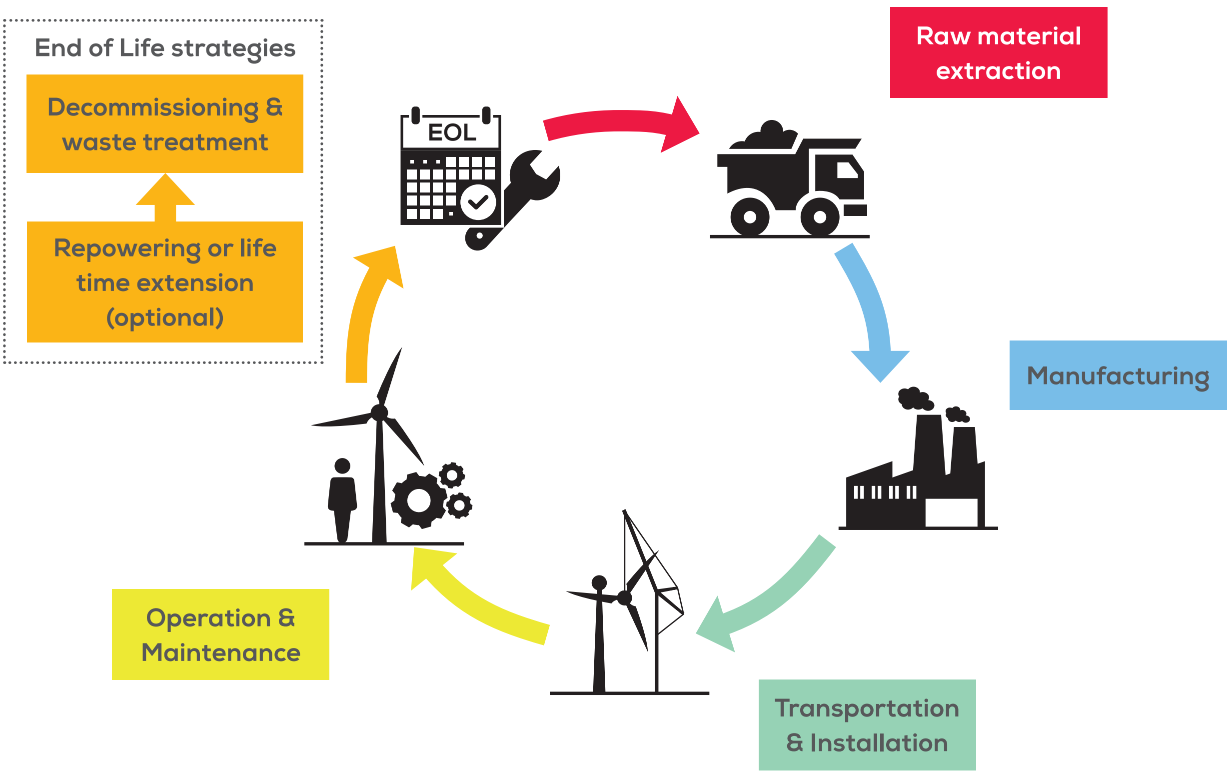
- The standard lifetime of a wind turbine is approximately 20-25 years, with some wind turbines now reaching up to 35 years through lifetime extension;
- There are increasing repowering opportunities i.e. replacing old models with newer and more efficient models, that can increase wind farm electricity output by a factor of 2.

Many of the wind turbines installed in the 1990s are of a few hundred kW and are under 60m in hub height. If replaced by taller and more powerful turbines, the increase in energy yields could be considerable. Indeed, the analysis of more than 100 repowering projects in Europe has shown that, on average, the number of turbines decreases by a third whilst wind farm capacity more than doubles [7].

If countries enable the repowering of an increasing amount of old wind turbines, **about 14,000 wind turbine blades could be decommissioned by 2023 [4], equivalent to between 40,000 and 60,000 tons.**

The wind industry is committed to promoting a more circular economy and determining ways in which it can support this. A sustainable process for dealing with wind turbines at the end of their service life is needed to maximise the environmental benefits of wind power from a life cycle approach (Figure 2). To do so, the wind industry is actively looking for industries and sectors that can make use of the materials and equipment decommissioned from wind farms. And the wind industry wants to work with them to build capacities in wind turbine blade circularity, including through the development of new, more easily recyclable structural design and materials.

FIGURE 2
The life cycle of a wind turbine



Source: WindEurope

2. COMPOSITES & THE WIND INDUSTRY

2.1 INTRODUCTION

Today around 85 to 90% of a wind turbine's total mass can be recycled [1], [2], [3]. Most components of a wind turbine such as the foundation, tower and components in the nacelle have established recycling practices. And the raw materials of these components have enough value for secondary markets. For example, the steel in towers is 100% recyclable [8]. It can be reused again without any loss of quality. Steel scrap is regarded as a valuable raw material for steel production. Because of its value, there is a well-established market for steel scrap.

Treatment of foundations during decommissioning differs from country to country. In some countries, foundations need to be removed. The concrete from removed foundations can be recycled into aggregate for building materials or road construction. In other countries, foundations may be (partly or fully) left in-situ where removal would lead to higher environmental impacts or if the land owner has specified so.

Wind turbine blades are more challenging to recycle, largely due to the composite materials used in their production. While various technologies exist that can be used to recycle blades (see Section 5), these solutions are yet to be widely available and cost-competitive. This section describes turbine blade structure and material composition highlighting recyclability properties. It also looks at future trends in blade design and material composition aimed at improving blade circularity.

2.2 BLADE STRUCTURE & MATERIAL COMPOSITION

Wind turbine blades are made of composite material, consisting of various materials with different properties, which boost the performance of wind energy by allowing lighter and longer blades with optimised aerodynamic shape. Today 2.5 million tonnes of composite material are in use in the wind energy sector globally [1]. Although material compositions vary between blade types and blade manufacturers, blades are generally composed of the following (Figure 3):

1. Reinforcement fibres e.g. glass and carbon. Glass fibre represents the primary reinforcement material in the composite components of wind turbine blades. Carbon fibre is also used in wind turbine blades (in the spar), but to a lesser degree. Carbon fibre's superior strength and higher stiffness offers many advantages over glass fibre but its higher cost per volume is a key barrier to further deployment in the wind power industry. Hybrids with a combination of glass and carbon fibre also exist.

2. A polymer matrix e.g. thermosets such as epoxies, polyesters, vinyl esters, polyurethane, or thermoplastics.

3. A sandwich core e.g. balsa wood or foams such as polyvinyl chloride (PVC), polyethylene terephthalate (PET);

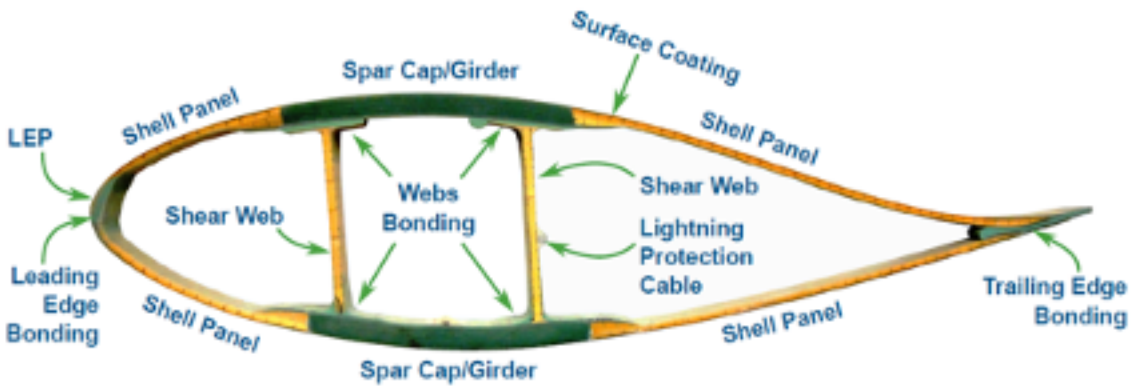
4. Structural adhesives e.g. epoxies, polyurethane (PUR)

5. Coatings e.g. polyester (UPR), polyurethane (PUR);

6. Metals e.g. copper or aluminium wiring (lightning protection system), steel bolts.

FIGURE 3

Generic cross-section of rotor blade



Spar Caps/Girders: Unidirectional (UD) Glass/Carbonfibre, supported by Epoxy, Polyester, Polyutherane or Vinylester matrix
Shear Webs and Shell Panels: Multiaxial GFRP Sandwich laminates using Balsa/PVC/PET as core material and Epoxy, Polyester, Polyutherane or Vinylester as matrix systems
Leading/Trailing Edge and Webs Bonding: Epoy/Polyutherane based structural adhesive
Lightning Protetion Cable: Aluminium or Copper
Surface Coating: Polyutherane based lacquer
LEP (Leading Edge Protection): Polyutherane based lacquer/tape

Source: TPI Composites

The combination of fibres and polymers, also known as composites, represents the majority of the blade material composition (60-70% reinforcing fibres and 30-40% polymer matrix by weight). In many respects, composites are advantageous because they:

- Combine properties of high tensile strength at relative low density (high strength-to-weight ratio) to withstand the mechanical load requirements and to optimally perform aerodynamically;
- Provide resistance to fatigue, corrosion, electrical and thermal conductivity important for the long-expected lifetime (20 to 30 years);
- Provide flexibility in design and manufacturing, allowing to optimise the aerodynamic shape of the blade, resulting in high turbine efficiency; and
- Enable high yields resulting in lower levelised cost of energy.

At present, wind turbine blades are made of composites based on thermoset polymers. These polymers become cross-linked in an irreversible process. The cross-linking is a key requirement for obtaining the desired performance in terms of fatigue resistance and mechanical strength.

Thermoplastics, unlike thermosets, do not undergo the crosslinking. Thermoplastics are therefore more easily recycled in simple shapes and components as they can be melted. They have the potential for easier recycling, though the structural design complexity of the blades makes it difficult. Furthermore, the mechanical properties, durability and processability of thermoplastics in comparable price ranges currently limit their applications in blades compared to thermosets.

2.3 FUTURE TRENDS IN BLADE MATERIALS

Table 1 presents future trends in blade materials aimed at addressing current challenges. Blade material challenges include stiffness optimisation, fatigue life, damage prediction methods and the production of light weight blade structures. Material selection is determined by price, process abilities, material integrity, geographical locations with more hostile environmental conditions and the demand for longer wind turbine blades. Design and material selection processes is rapidly evolving in order to also consider the overall sustainability of the materials chosen (life cycle assessment) including their impacts on recyclability and alignment with future recycling methods [9], whilst meeting the cost and performance criteria at the same time.

Besides improving efficiencies in waste collection and combining waste volumes, the high investment costs and energy requirements seem to be a common limitation to a greater implementation and scale-up of novel composite recycling technologies (see Section 5). Multiple projects are ongoing to improve energy efficiency by reducing the process time required for the same amount of materials and by increasing the material output of the processes. This would translate into lower costs and allow a more acceptable energy use whilst not offsetting the benefits of recycling materials. However, in order to make recycling technologies more efficient and sustainable, the development of these technologies needs to be coupled with material development [10].

Material innovations should strive to have positive effects on the production, maintenance, lifetime and environmental footprint of the blades. European technological platforms indicate that materials research for blades is an important research area [1], [11] and see accounting for sustainability and recycling as a strategic issue [12].

TABLE 1

Active areas in material research for wind turbines blade

	AREAS OF MATERIAL RESEARCH	EFFECT
Processing Design	Process modelling aimed to optimise and accurately control the curing processes of the composites	Increased lifetime, higher conversion efficiency
Process	Incorporating automatised manufacturing processes to ensure consistent material qualities and more robust manufacturing techniques	Increased lifetime, higher conversion efficiency
	Promoting cost- and energy-efficient manufacturing processes for carbon fibre reinforced composites, since the material provides enhanced mechanical properties. As a side benefit it is also financially more attractive to recover carbon fibre compared to glass fibre.	Enable manufacturing of longer blades, hence increasing conversion efficiency
Materials	Introducing innovative resin/fibre combinations with improved ductility and fatigue resistance	Increased lifetime
	New infusible thermoplastic resins which are processed by in-mould polymerisation (rather than melt processing) and have better mechanical properties	Cost reduction
	Introducing nano-components as strengthening agents in matrix and coatings, whilst respecting HSE requirements and ensuring it does not lead to more complex recycling methods	Increased lifetime
	Investigating fibre architectures – combining high performance glass fibres, carbon fibres and nano-engineered fibres to make hybrid reinforcements	Enable manufacturing of longer blades, hence increasing conversion efficiency
	Investigating durable coating materials to ensure improved erosion-resistance e.g. gel-coats, paint systems and tapes, resealable and self-healing coatings	Increased lifetime, higher conversion efficiency
	Development of bio-resins for improved performance, taking advantage of higher availability of bio-waste	Continued availability of raw materials and security of supply after depletion of fossil-based raw materials; Reduced carbon footprint
	Developing 3R-resins – a new family of enhanced thermoset resins and composites with better re-processability, repairability and recyclability properties	Increased lifetime; Improved recyclability

3. MARKET OUTLOOK

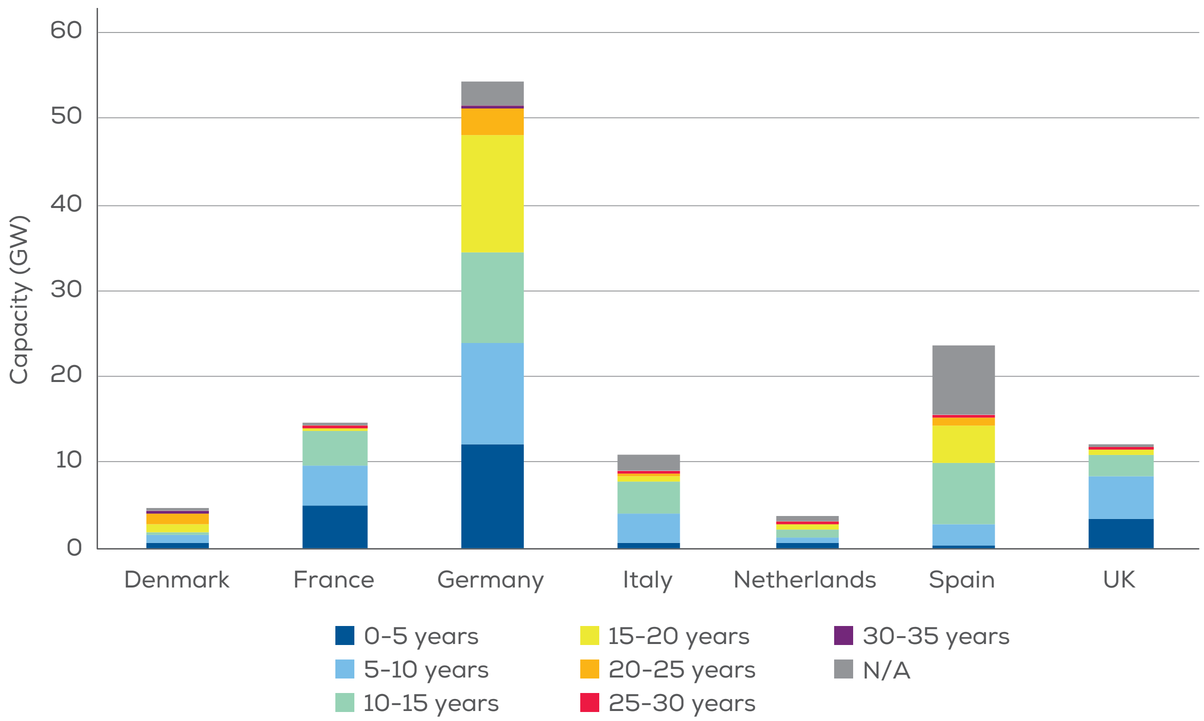
3.1 AN AGEING ONSHORE WIND FLEET

Figure 4 provides a picture of the ageing onshore wind fleet. Denmark, Germany, Spain and the Netherlands are the most mature wind energy markets. In terms of turbines that are over 15 years old, these countries respectively have 2.74 GW (~57%), 17 GW (~33%), more than 5 GW (~33%) and 0.6 GW (~21%).

Repowering project El Cabrito, Tarifa, Spain. Completed in 2018. It was 25 years old when dismantled and resulted with 87% fewer turbines with the same output capacity. Source: ACCIONA.

FIGURE 4

Age of the onshore wind fleet in Europe



Source: WindEurope

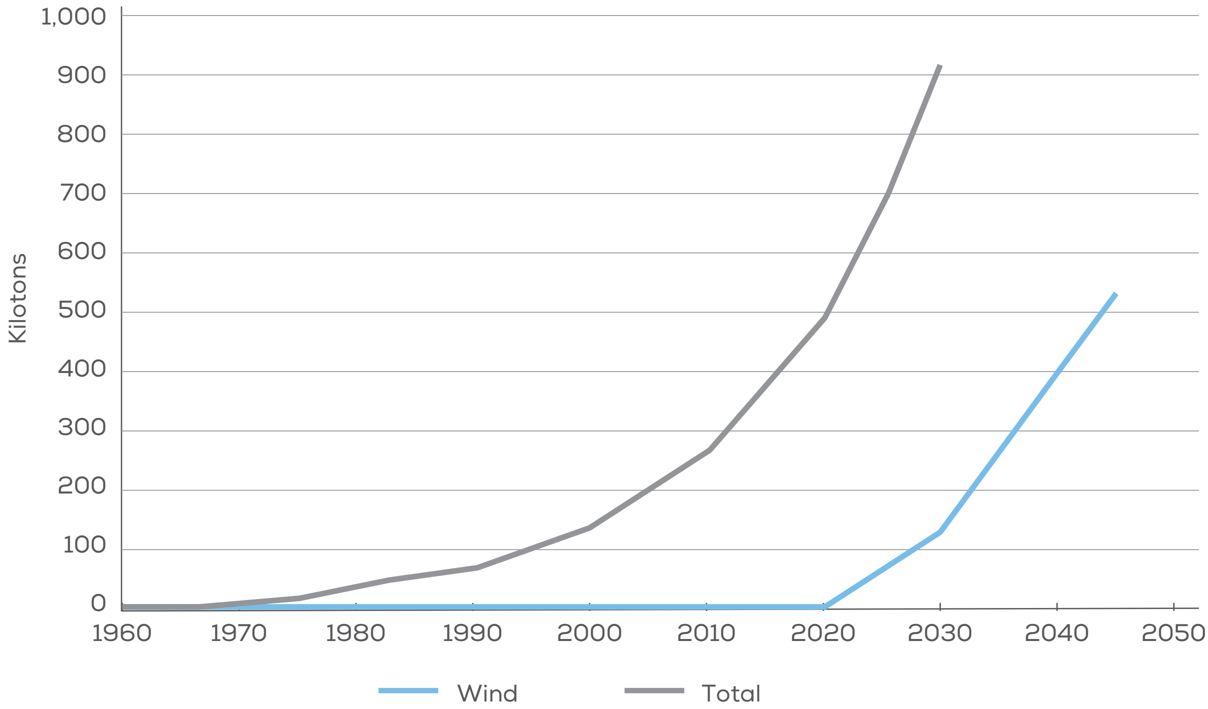
3.2 COMPOSITE WASTE: A CROSS-SECTOR CHALLENGE

WindEurope estimates around 2 GW of wind energy capacity could be repowered and another 2 GW could be fully decommissioned by 2023 in Europe [4]. This means about 4,700 turbines (or 14,000 blades equivalent to between 40,000 and 60,000 tons) could be decommissioned and would need to be sustainably disposed of. Recycling these old blades is a top priority for the wind industry. This requires certain logistics and technology in place to proceed to disassembling, collection, transportation, waste management treatment and reintegration into the value chain.

Composite waste amounts from the wind industry are expected to continue to increase (Figure 5). However, the wind industry produces far less composite waste than other industries. Based on EuCIA estimates wind will contribute 66,000 tons of thermoset composite waste in 2025. This is only 10% of the total estimated thermoset composite waste (and less than 5% of the total estimated composite waste combining thermoset and thermoplastics). Other composite-waste-producing sectors are building & construction, electrical & electronics, transportation, marine, production waste, aeronautics, consumer and tanks & pipes sectors.

FIGURE 5

Composite waste generation – sector trends (ktons/year)



Key assumptions: *20 years average lifetime for wind composites. First year of commercial use of wind composites is assumed to start in 2000. The analysis is based on global production figures of composites as supplied by JEC and assumes global composites production is the same as global composites consumption (based on thermosets only). It further assumes that as Europe's GDP (including Turkey) is 22%, the European consumption of composites is 22% of the global consumption of composites. The extrapolation of certain market segments is unsure and therefore the extrapolation of the total line does not exceed year 2025.*

Source: EuCIA, 2020

Composite recycling is a cross-sector challenge and not solely a challenge for the wind industry. Actually, the (low) volumes of composite wind blade waste make it challenging to build a recycling business based mainly on this waste stream. All the composite-using sectors must work together to find cost-effective solutions and value chains for the combined volume of composite waste. The wind industry has already teamed up with Cefic and EuCIA as mentioned above.

4.
LEGISLATIVE CONTEXT

4.1 INTRODUCTION

This section maps the existing regulation for composite waste in the EU. Today, there is limited legislation regulating treatment of composite or blade waste both at EU and national levels. In addition, existing national legislation is not necessarily aligned at international level. This is not surprising at the moment, as wind markets have developed at different paces. Decommissioning practice is only starting to emerge in those countries with a mature market and increasing decommissioning and repowering activity. Generally, authorities use different regulatory instruments to incentivise recycling. These include legally binding targets, landfill bans and/or taxes and requirements for Extended Producer Responsibility (EPR) (the latter particularly in other sectors). Going forward, there may be more harmonisation of guidelines and legislation. This would likely be more efficient for the development of a pan-European market for recycling blade waste. Ideally, there would also be alignment with other sectors of composite recycling. The wind industry is ready to contribute to that discussion. In particular, the wind industry is currently working on a proposal for international guidelines for the dismantling and decommissioning of wind turbines.

4.2 COMPOSITE WASTE CLASSIFICATION

According to the European classification of wastes, composite blade waste is **most often categorised as plastic waste from construction and demolition with the code 17 02 03**. The following other codes are also used at national level:

- 07 02 13 waste plastic from organic chemical processes;
- 10 11 03 waste glass-based fibrous materials from thermal processes;
- 10 11 12 waste glass other than those mentioned in 10 11 11 from thermal processes;
- 10 11 99 wastes not otherwise specified from thermal processes; and
- 12 01 05 plastics shavings and turnings from shaping and physical mechanical surface treatment of metals and plastics.

National authorities need to ensure the correct and suitable code is applied to blade waste. This would ensure efficient separate collection and sorting and help identify suitably authorised waste treatment options. Having a waste stream that can provide clean composite of a single type in large quantities increases the efficiency of the chosen waste treatment option. However, as shown above, composite waste is often classified as plastic waste. It may therefore become mixed with other types of plastics. Having a differing waste classification may also limit the potential for a pan-European market for recycled composites.

4.3 EXISTING REGULATION

To date, few regulatory requirements are in place for the composite waste sector. Nevertheless, there is a clear push towards more circularity in general at the European level as shown by the new EU Circular Economy Action Plan (2020) [13]. The 'European Strategy for Plastics in a Circular Economy' (2018) [14] stresses that the low reuse and recycling rates (less than 30%) of end-of-life plastics is a key challenge to be addressed. It sets out the vision for 'circular' plastics with concrete actions at EU level. The strategy also stresses that the private sector – together with national and regional authorities, cities and citizens – will need to mobilise to fulfil this vision. So far the focus has been on single-use plastics, microplastics, oxo-plastics and plastics packaging and not on composite waste.

At the national level, four countries make a clear reference to composite waste in their waste legislation: Germany, Austria, the Netherlands and Finland. These countries forbid composites from being landfilled or incinerated (see Country Case Studies below). France is considering introducing a recycling target for wind turbines in its regulatory framework (due to be updated in 2020) [15].

EXISTING REGULATORY INCENTIVES

LANDFILL BANS AND TAXES

Landfill bans or taxes, if well designed and correctly implemented, can act as a driver to change industrial practices. They can dissuade disposal and stimulate more circular solutions.

When comparing the cost of recycling composite waste with the levels of landfill taxes for wind turbine blade waste, the tax level in some countries is considered too low to trigger substantial changes towards more recycling.

Member States have used landfill bans and/or taxes to incentivise avoidance of landfill for different types of waste.

Country focus - Germany: A ban on directly landfilling waste with a total organic content higher than 5% came into force in 2009. Considering blades contain an organic part (due to the resin that glues together the glass fibres), they cannot be landfilled. In response to this regulatory constraint a technical solution was developed for handling bigger amounts of glass fibre-reinforced polymers waste called the "cement kiln route" or cement co-processing. A cement co-processing plant was established in northern Germany which uses around 15,000 tons of composite waste annually, 10,000 tons of which comes from wind turbine blades. The plant has a total current capacity of 30,000 tons/year. Cost is around 150 EUR/t (gate fee).

Country focus - The Netherlands: Under the 3rd edition of the National Waste Management Plan landfilling of composite waste is banned 'in principle'. However, wind farm operators can benefit from an "exemption" if the cost of alternative treatment is higher than 200 EUR/t. According to a survey conducted by WindEurope, the cost of mechanically recycling wind turbine blades in the Netherlands ranges between 500-1,000 EUR/t including onsite pre-cut, transport and processing. Mechanical recycling itself costs between 150-300 EUR/t. This means landfilling is still practised.

Regardless of such legislation affecting composite waste, the wind industry seeks to avoid landfill for blade waste treatment as per the EU's waste hierarchy (Figure 6). It is actively seeking recycling alternatives, along with other composite users.

EXTENDED PRODUCER RESPONSIBILITY

Extended Producer Responsibility (EPR) is a policy approach that has been used in other sectors to drive change in industrial practices. Producers are given a significant responsibility – financial and/or physical – for the treatment or disposal of post-consumer products. For example, EPR exists today for **electronic and electrical equipment** under the Waste Electrical and Electronic Equipment Directive (2012/19/EU). **The photovoltaic (PV)** sector has also adopted a similar scheme since 2014.

In the UK, the PV Cycle Distributor Take-back Scheme (DTS) has received full government accreditation, enabling UK Distributors (i.e. any organisation selling PV panels for private households) to carry out their collection and recycling obligations with a comprehensive support system at reasonable cost. This means any distributor must have a procedure in place to take back PV waste. Distributors can choose to set up their own free take-back operation or join the PV CYCLE Distributor Take-back Scheme.

In other industries, EPR is taken into account by use of Environmental Product Declarations (EPD). These declarations provide information on material composition and life cycle assessment, and can also provide dismantling instructions and recycling options. For example, the use of EPD is established in the building and construction sector. There is a European Standard describing the 'core rules' for these documents (UNE EN 15804:2012+A1:2014 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products).

In France and Germany EPR for the wind industry has been discussed (see country case studies below). In general, wind turbine blades are very large structures and therefore, unlike batteries, computers and PV panels, they are unlikely to become mixed with local/municipal waste streams. This is already recognised in the WEEE Directive where wind turbines are excluded because they are considered 'Large Scale Fixed Installations'.

Country focus - In France, the Ministry for a Just and Ecological Transition commissioned a study on wind turbine circularity. The report, published in October 2019, recommended introducing EPR for blades [16]. EPR responsibilities already exist in 14 sectors including end-of-life vehicles, end-of-life ships, tyres and unused medical drugs.

The new law on circular economy adopted on 10 February 2020 extended EPR responsibilities to new products such as toys, cigarettes, textiles for healthcare and building materials. Wind turbine blades were not included in this new list. It was deemed that EPR for wind turbine blades would not be effective in increasing blade recycling. Instead, joint efforts between authorities and the industry were deemed more likely to be successful.

Country focus - In Germany, UBA, the Federal Environment Agency, commissioned a study on wind turbine decommissioning and waste management. Results from the study formulate recommendations for the set-up of an efficient dismantling system in Germany [3]. This assumes among others to potentially include specific elements of product responsibility for Original Equipment Manufacturers (OEMs) including:

- "Information and labelling obligations regarding the material composition of the rotor blades;
- Separate processing with the aim of quality assurance of recyclates and substitute fuels;
- Obligation for high quality recycling or guarantee of disposal safety;
- Inclusion of manufacturer's knowledge and processing technologies adapted to product-related technological change; and
- Cause-related allocation of disposal costs and organisational obligations during disposal".

However, the report also highlights the following challenges speaking against the introduction of a specific product responsibility for rotor blades:

- "Many wind turbine manufacturers are active across Europe. An isolated regulation in Germany is possible but is at odds with the fundamental idea of EU internal market;
- Format and storage location (manufacturer, operator, authority) as well as competition relevance of the data collected;
- Long service lives of rotor blades are an obstacle to an individual product responsibility; and
- The discussion on disposal options for [glass reinforced polymers/carbon reinforced polymers] also extends to other products made of such materials and may have to be addressed more specifically for materials flows than for products".

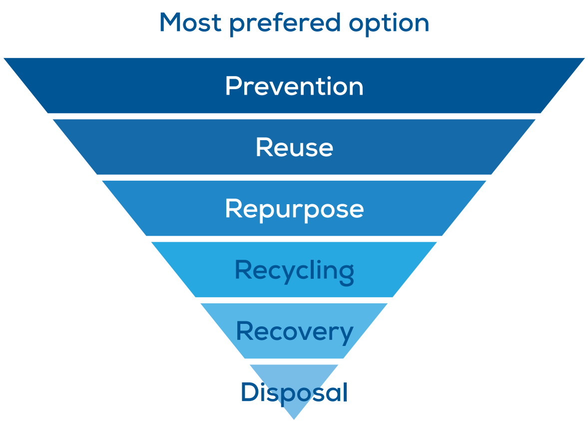
Currently, there is no initiative for legislation in Germany related to this issue. UBA is commissioning another study on the "development of decommissioning and recycling standards for rotor blades". The study will start in 2020 and run for 20 months.

5. BLADE WASTE TREATMENT METHODS

5.1 THE WASTE HIERARCHY

The European Waste Framework Directive (2008/98/EC) defines basic concepts related to waste management. It emphasises the need for increased recycling and highlights the reduced availability of landfill. It also establishes the waste hierarchy shown in Figure 6.

FIGURE 6
The waste hierarchy for sustainable blade waste management



Source: ETIPWind

PREVENTION

The wind industry is committed to sustainable waste management in line with the waste hierarchy. The first step is **prevention** of blade waste through reduction and substitution efforts in design. For example:

- Mass reduction resulting in less material to recycle;
- Decrease failure rate and extend design lifetime. Testing and certification plays a crucial role here. Blade failures seen in the field are not always triggered in the testing phase as past standards are not up to date for large blades (> 50m). More recent testing and certification standards like DNVGL-ST-0376 and the upcoming IEC 61400-5 open potential for better design; and
- Design for easy upgrade of existing blade to new versions, e.g. segmented/modular blades. However, these are not standard design yet.

REUSE

The blade should be used and **reused** for as long as possible before waste treatment is needed. Routine servicing and repair is required to achieve a blade's design lifetime. For lifetime extension, a 'remaining useful lifetime assessment' (i.e. a fatigue load analysis using SCADA data or types of data) must be conducted, in combination with site inspections and review of maintenance actions performed since commissioning of the blade. This might lead to repair actions and reinforcement of certain areas. DNV-GL has developed a standard for lifetime extension of wind turbines (DNVGL-ST-0262). And the International Electrotechnical Commission (IEC) is currently developing a standard for the through-life management and life extension of wind power assets (IEC TS 61400-28). Finally, several European and North American companies have established businesses for selling refurbished turbines and components.

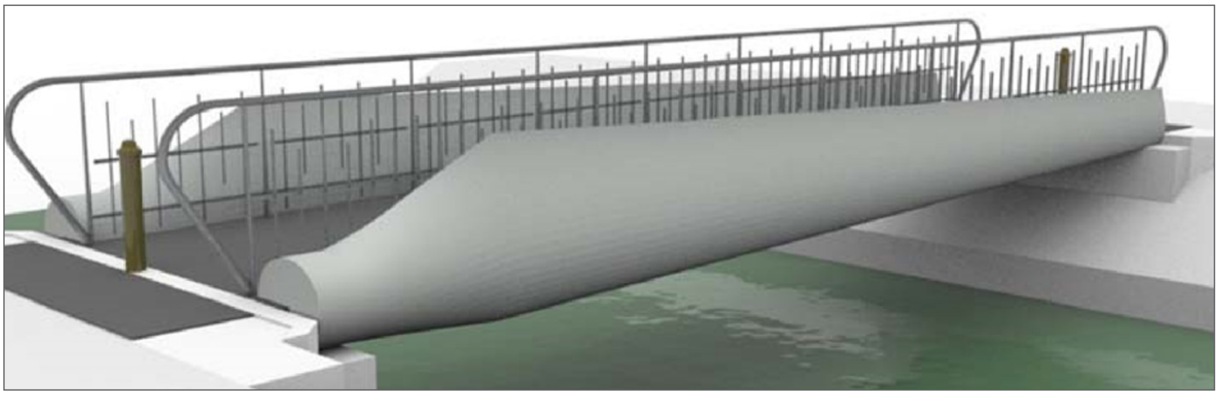
REPURPOSING

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. For example:

- Reusing the blades for playgrounds or street furniture [17], [18], [19], [20].
- Specific structural parts of the blade can also be repurposed for building structures e.g. bicycle shelters [21], bridge in Nørresundby, Denmark (yet to be built) [22], walkways, architectonic reuse [23].

However, to date the repurposing examples represent demonstration projects that are unlikely to be a large-scale solution for future expected volumes.

FIGURE 7
Examples of blade repurposing



A conceptual design of pedestrian bridge using A29 wind blades as main girders, Re-Wind research project [24]

FIGURE 7

Examples of blade repurposing

Bike shed in Aalborg, Denmark

Source: Re-Wind and Port of Aalborg, Denmark

RECYCLING & RECOVERY

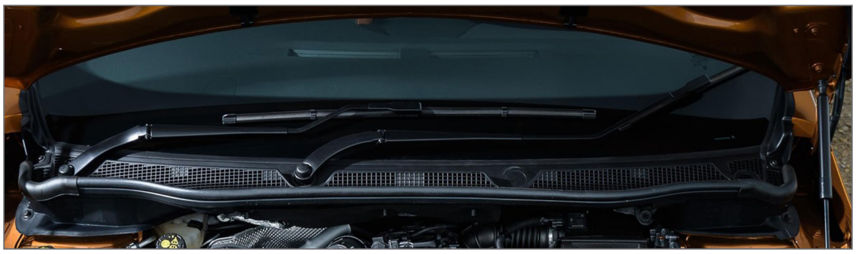
Where repurposing is not possible, **recycling** and **recovery** are the next options. Recycling means the blade becomes a new product or material with the same or different functional use. Recycling requires energy and other resources in order to convert the blade waste into something else. Recovery means turning waste into a fuel or thermal energy after removing all individual components that can be used again. Section 5.2 describes the existing recycling and recovery technologies for composite waste. There is an increasing number of companies that offer composites recycling services. For an indicative and non-exhaustive list of companies active in that area, you may contact WindEurope at Sustainability-Platform@windeurope.org.

FIGURE 8

Examples of products based on recycled blade composites (demonstrator projects)

a) FiberEUse – Large scale demonstration of new circular economy value chains based on the reuse of end-of-life fibre reinforced composites

FiberEUse



Cowl tool support (automotive), Maier

Modern urban furniture, DesignAustria

Bathroom furniture, Novellini

Source: FiberEUse (H2020-CIRC-01-2016-2017, GA nº 730323)

b) Mechanically recycled fibres from wind turbine blades added as short reinforcing fiber to concrete

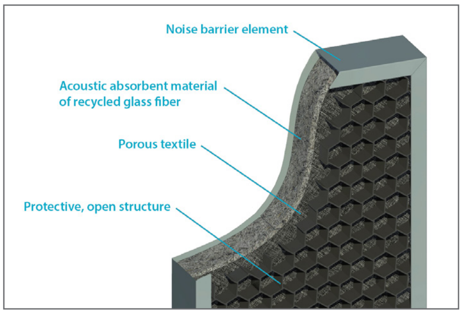
Precast concrete LEGO type blocks

Precast concrete manhole module

Precast concrete New Jersey barriers

Source: Courtesy of TECNALIA Research and Innovation

c) Noise insulation barriers



Source: Miljoskarm

DISPOSAL

Disposing blades via landfill or incineration without energy recovery are the least favoured waste treatment methods because there is no material or energy recovery.

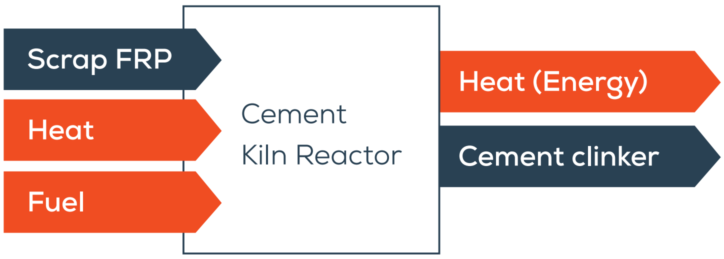
5.2 RECYCLING AND RECOVERY TREATMENT METHODS

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 levels of maturity and not all of them are available at industrial scale, as shown by the technological readiness levels (TRL) presented in the tables below for each existing treatment method [1], [25]. 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 end-of-life. As such, the wind industry is involved in a number of research & development projects (Appendix A).

CEMENT CO-PROCESSING (CEMENT KILN ROUTE)

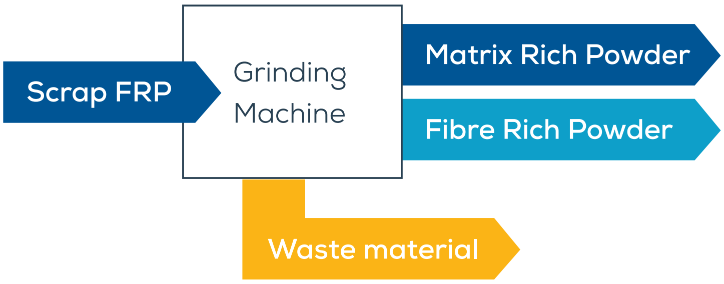
In **cement co-processing** the glass fibre is recycled as a component of cement mixes (cement clinker). The polymer matrix is burned as fuel for the process (also called refuse-derived fuel), which reduces the carbon footprint of cement production. Cement co-processing offers a robust and scalable route 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 efficacy, in this process the fibre shape of the glass disappears and therefore cannot be used in other composites applications [26].



TRL	STRENGTHS	DISADVANTAGES	POINTS OF ATTENTION
9	• Highly efficient, fast and scalable • Large quantities can be processed • Capability to reduce CO_2 emissions of cement manufacturing by up to 16% • Slightly increasing energy efficiency of cement manufacturing • No ash left over	• Loss of original fibre's physical shape	• Pollutants and particulate matter emissions (although appropriate mitigation exists in compliance with the Industrial Emissions Directive) • So far only suitable for glass-reinforced composites

MECHANICAL GRINDING

Mechanical grinding is a commonly used technology due to its effectiveness, low cost and low energy requirement. It does however drastically decrease the value of the recycled materials. The recycled products, short fibres and ground matrix (powder), can be used respectively as reinforcement or fillers. Because of the deterioration of the mechanical properties, the incorporation level of filler material is extremely limited in thermoset composite applications (less than 10%). For re-use of the fibres as reinforcement in thermoplastic applications, the variation in composition and potential contamination with resin particulates has a negative impact on reinforced thermoplastic resin manufacturing speed and thermoplastic resin quality. This could be minimised if the separating and dismantling processes were upgraded and could be suitable in cases where no more value retention is possible [26].

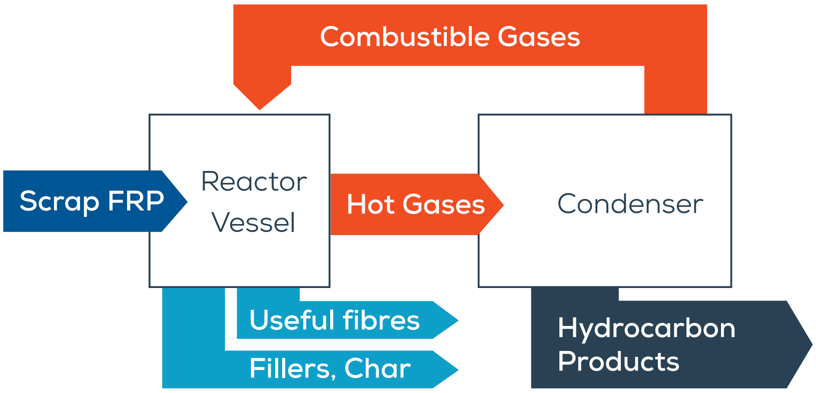


TRL	STRENGTHS	DISADVANTAGES	POINTS OF ATTENTION
Glass fibre: 9 **Carbon fibre: 6/7**	• Efficient and high throughput rates	• Not competitive (yet) with use of virgin raw materials • Quality of recyclates compromised due to the high content of other materials • Up to 40% material waste generated during grinding, sieving and processing • Consequently, large volume applications not (yet) developed	• Requires dedicated facilities with closed area to limit dust emissions

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. 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 [26].

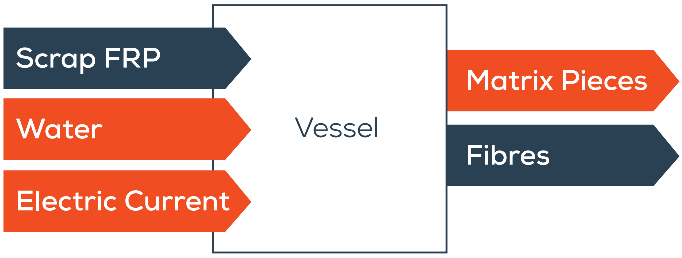
Economic viability depends on the scale and re-use that the matrix-obtained chemicals can have. To date, this recycling technology is only economically viable for carbon fibres. It is, however, not currently implemented at large scale since the volumes of carbon fibre reinforced composites are low. With 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.



TRL	STRENGTHS	DISADVANTAGES	POINTS OF ATTENTION
Pyrolysis: 9 Microwave: 4/5	• The bi-products (Syngas and oil) can be used as energy source or as base chemicals/building blocks • Easily scaled-up • Microwave pyrolysis: Easier to control. Lower damage to the fibre • Already used at commercial scale for recycling carbon fibre composites	• Fibre product may retain oxidation residue or char • Loss of strength of fibre due to high temperature • Decreased quality of the recovered carbon fibres from original material (lowest value loss in comparison to other mature recycling technologies)	• Economically sound for carbon fibre recovery to date

HIGH VOLTAGE PULSE FRAGMENTATION

High voltage pulse fragmentation is an electro-mechanical process that effectively separates matrices from fibres with the use of electricity. However, only short fibres can be recovered from the process and obtaining quality fibres requires high levels of energy, an issue that could be overcome by operating at higher rates. Compared to mechanical grinding, the quality of the fibres obtained is higher; fibres are longer and cleaner [26].

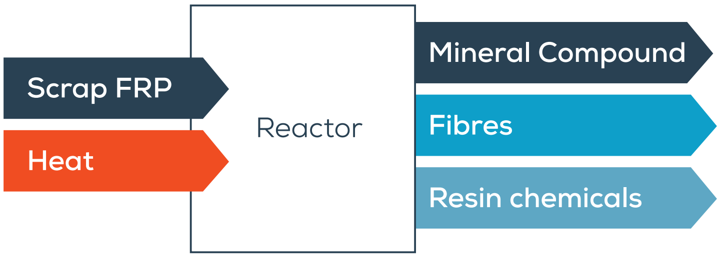


TRL	STRENGTHS	DISADVANTAGES	POINTS OF ATTENTION
6	• Potential to be scalable to treat large amounts of waste • Low investments required to reach the next TRL	• Only laboratory- and pilot-scale equipment are available • Decreased quality of the recovered glass fibres from original material	• Size of the available installations might be suboptimal to recycle the current stock of wind turbine

SOLVOLYSIS

Solvolysis is a chemical treatment where solvents (water, alcohol and/or acid) are used to break the matrix bonds at a specific temperature and pressure. Solvolysis offers many possibilities due to a wide range of solvent, temperature and pressure options. Compared to thermal technologies, solvolysis requires lower temperatures to degrade the resins, resulting in a lower degradation of fibres. Solvolysis with super-critical water seems to be the most promising technology since both fibres and resins can be retrieved without major impacts on their mechanical properties. Solvolysis is easily scalable but investment and running costs are high and it is still at a relatively low TRL [26].

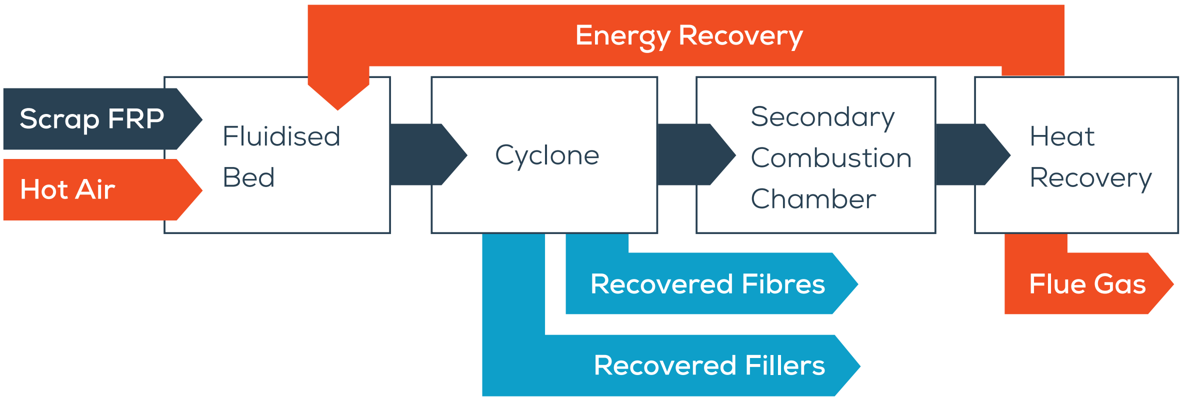
To date, only the carbon fibres are recycled through solvolysis. However, it is not currently implemented at large scale since the volumes of carbon fibre reinforced composites are low. With the next generation of mega-turbines, the required weight reduction and mechanical properties will enhance the preferred use of carbon fibre composites and the market volume might grow accordingly.



TRL	STRENGTHS	DISADVANTAGES	POINTS OF ATTENTION
5/6	• Recovery of clean fibres at their full length • Soup of resin chemicals produced which can be used as chemical building blocks • Low risk solvents are used such as alcohols, glycols and supercritical water	• High energy consumption due to high temperature and high pressure of some processes • Uses large volumes of solvents, although these are mostly recovered and reintegrated into the process • Decreased quality of the recovered carbon fibres from original material	• To date only the carbon fibres are recycled

FLUIDISED BED

The unique characteristic of this process is that it can treat mixed material (e.g. painted surfaces or foam cores), and therefore could be particularly suitable for end-of-life waste [26].



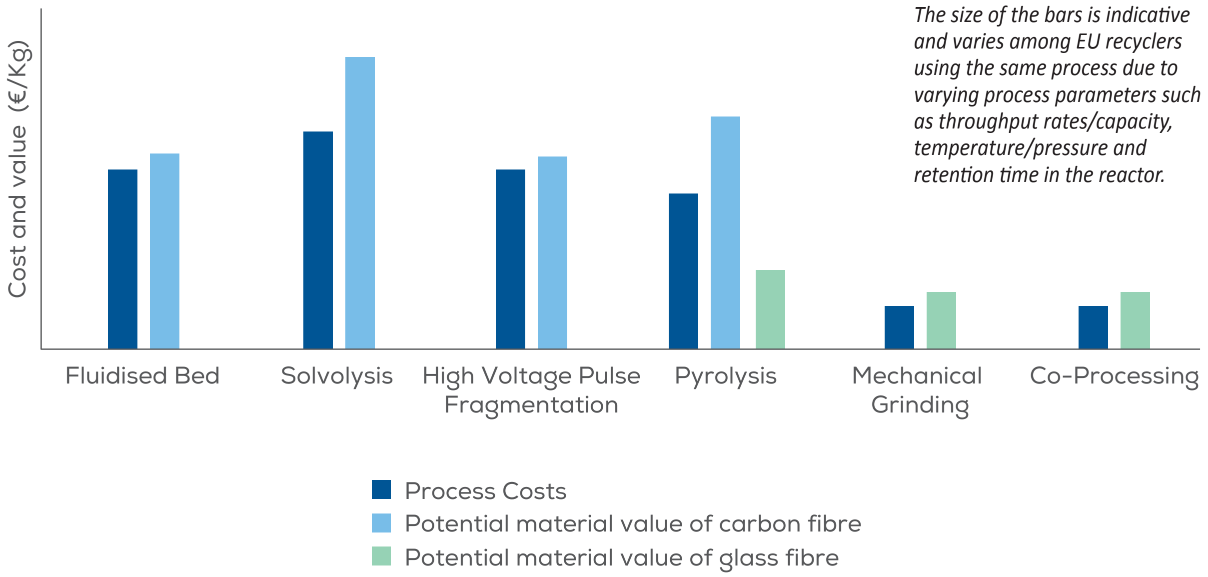
TRL	STRENGTHS	DISADVANTAGES	POINTS OF ATTENTION
5/6	• More tolerant of contamination • Recovery of energy or potential precursor chemicals • High efficiency of heat transfer	• More degradation of fibres than solvolysis/pyrolysis	• Process-related emissions (although appropriate mitigation exists) • Scale-up still needs to be developed

5.3 CONCLUSION

The above highlights that while various technologies exist to recycle glass fibre and carbon fibre from wind turbine blades, these solutions are yet to be widely available at industrial scale and to be cost-competitive. In many cases, the recycled material cannot compete with the price of virgin materials. For example the price of virgin glass fibre (1-2 €/kg) does not make the recovery of fibre as standalone product economically competitive. However, it is envisaged that the recovery of the whole composite materials into chemical building blocks will represent a viable route. This is based on the recovery of pyrolysis oils and of chemicals obtained through gasification, which is happening in other large volume sectors and value chains (i.e. plastic waste).

FIGURE 9

Estimated relative costs and values of composite recycling technologies



Source: Bax & Company and ETIPWind

Today, the main technology for recycling composite waste is through cement co-processing. WindEurope, Cefic and EuCIA strongly support increasing and improving composite waste recycling through the development of alternative recycling technologies which produce higher value recyclates (both in terms of resin and fibre) and enable production of new composites. Further development and industrialisation of alternative thermal or chemical recycling technologies may provide composite-using sectors, including the wind industry, with additional solutions for end-of-life.

The **best strategy for wind blades** is the one that combines design, testing (according to latest standards to decrease repair and failure rates), maintenance, upgrades (e.g. reinforcement) and the appropriate recycling technology to ensure the maximal value of the material is retrieved throughout its lifetime. It should also systemically allow the re-use of materials for the same or similar purposes (e.g. allows polymer matrices to revert to monomers and avoids fibre damage during the process). Having a good understanding of the environmental impacts associated with the choice of materials during design and with the different waste treatment methods at end-of-life through life cycle assessments will also help define the appropriate strategy.

6. TAKING BLADE RECYCLING TO THE NEXT LEVEL

As described in previous chapters, technologies for recycling composites exist. Cement co-processing is commercially available for processing large volumes of waste (albeit not in all geographies yet). In this process the mineral components are reused in the cement. However, the glass fibre shape is not maintained during the cement manufacturing process. Alternative recycling technologies are at different levels of maturity and/or too expensive at the moment, which means not all are fully commercially available yet. The wind industry is pushing for the development and industrialisation of alternative technologies to provide all composite-using sectors with additional solutions for end-of-life products. As such, the wind industry is involved in many research & development projects (Appendix A). However, in order to succeed, it's crucial to consider the following:

- Increased research and innovation (R&I) funding is required to diversify and scale up composite recycling technologies.

- R&I funding should also be earmarked for the development of new high-performance materials with enhanced circularity (design for longer lifetime, reuse/repurpose and 'from and for recycling' approach).

- The scientific understanding of the environmental impacts associated with the choice of materials during design and with the different waste treatment methods at end-of-life should also be improved (life cycle assessment).

The European Wind Energy Technology platform (ETIPWind) had produced a brochure [1] on blade recycling that provides R&I recommendations for policy makers as reproduced in the tables below. The SUSCHEM's Strategic Innovation and Research Agenda [10] provides further R&I recommendations, particularly on the design approach.

END-OF-LIFE APPROACH: COMPOSITE RECYCLING TECHNOLOGIES OF EXISTING BLADES
• Provide funding for research study comparing the economic viability of new recycling technologies, including market barriers associated with different end-users
• Promote proliferation of existing treatment routes like cement co-processing and increase acceptance around Europe
• Set up large-scale demonstration facilities to industrialise and scale up new recycling solutions for wind turbine blades
• Provide funding to support new manufacturing processes using recycled materials from blades in other sectors e.g. for production of new composites
• Establish a European cross-sectorial platform (including the building, transportation and energy sectors) to share best practices in recycling composites
• Promote reinforcement of value chain for recycling of composite waste from all sectors

DESIGN APPROACH: DEVELOPMENT OF NEW MATERIALS FOR FUTURE BLADES
• Earmark R&I funding for the development of new high-performance materials that are more easily recyclable
• Support demonstration facilities to test and integrate newly developed sustainable materials into next generation wind turbine blades
• Fund research into “smart” materials that enable better blade designs. In addition, embed sensors in turbine blades to enable material health monitoring and health forecasting capabilities
• Establish a full-scale demonstrator of a next generation wind turbine using “smart” materials that help optimise maintenance and increase lifetime
• Encourage blade designers to consider recycling technologies and reuse options during the process of structural design and materials selection

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APPENDIX A.

ADDITIONAL RESOURCES

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PUBLICALLY FUNDED PROJECTS

AIRPOXY
Introducing a novel family of ground-breaking thermoset composites that preserve all the advantages of conventional thermosets, but can also be easily processed and repaired and even recycled.
Date: 2018-2022 - https://www.airpoxy.eu/

ReDisCoveR
Transform the UK's wolrd leading composite end-of-life academic and commercial capabilities into a fully functioning and interconnected supply chain as the fledging market expands exponentionally.
Date: 2019 - https://www.nccuk.com/work-with-us/cross-catapult-projects/rediscover-composites/?popupclosed=true

R3FIBER
Thermal recycling process: technical and economic feasibility of R3FIBER process, obtaining high quality glass and carbon fibres in a self-sustained process.
Date: 2018 - https://www.bcircular.com/r3fiber/

ECOBULK
Large-scale European initiative which will demonstrate that re-using, upgrading, refurbishing and recycling composite products is possible, profitable, sustainable and appealing. The project selected products in the furniture, automotive and building sectors as demonstrators.
Date: 2017-2021 - https://www.ecobulk.eu/

FiberEUse
Large scale demonstration of new circular economy value-chains based on the reuse of end-of-life fiber reinforced composites.
Date: 2017-2021 - http://fibereuse.eu/

Re-Wind
Compare sustainable end-of-life reuse and recycling strategies for composite material wind turbine blades using Geographic Information Science (GIS) platform coupled with environmental, economic and social Life-Cycle Assessments (LCA).
Date: 2017-2019 - https://www.re-wind.info/

ReRoBalsa
Recycling of rotor blades in order to recover balsa wood/foam for the production of insulation materials.
Date: 2017-2019 - https://www.wki.fraunhofer.de/en/departments/hnt/profile/research-projects/Recycling-of-rotor-blades.html

Developing a concept and measures for resource saving dismantling of wind turbines
19 month project to develop a circular economy approach for end-of-life onshore wind turbines.
Date: 2017-2019 - https://ramboll.com/media/environ/supporting-a-major-circular-economy-project-in-the-german-wind-energy-sector

Dreamwind
Investigating new ways to recycle and manufacture reusable composite materials for wind turbine blades via bio-based resources and stimuli-responsive materials.
Date: 2016-2020 - http://www.dreamwind.dk/en/

NANOLEAP
Developing demonstrators and business cases for new applications of secondary raw materials stemming from composite waste streams.
Date: 2015-2018 - https://cordis.europa.eu/project/id/646397

WaliD
Wind blade using cost-effective advanced lightweight design, part of the project has been designing approaches for recyclable rotor blades.
Date: 2015-2017 - https://cordis.europa.eu/project/id/309985

LIFE BRIO Project
Optimising procedures for the dismantling of wind farms, taking into account the proper management of composite waste from blades, as well as developing policy and legislative recommendations to the European Commission.
Date: 2014-2017 - http://www.lifebrio.eu/index.php/en/

ForCycle
Recycling of composite parts from plastics with matrix materials.
Date: 2014-2016 - https://www.ivv.fraunhofer.de/en/recycling-environment/recycling-of-plastic-composites/forcycle.html

EXHUME
Development of new and resource efficient composite recycling and re-manufacturing processes in collaboration with industry.
Date: 2013-2016 - https://www.cranfield.ac.uk/case-studies/exhume

Genvind Innovation Consortium
Demonstrated how composite waste can be applied in different products, components and structures which were based on cradle-to-cradle philosophies.
Date: 2012-2016 - https://www.dti.dk/genvind/35154

SELFRAG CFRP
Development of a high voltage pulse fragmentation process for the recycling of thermoset composite materials.
Date: 2012-2014 - https://cordis.europa.eu/project/rcn/106311/reporting/en

SUSRAC
Mechanical recycling of aircraft composites using grinding and identification of novel applications.
Date: 2011-2013 - https://cordis.europa.eu/project/rcn/101279/reporting/en

Recycling of Waste Glass Fibre Reinforced Plastic with Microwave Pyrolysis
Recycling FRP thermosets via microwave pyrolysis.
Date: 2011-2012 - http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.createPage&s_ref=LIFE07%20ENV/S/000904&area=2&yr=2007&n_proj_id=3308&cfid=35676&cftoken=f9a755eebb6457c1-BA9893A6-9033-00C6-0E8F85F614A-2DAD6&mode=print&menu=false

EURECOMP (Recycling Thermoset Composites of the SST)
Recycling FRP thermosets via solvolysis.
Date: 2009-2012 - http://cordis.europa.eu/result/rcn/54152_en.html

REACT (Re-use of Glass Fibre Reinforced Plastics by Selective Shredding and Re-activating the Recyclate)
Recycling FRP thermosets via mechanical processes.
Date: 2003-2005 - http://cordis.europa.eu/project/rcn/68366_en.html

Cefic, the European Chemical Industry Council, founded in 1972, is the voice of large, medium and small chemical companies across Europe, which provide 1.2 million jobs and account for about 17% of world chemicals production.

Cefic members form one of the most active networks of the business community, complemented by partnerships with industry associations representing various sectors in the value chain. A full list of our members is available on the Cefic website.

Headquartered in Brussels, the European Composites Industry Association (EuCIA) represents European national composite associations as well as industry-specific sector groups at EU level. With the support of its members EuCIA is actively contributing to building an economically and environmentally sustainable European composites industry. EuCIA closely monitors relevant standards and legislation, actively communicates the ways in which composites contribute to a more sustainable world, and promotes educational activities. Our initiatives aim to enable the healthy growth and continued competitiveness of more than 10,000 companies and an estimated 150,000 employees involved in composites manufacturing across Europe.

WindEurope is the voice of the wind industry, actively promoting wind power in Europe and worldwide. It has over 400 members with headquarters in more than 35 countries, including the leading wind turbine manufacturers, component suppliers, research institutes, national wind energy associations, developers, contractors, electricity providers, financial institutions, insurance companies and consultants. This combined strength makes WindEurope Europe's largest and most powerful wind energy network.

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