SUSTAINABLE DECOMMISSIONING: WIND TURBINE BLADE RECYCLING

REPORT FROM PHASE 1 OF THE ENERGY TRANSITION ALLIANCE BLADE RECYCLING PROJECT

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Technology Driving Transition OGTC

With contributions from:

University of Leeds

National Composites Centre

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ACKNOWLEDGEMENTS

This report was written by Lorna Bennet, Project Engineer at the Offshore Renewable Energy (ORE) Catapult. ORE Catapult would like to thank the following partners for their help and expertise in compiling the report:

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- Annabel Fitzgerald, James Lightfoot and Jonathan Fuller of the National Composites Centre (NCC)
- Jeff Hailey and Pamela Lomoro of OGTC

SUMMARY

Thirty years ago, it would have been hard to imagine that offshore wind could power every home in the UK. Today, that target is one of the key pillars of the UK Government's climate change policy. This vision has been driven by the passion of wind industry pioneers to forge this new sector and make renewable energy a commercial reality.

With this has come an unrelenting drive to develop high-performance, next-generation wind turbines that will achieve the necessary energy capture and cost efficiency. For the blades, composite layers of stiff carbon or glass fibres in a resin matrix were found to be the optimal material, delivering exceptional strength, stiffness-to-density and flexibility in processing.

As the wind industry has grown, it has become a major user of these materials, which have long been a solution to design challenges in the oil and gas, aerospace, automotive, defence and leisure industries. They are found in the pipe systems at oil and gas rigs, in car seats and interiors, aeroplane wings, bicycles, skis and surfboards, to name but a few applications.

Composite blades are now the final hurdle towards fully recyclable wind turbines (85-90% of a turbine is technically recyclable already[1]). At the end of their lives, they have proven difficult and costly to reclaim and reprocess. To fully satisfy the sector's future growth plans and sustainability goals, finding the right solution for recycling them is becoming imperative, especially as the first generation of wind farms are starting to reach the end of their 25-year lifecycles.

In the year of COP26, this is the moment for the wind and other industries to pause and take stock. Pooling our collective experience and resources, we can achieve the feats of engineering that will make the energy transition and pan-sector circular economy a reality.

This report is the result of one such cross-sector collaboration between OGTC, Offshore Renewable Energy (ORE) Catapult, University of Leeds and National Composites Centre (NCC). It is the first phase in our work to identify, study and then demonstrate scalable, cost-effective, and sustainable composite recycling technologies that will be applicable to the wind industry.

When it comes to blade recycling, collaboration between the wind and oil and gas sectors will be crucial to accelerating recycling technologies for plastic composites. Both sectors are users of glass and carbon fibre reinforced plastics, which have proven to be optimal materials for both wind turbine blades and pipe systems on oil and gas rigs. Both now face the challenge of finding good solutions for decommissioning these materials in the coming decades.

For the wind sector, that is an urgent challenge here and now as the first generation of wind farms are starting to reach the end of their service life. Longer term, by 2050, the global offshore wind industry will decommission up to 85GW of capacity (cumulatively, and assuming a 25-year lifecycle). Onshore wind will decommission another 1,200GW. The oil and gas sector will likely begin to decommission today's composite pipelines around the same time.

The wind industry is already a major collaborator in many new innovation programmes in the composites arena – **Carbo4Power**, **SusWIND** and the **Circular Economy for the Wind Sector Joint Industry Project (CEWS)**. Under the latter project, ORE Catapult has set the target for an at-scale demonstration of wind turbine blade recycling in the UK ***within five years.***

The report sets out the huge opportunity for the UK supply chain in designing solutions to tackle the recycling challenge and capturing a global market that encompasses 2.5 million tonnes of composites already in use in the wind energy sector. Many of the recycling technologies discussed in the report require further study but show promise in terms of the quality of recovered materials.

Recycling is just the start. Moving turbines towards zero waste will be the next opportunity for the UK supply chain through remanufacturing, reuse, repowering and upgrading of components too. If realised, a spin-off circular economy from offshore wind could extend the current projection of 60,000 jobs in the sector by an additional 20,000 jobs.

As you will find in these pages, there are many reasons for optimism in the many techniques and technologies that are already being trialled in this area. We are excited at the prospect of taking these forward together with our industry partners and showing how the wind turbine, the workhorse of the clean energy revolution, will take its next steps towards circularity.

Table 1.
Results of the Technology Review, ETA Blade Recycling Project Phase 1

GF = glass fibre
CF = carbon fibre
GFRP = glass fibre reinforced plastic
CFRP = carbon fibre reinforced plastic
% figures refer to material properties retained post recycling compared to virgin fibres

	PROCESS	TRL GFRP	TRL CFRP	COST	SCALE	END PRODUCT/ USES	INNOVATION CHALLENGES
Mechanical	Grinding	9	6	Low	Large	GFRP powder for filler or reprocessing	Microplastics and dust
	Cement kiln co-processing	9	N/A	Low	Large	Energy recovery and cement clinker	Potential pollutants and particulate matter
Thermal	Pyrolysis	5	9	High	Small	Low quality GF High quality CF (90%) Oils from resins	Energy Intensive
	Fluidised bed pyrolysis	4	5	High	Small	Good quality, clean CF (70-80%)	Energy Intensive
	Microwave assisted pyrolysis	N/A	4	High	Very Small	Good quality CF (75%)	Less energy intense
	Steam pyrolysis	N/A	4	High	Very Small	High quality CF (>90%)	Energy Intensive
Chemical	Solvolysis	5	6	High	Small	Good quality GF (70%) High quality CF (90%) Matrix material	Additional cleaning process required Energy Intensive
	High temperature and pressure solvolysis	4	4	High	Very Small	Good quality, clean CF	High energy intensive Corrosive, high pressure
	Low temperature and pressure solvolysis	4	4	High	Very Small	Good quality, clean CF Epoxy monomers	Less energy intensive Acids required that are difficult to dispose of
	Electrochemical	4	4	Very High	Very Small	Reasonable GF	High energy intensive Inefficient
Reprocessing	Milled fibre (post grinding)	9	6	Low	Large	Powder additive/filler for tailored electrical & thermal conductivity	Microplastics and dust
	Chopped fibre (post pyrolysis/ solvolysis)	9	6	Low	Medium	Thermoplastic compounding/SMC/ BMC, cement reinforcing, prepreg tape	Handling of dry fibres
	Pellets	6	9	Low	Medium	Injection moulding (thermoplastic)	Microplastics and dust
	Non-woven mat	9	9	Low	Medium	Press moulding, resin infusion, wet pressing, prepregs, semi-pregs and SMCs	Handling of dry fibres
	Component reuse	8	N/A	Medium	Very Small	Structural components: bridge support, bike shelter, roofing, etc	Low impact as no need for energy intensive methods to reclaim and process materials

IF REALISED, A SPIN-OFF CIRCULAR ECONOMY FROM OFFSHORE WIND COULD EXTEND THE CURRENT PROJECTION OF 60,000 JOBS IN THE SECTOR BY AN ADDITIONAL 20,000 JOBS BY 2030.

REPORT SCOPE

This report is the conclusion of the first phase of the Energy Transition Alliance's Blade Recycling Project. In Phase 2, the project partners ORE Catapult and OGTC will select the most promising solutions from this study for further exploration and demonstration under the third and final phase of the project.

Here, the current methods of blade disposal are reviewed, the future scale of composite blade decommissioning is projected, and the influence of a changing regulatory framework is evaluated.

The next step is an outline and assessment of all the scenarios for recycling of glass and fibre reinforced plastics that are under development and trial or are establishing themselves across various sectors. The emphasis throughout is on the feasibility of these technologies and approaches for use at the scale and cost that will be required by a sector that is expected to decommission 40,000 to 60,000 tonnes of composite materials in the next two years alone[1].

It is worth highlighting at this point that the assumption that lies behind this project is that blade recycling will be a stepping-stone towards even more sustainable solutions in the future, and for this reason, some early examples of blade reuse in civil engineering and construction are touched upon too.

This is in tune with the philosophy of a circular economy: designing out all waste at the start is the ultimate end point of this journey, but one that will not be achieved imminently. The next best solutions are lifetime extension of turbines and components, repowering of whole wind farms and a whole host of refurbishing, reuse, and remanufacturing approaches too.

While the wind industry continues its work to develop more sustainable solutions[2,3], recycling is one of the best solutions achievable for these first-generation blades. And it is a solution that will be needed imminently in order to meet the minimum resource security that will sustain offshore wind's ambitious growth pathway. Wind turbines are increasing rapidly in number and size (turbine capacity has increased from 1.5MW in 2005 to 12MW in 2021).

A study completed by Topham et al[4] concluded that the material demands to manufacture a single large turbine are higher than the resources required to build two smaller turbines for the same power capacity. In addition, the quantity of carbon fibre utilised also increases as blades become longer in order to achieve the necessary stiffness without significantly increasing weight.

Landfill, which has been the most common solution for blade disposal to date, is out of the question as a future destination of these blades; primarily, as it does not match the industry's own ambitions for circularity and sustainability. The report concludes that this momentum from the wind industry itself is proving to be the crucial driver towards recycling.

A key conclusion of the report is that if the wind industry is to have security of supply in the coming years, establishing reliable and efficient recycling processes is a necessity. With that comes a positive financial case, as it is estimated that the resultant onward sale of materials could recoup up to 20% of decommissioning costs for an offshore wind farm[5].

As yet, there remains a technology gap for recycling blades. While various technologies exist to recycle their composite materials, and an increasing number of companies are offering composite recycling services, these solutions are not yet widely available nor cost competitive. That is why this report's additional exploration of technologies at the research and development stage is so important.

A KEY CONCLUSION OF THE REPORT IS THAT IF THE WIND INDUSTRY IS TO HAVE SECURITY OF SUPPLY IN THE COMING YEARS, ESTABLISHING RELIABLE AND EFFICIENT RECYCLING PROCESSES IS A NECESSITY.

CRITERIA FOR ASSESSING RECYCLING TECHNOLOGIES

Each of the technologies and processes investigated in this report are reviewed against core criteria for meeting the wind industry's needs:

ENVIRONMENTAL IMPACTS

COST IMPLICATIONS FOR TURBINE END-OF-LIFE MANAGEMENT

COMPLIANCE WITH A DYNAMIC REGULATORY LANDSCAPE (INCLUDING HEALTH AND SAFETY, USE OF CHEMICALS AND PROCESS EMISSION REGULATIONS)

STAGE OF TECHNOLOGY DEVELOPMENT

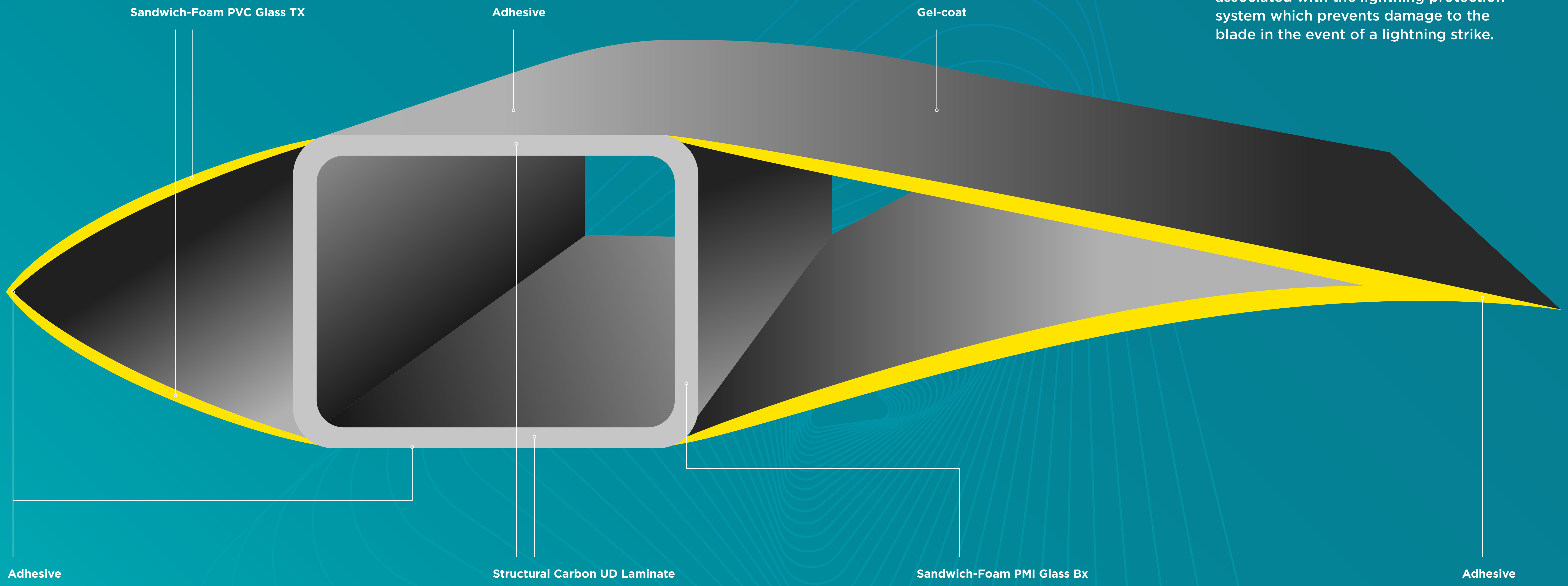
USEFULNESS AND VALUE OF THE END PRODUCTS

Three main forms of material reclamation were identified: mechanical, thermal and chemical. Once fibres and other materials have been recovered, further steps are required to reprocess them into usable materials which can be recycled in the manufacture of new products and components across a wide range of industries.

ANATOMY OF A WIND TURBINE BLADE

Blades are typically constructed of a polymer resin matrix that is reinforced with glass fibres and carbon fibres. A hybrid of glass and carbon fibres is also increasingly coming into use in the industry. A laminate core material, often made from high density foam or balsa wood, provides additional strength. The exterior of the blade is coated for weather protection and improved aerodynamic performance. There are also some metal components associated with the lightning protection system which prevents damage to the blade in the event of a lightning strike.

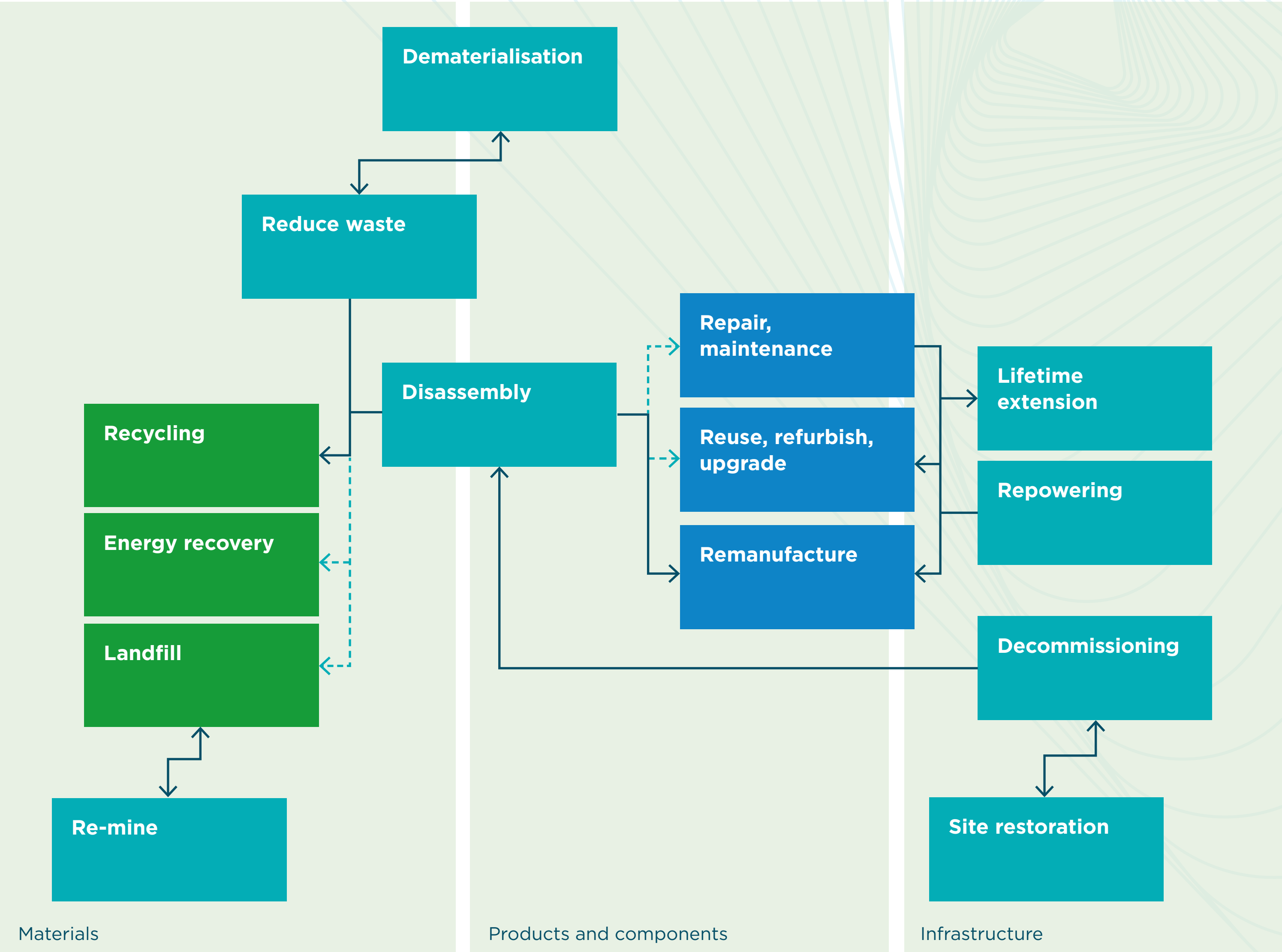
Figure 1. Generic Composition of a Wind Turbine Blade[6]



DEFINING 'CIRCULAR' AND 'RECYCLING'

'Recycling' and 'Circular Economy' are terms in common parlance, but they are too often confused or wrongly applied. Recycling is just one of the solutions that can form part of a circular economy, but a circular economy is much more than just one component or even one industry. It is an entire economic system aimed at eliminating waste and ensuring continual use of resources.

Figure 2.
Circular Economy Strategies[7]



DEFINING 'CIRCULAR ECONOMY'

A Circular Economy is seen as an alternative to a linear economy, or the 'take-make-dispose' model. Its aim is to keep resources in circulation, which means serving a useful purpose and for as long as possible. This approach requires us to extract the maximum value from components while they are in use, then recover and regenerate products and materials at the end of each service life[8].

The objectives of a Circular Economy are to:

- **Reduce waste**
- **Reduce the environmental impacts of production and consumption**
- **Drive greater resource productivity and efficiency**
- **Address emerging concerns with regard to resource security and scarcity**

When this report refers to 'Circular Economy' in the wind sector, it is referencing strategies that form a coherent design for circularity across all stages of a wind farm's life.

These strategies can be grouped into four main areas:

Narrowing resource flows, which means using less resources to begin with, and thus limiting waste.

Slowing resource flows through repair, reuse and remanufacturing strategies as well as lifetime extension and repowering of wind farm sites.

Closing resource flows hrough recycling of components, decommissioning and re-mining.

Integrating resource flows by entrusting materials to natural biogeochemical processes during site restoration and landfill.

DEFINING 'RECYCLING'

There is some ambiguity around what constitutes true recycling. The UK's Chartered Institution of Wastes Management defines it as: "Any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy[9]". While the Department for Environment, Food and Rural Affairs (DEFRA) have described it more succinctly as "turning waste into a new substance or product[10]".

The question is whether this is simply the collection and preparation (or 'harvesting' and 'reclamation') of wastes into their core materials, or whether that operation must be followed by reprocessing into new products to qualify them as 'recycled'. The latter is implied by den Hollander et al: "The recycling process involves the dismantling and disintegration of a product and its constituent components and the subsequent reprocessing of the product's materials" [11].

For the purposes of this project, the focus is towards the reclamation and reprocessing of composites into materials that are in good enough condition for a future reuse.

Related definitions

There are a number of other definitions that will be used in this report that should not be confused with 'recycling':

Repair: preventative, planned or ad hoc inspection/servicing tasks, which may involve repairs to restore a component to a good working condition.

Remanufacturing: components are sorted, selected, disassembled, cleaned, inspected and repaired/replaced before being reassembled and tested to function as good as new or better.

Component reuse and repurposing: components are used again for the same (reuse) or different (repurpose) function.

Harvesting: the act of collecting and sorting fibre reinforced plastic waste.

Reclamation: the process of separating the fibres and resin.

Reprocessing: where the reclaimed fibre is used to produce a useful material form, such as a discontinuous fibre mat.

GOVERNANCE LANDSCAPE

In the UK, the decommissioning of offshore wind farms is regulated by the Energy Act 2004[12] and the provision of a decommissioning programme is part of the consent process prior to development. While decommissioning programmes are primarily concerned with financial assurances to cover the costs of offshore wind decommissioning, recent research found that currently the regulation fails to do so[2]. Moreover, proposed decommissioning operations were found to be neither attuned to minimal resources and waste management standards nor sensitive to resource security concerns about meeting the material demands that will sustain the sector's ambitious growth pathway[2].

Overall, the general direction of travel in the UK is for clean growth and a circular economy, as set out in the Industrial Strategy[13]. Within the governance system, however, energy, infrastructure and circular economy generally persist in policy siloes[14]: Energy is handled by the Department for Business, Energy and Industrial Strategy (BEIS); infrastructure is part of the Treasury's activities; while resources and circular economy sit with (Department for Environment, Food and Rural Affairs (DEFRA). However, there have been recent moves to align these areas of governance more closely.

Energy and climate

Growth of wind power started relatively slowly, but the Stern Review (2006)[15] and Climate Change Act 2008[16] raised ambitions for faster deployment[17] by introducing legally binding greenhouse gas reduction targets for the UK. In 2019, the UK Government set a net-zero target for carbon emissions by 2050 and reforming the energy system is a major pillar of the low-carbon transition. Arguably the Clean Growth Strategy will be followed by a new Integrated National Energy and Climate Plan, but so far only a draft version from 2019 could be located online[18]. Low-carbon energy has seen a strong growth[19], but further reforms of the energy system are necessary, and a more integrated governance structure should be brought into place to allow for flexible adaptive governance[20].

On the other hand, the Maximising Economic Recovery (MER) policy, implemented by the Oil & Gas Authority[21] goes against the Clean Growth Strategy. This affects decommissioning, as the MER obliges operators to continue extraction. It also affects the offshore wind sector by presenting a continued push to lower short-term levelised cost of energy (LCOE).

Circular economy

Circular Economy primarily concerns itself with the stocks and flows of materials and products within the economy. As such, the circular economy primarily pertains to policy and regulation on resources and waste, which are largely driven by the EU Circular Economy Package – a major pillar of the European Green Deal – and the Waste Framework Directive[22,23]. Major aspects of the EU Circular Economy Action Plan are the reduction of average per capita consumption and the doubling of the use of recovered materials by 2030. Some materials and components that are commonly used in offshore wind are already prioritised (such as electronics and electrical items, steel and cement).

The Waste Framework Directive sets out the legislative framework for waste handling and establishes key principles such as the waste hierarchy, managing wastes in a manner that does not harm the environment or human health, and the polluter-pays principle[22]; which for the offshore wind sector, means that the responsibility of waste management and its costs falls on original equipment manufacturers (OEMs) and operators, and to a lesser extent on operations and maintenance (O&M) providers.

ENERGY, INFRASTRUCTURE AND CIRCULAR ECONOMY GENERALLY PERSIST IN POLICY SILOES BUT MOVES ARE UNDERWAY TO ALIGN THESE AREAS OF GOVERNANCE MORE CLOSELY.

Following Brexit, the European Commission's Circular Economy Package was transposed into UK law. A **brief overview** of the strategy for the UK and devolved nations backs up these ambitions. The Resources and Waste Strategy (RWS) for England aims to double resource productivity and eliminate all avoidable waste by 2050. The Strategy forms part of the Government's commitment under the 25 Year Environment Plan to leave the environment in a better state than we inherited it, including eliminating all avoidable plastic waste.

The Welsh Government's strategy, Beyond Recycling, sets out its aim of making a circular, low carbon economy in Wales a reality with a set of key actions to deliver the objective of zero waste by 2050. The Scottish Government's circular economy strategy, Making Things Last, published in 2016, sets out a clear vision and priorities for action to move towards a more circular economy; and Scotland has set a series of ambitious targets to drive circularity. In Northern Ireland, the Department of Agriculture, Environment & Rural Affairs (DAERA) is currently developing the Environment Strategy for Northern Ireland, which will consider the main long-term environmental priorities for Northern Ireland."[24]

At the UK level, the forthcoming Environment Bill is expected to enshrine more ambitious targets into law. The anticipated higher ambitions will place more demands on the wind industry and require that companies invest now in the processes that will deliver them.

Resources and waste regulation are highly dynamic, but the continued direction of travel is towards the diversion of waste materials (that can be reused or recycled) from going to incineration or landfill facilities. This could limit the potential for turbine blades, which predominantly consist of glass fibre reinforced plastics, to enter processes aimed primarily at energy recovery. Despite provisions to limit incineration of technically recyclable materials, a part of the waste sector is campaigning for large-scale investment into more Energy from Waste (EfW) capacity in the UK[25]. Already, more than 80% of investment into waste management infrastructure is directed towards energy-from-waste facilities or facilities to prepare refuse derived fuel[26]. The risk is that waste incineration becomes locked in and UK plc loses valuable business opportunities, as observed already in Scandinavian countries[27].

THE RISK IS THAT WASTE INCINERATION BECOMES LOCKED IN AND UK PLC LOSES VALUABLE BUSINESS OPPORTUNITIES, AS OBSERVED ALREADY IN SCANDINAVIAN COUNTRIES.

THE RECOMMENDED APPROACH IS TO PROACTIVELY WORK WITH THE REGULATOR AND TO PREVENT A MATERIAL FROM BECOMING CLASSED AS A WASTE IN THE FIRST PLACE.

Incineration of turbine blades is regulated under the Industrial Emissions Directive (IED)[28], which works in accordance with Best Available Techniques (BAT). The combustion of wind turbine blades does not appear to be specifically mentioned in existing BATs or BAT Reference Documents (BREFs)[29] but the BREF on cement does mention glass fibre[30]. IED permits are subject to continuous improvement giving consideration to evidence that the proposed technology is low waste and contributes to further recovery of materials, advances in the (academic) knowledge base, and minimising environmental risks and impacts.

The end-of-waste regulations and the procedures through which end-of-waste solutions are assessed by the regulator involve four tests, each of which must be met:

1. **Evidence that the recycled product is different from the original waste, and for meeting this test a mechanical recycling route is normally not sufficient;**
2. **Presence of a clear and demonstrable market, which may need to be developed as part of achieving end-of-waste;**
3. **The product can be used in the same way as a non-waste alternative; usually this is assessed through a comparison with an appropriate virgin material;**
4. **Evidence that the product can be stored and used with no worse environmental effects than the material it replaces.**

There are many challenges with these procedures such as the subjectivity in interpretation and the forced processing of materials using environmentally costly means, along with the end-of-waste panel that handles applications being unavailable for extended periods.

Companies can make their own assessment: however, this is risky as the regulator can sue companies as evidenced by the fact that End-of-Waste is riddled with case law. The recommended approach is to proactively work with the regulator and to prevent a material from becoming classed as a waste in the first place. If a recyclate remains classed as a waste after recovery processing, then the commercial value of the material may be significantly less, possibly rendering investment in associated recycling processes uneconomical.

While landfilling wind turbine blades is not prohibited anywhere in the UK (as in some European countries), available landfill space is rapidly diminishing. The landfill tax makes it economically unattractive. Scotland and Wales, along with several EU countries, have already begun severely limiting landfill. When it comes to export of wastes, the relevant legislation is the Transfrontier Shipment of Waste Regulations 2007[31]. Shipment to or from the UK is subject to a permit, regulatory fees for every shipment and very strict rules.

The current general interpretation of the regulation is that the export of wastes for which a solution can be reasonably found or brought into place inside the UK is in principle not allowed. Moreover, in recent times the major destinations for waste from the UK, primarily in Asia, are tightening their rules and have stopped accepting numerous low-value materials. When exporting to countries with more lenient waste regulations, waste producers remain responsible for them under duty of care regulations.

Developing the required end-of-use infrastructure in the UK is subject to planning regulations (in England and Wales under the Localism Act 2011[32]) and likely will be subject to guidance set out in the Green Book[33]. This will take time, which has to be factored in, to get UK infrastructure in place.

Decommissioning

Offshore wind decommissioning is primarily governed by provisions made in the Energy Act 2004 implemented with guidance prepared by BEIS which states that: "The Government's approach is to seek decommissioning solutions which are consistent with relevant international obligations as well as UK legislation, and which have a proper regard for safety, the environment, other legitimate uses of the sea and economic considerations including protection of the taxpayer from liabilities relating to decommissioning. The Government will act in line with the principles of sustainable development."[34]

There is a general lack of detail in offshore wind decommissioning programmes regarding the waste management operations and a high likelihood that costs have been significantly underestimated. This suggests that the first two obligations regarding the contents of decommissioning programmes have not yet been met:

- **Programmes must set out measures to be taken for decommissioning the relevant object;**
- **Plans must contain an estimate of the expenditure likely to be incurred in carrying out those measures.**

Should best environmental solutions not be available in line with circular economy and sustainable development policies, i.e. to deliver absolute environmental improvements, then it can be argued that the precautionary principle applies. In those cases, the offshore wind sector can specify the knowledge gap and co-produce plans as part of the decommissioning programme to increase chances that solutions will be available in support of environmental sustainability at every lifecycle stage, including waste management. This will have the added benefit of reducing decommissioning costs or even opening new income streams for the sector.

BEIS (2019) states that: "Waste from decommissioning should be reused, recycled or incinerated with energy recovery in line with the waste hierarchy, with disposal on land as the last option". This does not integrate recent updates to resources and waste policies, however, and the implications for waste management in offshore wind decommissioning will be greater proactivity on decommissioning and waste management in the design of wind farms and the manufacturing of components.

A more proactive approach would include consultation with parties capable and/or likely to be involved in the end-of-use management, such as the removal and resources sectors as well as offshore wind OEMs, to investigate potential for component reuse, repurposing, repair and remanufacturing. When these solutions are not suitable, recycling, incineration, disposal and landfill solutions can be detailed as a means of last resort. This information will enable a feedback loop to the design of wind farms, to adapt the design with a view to optimise performance from environmental, social and economic perspectives at each stage of the lifecycle.

While industry is in the first instance responsible for the preparation of a decommissioning programme of sufficient quality, Government can step in and prepare the programme on their behalf if necessary (under Section 107 of the Energy Act 2004).

The Energy Act also applies to repowering, but more clarity is required to understand the extent to which decommissioning programmes must be amended in the case of repowering and whether this also applies to cases of lifetime extension. As previously mentioned, decommissioning became a devolved matter in 2017, with decommissioning responsibilities and powers being transferred to the Scottish Government[35]. Marine Scotland has expressed the inclination to stay close to legislation laid out for England and Wales[36].

THERE IS A GENERAL LACK OF DETAIL IN OFFSHORE WIND DECOMMISSIONING PROGRAMMES REGARDING THE WASTE MANAGEMENT OPERATIONS AND A HIGH LIKELIHOOD THAT COSTS HAVE BEEN SIGNIFICANTLY UNDERESTIMATED.

FUTURE MARKET OPPORTUNITY

This report summarises previous and current projects underway in the UK and globally to develop a blade recycling solution for wind turbines. As already mentioned, a flotilla of new UK-based projects, initiated by the wind industry, has come online in the past year. Many more have been underway in countries such as Spain, Denmark and the Netherlands for some time.

At present, there are few UK companies actively pursuing this opportunity. Stand-out amongst them, Scotland's Renewable Parts, is a fast-growing enterprise focussed upon component refurbishing and reuse that is now expanding its operations into larger facilities to meet growing demand.

Aside from a few trailblazers, there is low awareness amongst the UK supply chain of the economic opportunity that blade recycling, and the broader drive towards a circular economy in the wind sector brings. The University of Leeds, a contributor to the report, estimates that if we can invest now in the birth of a circular economy sector, the UK can extend its wind sector job creation targets by at least a third.

This assertion is supported by research from the Green Alliance and WRAP (2015) that focussed upon the UK waste sector. They estimated that without new initiatives, 31,000 jobs could potentially be created in that sector, in the coming years (relying upon energy from waste and landfill). If we add job creation based upon recycling development, that increases to 205,000 new UK jobs. Even better, if we develop reuse and repair of products and components, we can increase this projection to 517,000 new and higher value UK jobs.

The report's authors conclude that the creation of a blade recycling segment of the wind economy could extend the UK's current job creation targets (60,000 direct and indirect jobs by 2030) by an additional 5,000 jobs. By adding more advanced circular economy approaches (reuse, remanufacturing, refurbishment, etc.) these targets could be increased by at least 20,000 jobs by 2030.

GLOBAL FORECAST FOR WIND FARM DECOMMISSIONING

Today, 2.5 million tonnes of composite material are in use in the wind energy sector globally[2]. It is estimated that there are 12-15 tonnes of glass fibre reinforced plastic per MW of power[37]. Glass fibre reinforced plastic (GFRP) represents the majority of the USD 75 billion global market for composites. In Europe alone, over one million tonnes are produced annually, with the construction, infrastructure and transport sectors accounting for almost 70% of that figure[38].

When it comes to carbon fibre reinforced plastic (CFRP), the global demand has tripled in the past decade (2010 – 2020) to around 160,000 tonnes[38]. Wind energy now represents the biggest sector with 24% of the global demand for this material, just surpassing the aerospace (23%), sports (13%) and automotive (10%) sectors. In terms of value, however, the wind industry represents only 4% of the global market (at £772 million) due to the use of low-cost, and often lower quality, carbon fibres (see Figures 3 and 4)[39].

In the UK, current landfilling rates are 35% for CFRP and 67% for GFRP, out of which only 20% of CF and 13% of GF are recycled and 2% of CF and 6% of

Figure 3.
Global Carbon Composite Demand in 2018[39]

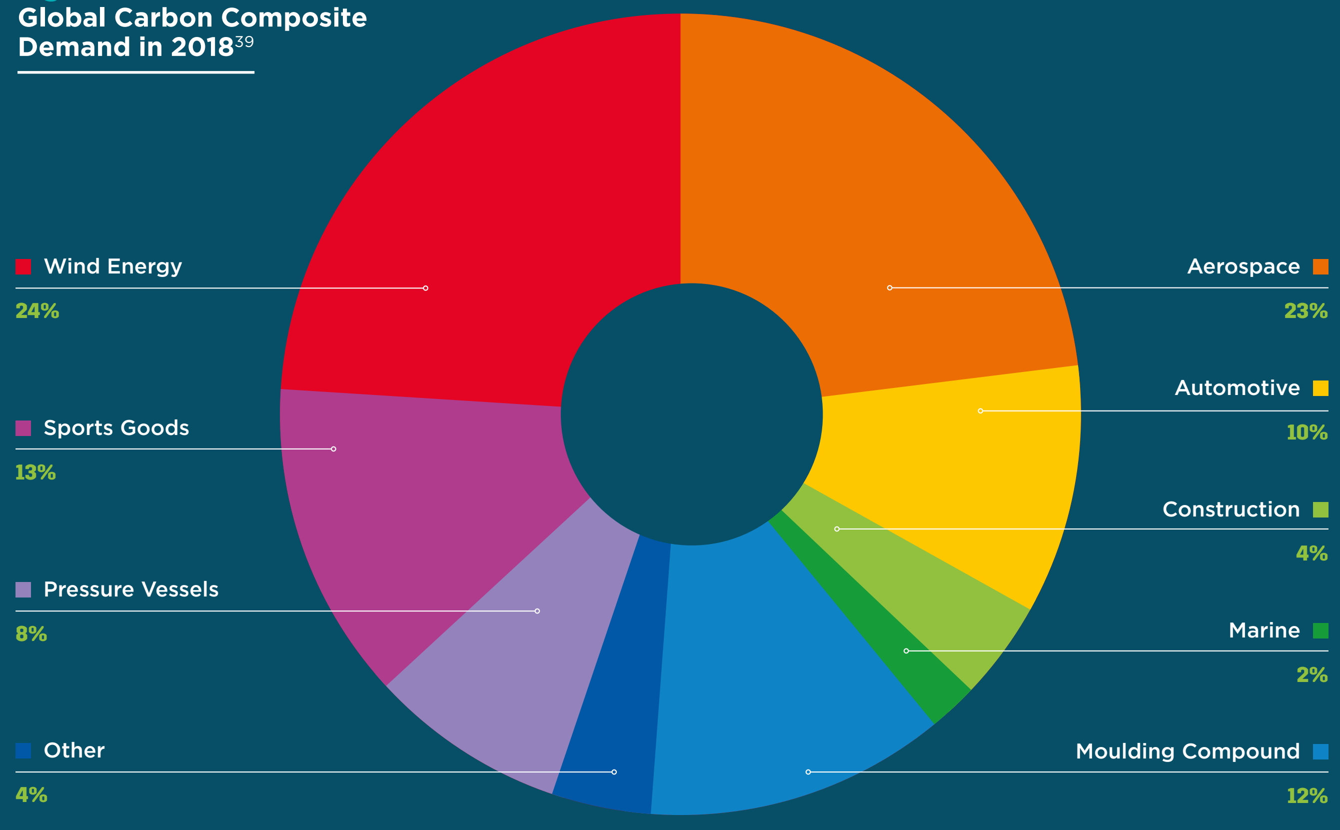


Figure 4.
Global Carbon Fibre Demand by Sales (£million) in 2018[39]

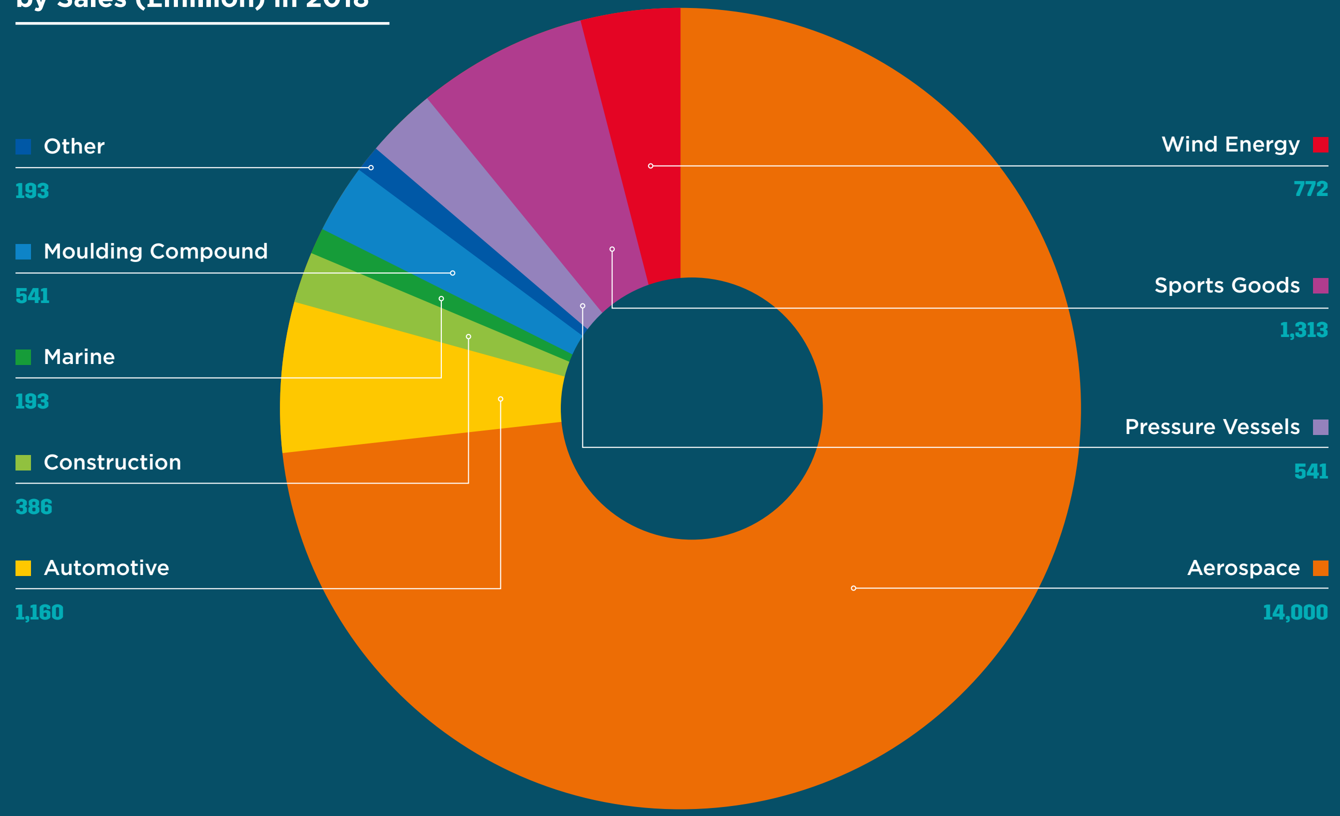
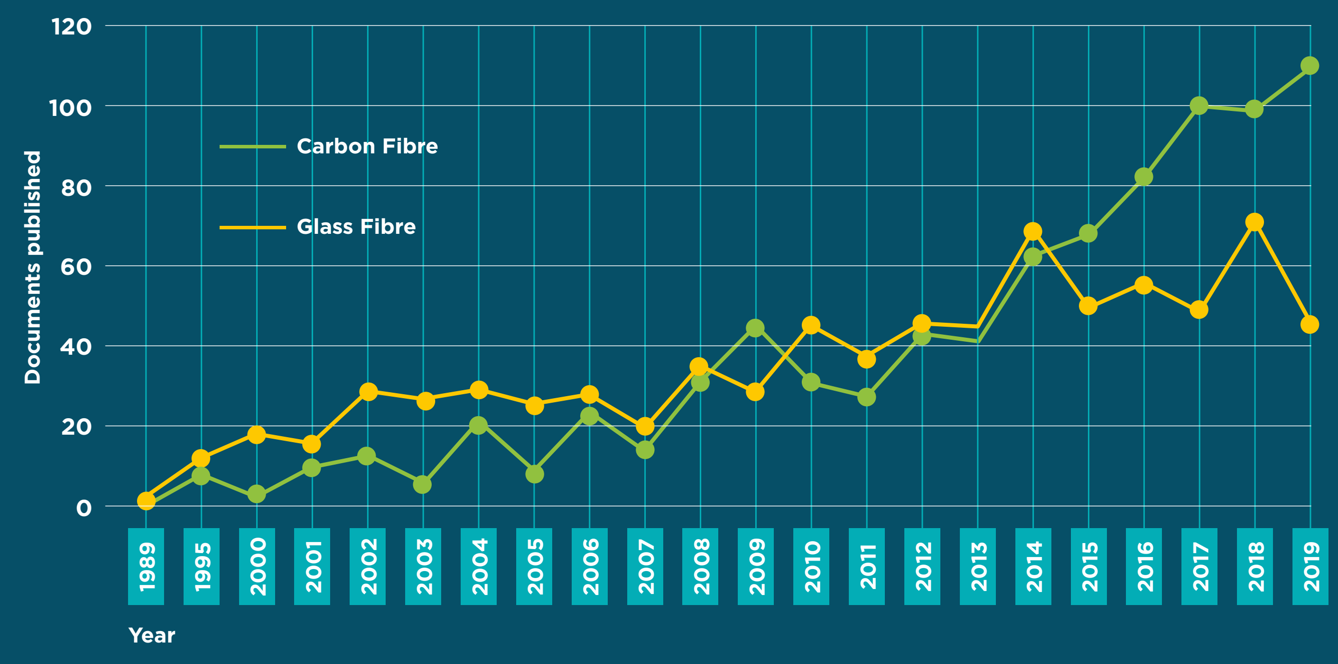


Figure 5.
Number of Articles Published on Carbon and Glass Fibre Reinforced Plastic Recycling 1989-2019[40]



GF are reprocessed. Recycling even 20% of UK GF and CF would be able to generate millions or even billions of pounds depending on the end product[40].

This is a topic of interest for materials researchers, circular economy and environmental impact studies as well as for individual industries (aerospace, marine, wind energy, oil and gas, etc) as evidenced by the increasing number of papers on the topic (Figure 5). All of this research is complimented by projects established by companies and government institutions in order to develop a cost-effective environmental solution for composite end of life, many of which will be discussed in this report.

The two largest sectors (wind and aerospace) have the opportunity to develop a new type of supply chain targeting reclaimed fibres from composites. Industries like sports goods have low retrieval rates of used goods; firstly, because they are consumer goods, and secondly, because they contain small quantities of composites. Wind and aerospace, on the other hand are comprised of large quantities per product and, in addition, the assets are managed by a small number of companies (compared to the millions of individual consumers of sports equipment, for example). This allows for relatively easy predictions of the volume of composites that will be disposed of in upcoming years, which will encourage the supply chain to develop new products which reuse blades or use recyclates of the blades.

UK FORECAST FOR WIND FARM DECOMMISSIONING

As of 2019, there was a total of 24GW of wind capacity installed in the UK, 10GW of which was offshore[41] representing nearly half of Europe's installed offshore wind capacity of 22GW and a third of the operational 29GW offshore globally[2]. If the turbines that are currently being installed offshore are included, the capacity grows by 13GW. Onshore there are 13.6GW installed.

Overall, there are 2,555 turbines and approximately 7,655 blades installed in UK waters, while onshore there are 8,625 commercial turbines with 25,875 blades[2]. Figure 6 shows the cumulative mass of all composite wind turbine blades installed onshore and offshore in the UK as well as the projections for the years to come. Assuming 20 years of operation, the number of wind turbines and blades that will be expected to be decommissioned can be calculated and is presented in Figure 7.

It should be noted that these predictions are for wind turbine blade waste and do not include other components that are also often made of composites (such as nacelle covers and rotor hub nose cones).

In 2018-2019 only 10% of all fibre reinforced plastic waste was diverted from landfill. Optimistic estimates suggest this number can increase by 20% per annum. However, by 2030 this would still leave a gap of 67% of all waste that would go to landfill[2].

Figure 6.
In-Use Fibre Reinforced Plastic (FRP) Blade Mass and All Source End-of-life FRP Recycling Capacity Gap in the UK[2]

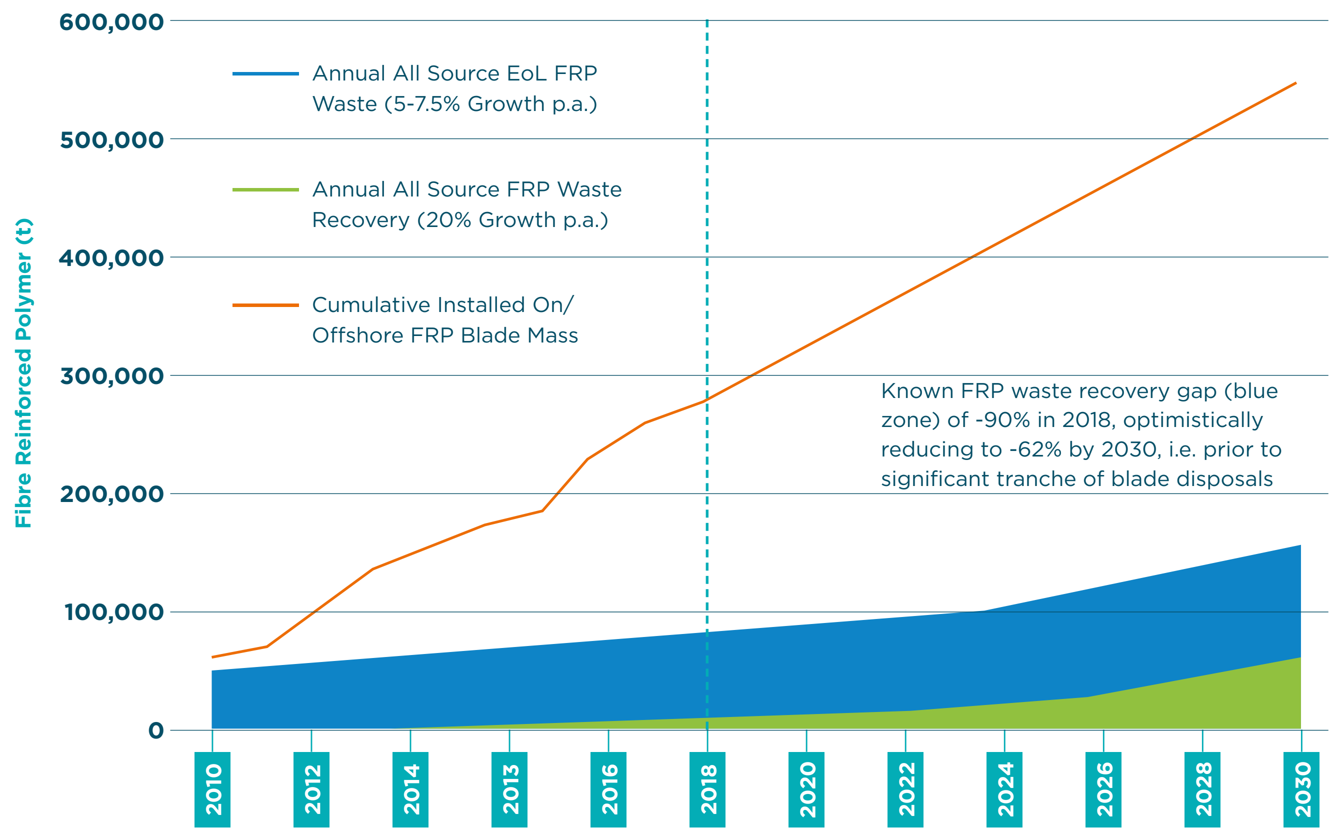


Figure 7.
Offshore Wind Farm Decommissioning Projections (25-year lifecycle - UK), an analysis of data from 4C Offshore[45]

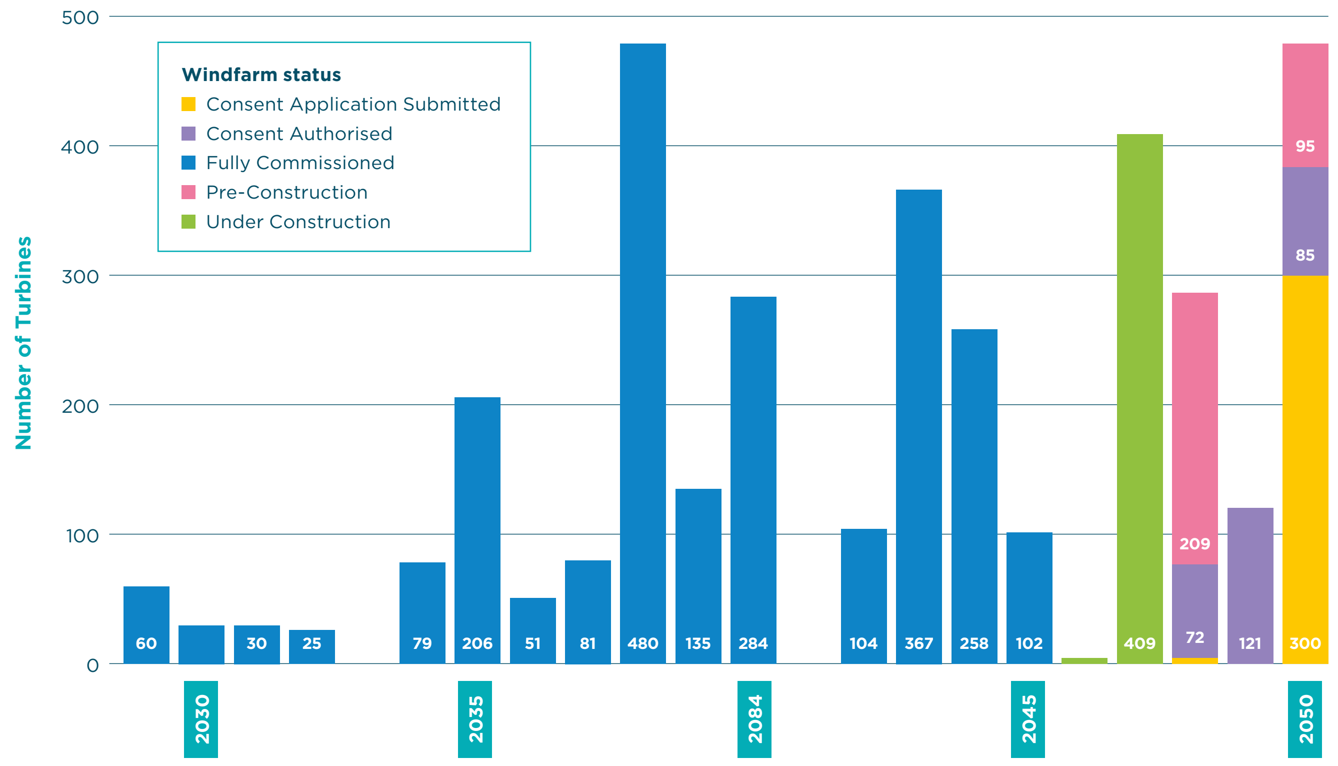


Figure 8.
Global Onshore Wind Capacity[44]

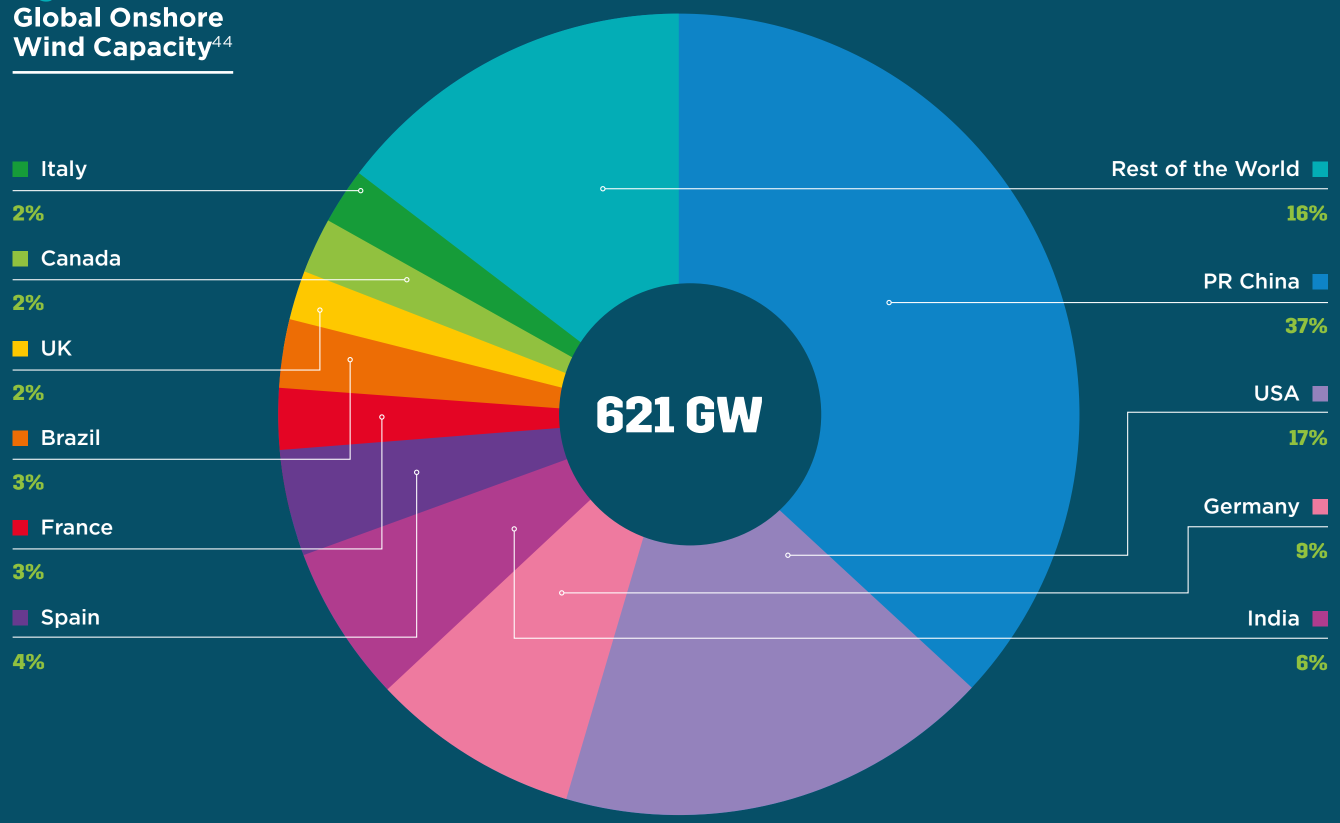
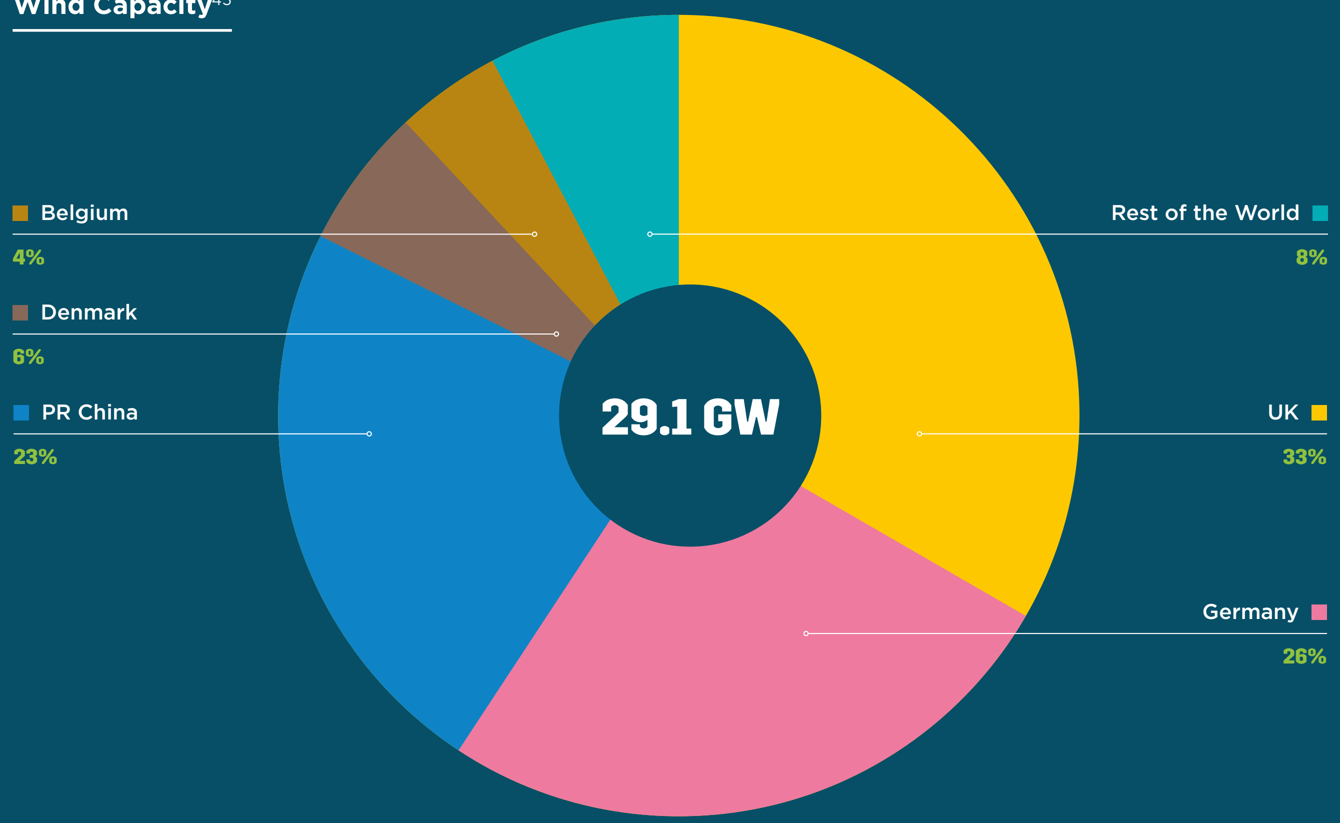


Figure 9.
Global Offshore Wind Capacity[45]



GLOBAL FORECAST FOR WIND FARM DECOMMISSIONING

In 2019, there were 29.1GW of offshore wind power installed globally. By 2050, it is predicted that 85GW of this wind farm capacity will be decommissioned, adding up to 325,000 blades. It should be noted that this is a maximum estimate as it does not account for the possibility for life extension or repowering and assumes that wind farms will be decommissioned at the end of their operating life of 25 years.

Europe is the largest market (75% of all offshore wind), followed by China, Taiwan and Vietnam[42]. North America currently operates only 30MW although this number is expected to grow in the following years. Overall, the top five countries by installed capacity are UK, Germany, China, Denmark and Belgium. Onshore, there are more than 600GW installed. Out of those, 230GW are in China and 106GW in the USA, followed by India, Spain and Sweden[42] (Figures 8 and 9).

As growth in the coming years is expected to increase (Figure 10), it is time to start thinking about what happens at the end of life of materials that make up wind turbines.

LIFE EXTENSION DOES NOT SOLVE THE PROBLEM OF BLADE DISPOSAL, IT MERELY DELAYS DECOMMISSIONING FOR A FEW YEARS AND WILL SLIGHTLY REDUCE THE STEEPNESS IN THE RATE OF THE COMPOSITE WASTE CURVE.

Figure 10.
Rate of Wind Turbine Installation Globally (GW installed per year)[42]

CAGR = Compound Annual Growth Rate

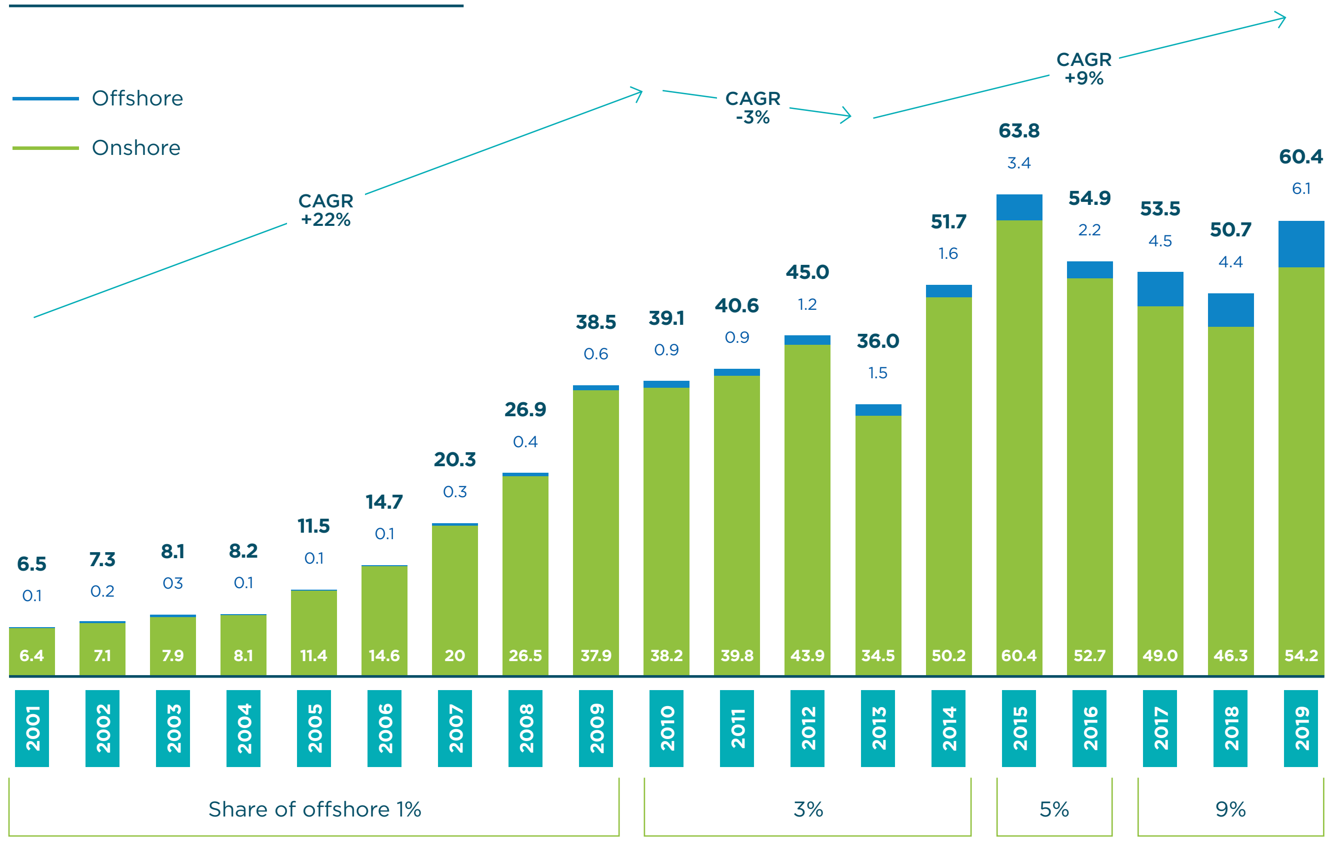


Figure 11.
Global projections for offshore wind turbine decommissioning up to 2050[45]

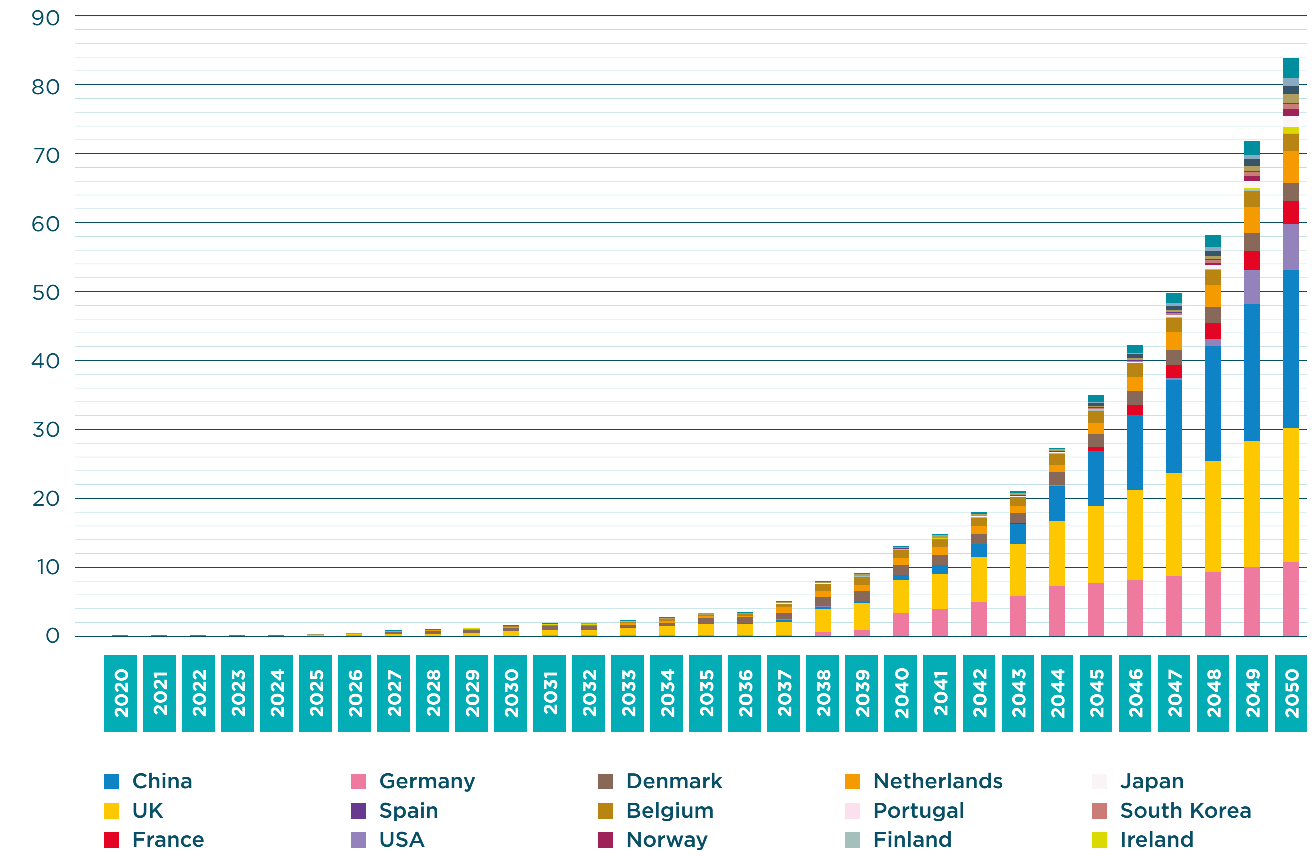
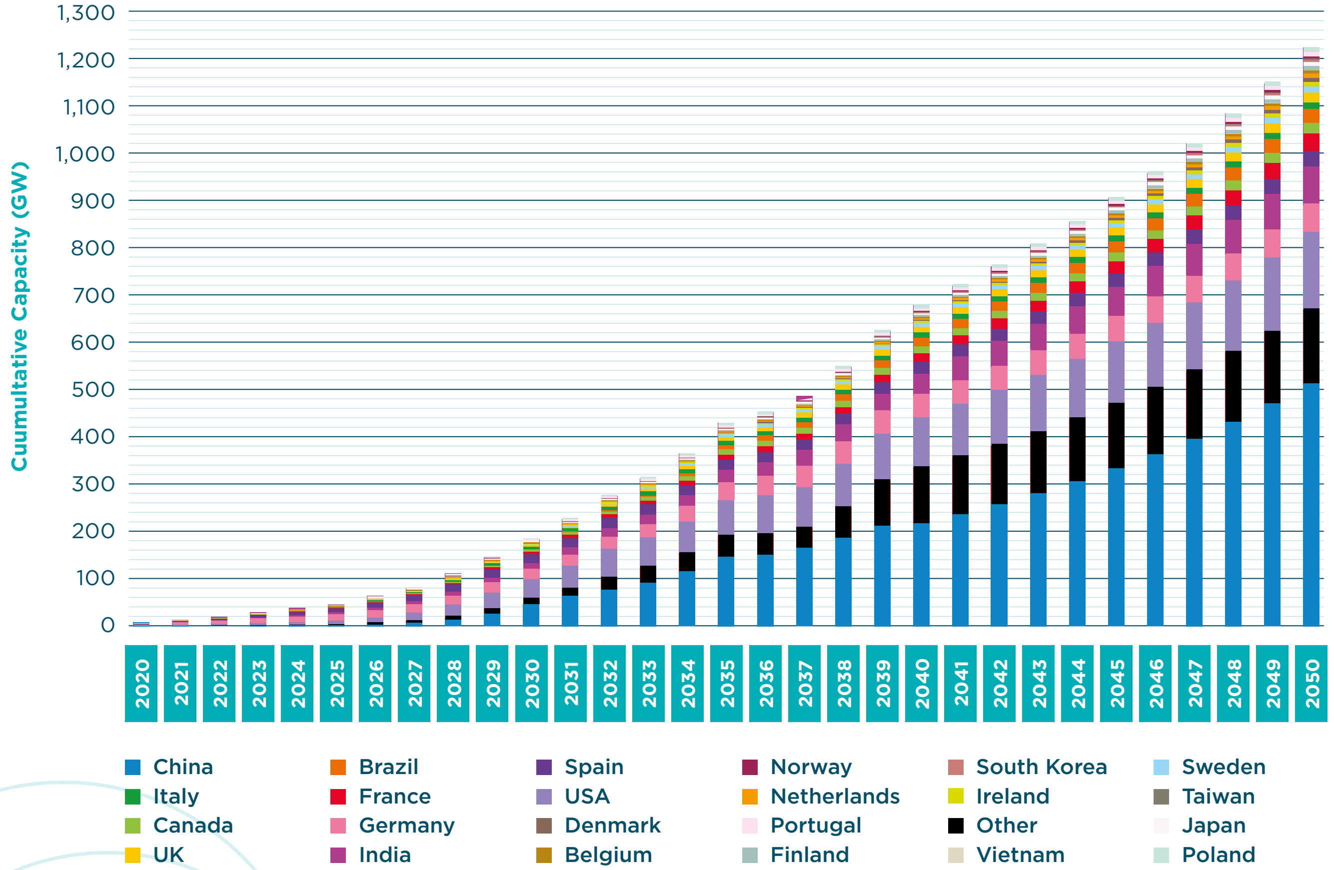


Figure 12.
Global projections for onshore wind turbine decommissioning up to 2050[45]



Current decommissioning costs are estimated to be in the region of USD 223,000 - 668,000 per MW[43]. Again assuming 20 years of operation, globally the rate at which wind farms are decommissioned and the rate at which landfills fill with wind turbine blades is only going to grow if recycling and reusing technology, as well as the supply chain, is not advanced..

While lifetime extension offers a short-term alternative to decommissioning, extending the operational life of a wind farm (say, for up to 10 years) will depend upon having a detailed assessment of the remaining useful life, environmental conditions, reliable monitoring of the systems as well as overall operations and maintenance costs and expectations over the life of the wind farm. There are no clear statistics on how many wind farm owners will pursue this option. Furthermore, life extension does not solve the problem of blade disposal, it merely delays decommissioning for a few years and will slightly reduce the steepness in the rate of the composite waste curve. Making use of this delay in decommissioning by developing promising reprocessing technologies is crucial to increase recycling efficiency rates and to produce higher quality recyclates.

Over the next 30 years, global wind energy capacity is expected to grow as discussed. However, assuming an operational life span of 20 years, wind farms that are installed over the next 10 years will be decommissioned by 2050. Figures 11 and 12 show the projected capacity of onshore and offshore wind power that is anticipated to be decommissioned by 2050 based on the current consent agreements, planning applications and government targets that have been declared. These estimates do not consider the possibility of life extension and repowering and assumes that windfarms will be discontinued at the end of their operating life of 25 years.

CURRENT METHODS OF BLADE DISPOSAL

Fibre-reinforced plastics (FRPs) are a combination of plastic resins, glass, carbon and other fibres. There are two main forms of plastic resins: thermosets, which form an irreversible solid polymer and are most commonly used in the manufacture of wind turbine blades, and thermoplastics, which can be remelted and recycled. Fibre reinforced composites are used in numerous applications such as vehicle components, doors, bathtubs and wind turbine blades.

From an environmental point of view, the material offers significant benefits in the use-phase of a product because it is light, strong and long-lasting. For example, it can reduce the weight of vehicles, cutting their fuel consumption and thus their greenhouse-gas emissions. Fibre reinforced plastic is also vital for the ever-larger blades of wind turbines, as blades made from steel would be incredibly heavy, less efficient and very expensive.

At the end of their lives, they have proven difficult and costly to reclaim and reprocess. To fully satisfy the sector's future growth plans and sustainability goals, finding the right solution for recycling them is becoming imperative, especially as the first generation of wind farms are starting to reach the end of their 25-year lifecycles.

Approximately 60% of waste fibre reinforced plastic is landfilled, while another significant portion of it is incinerated for energy recovery as heat. Where it is recycled, the reclamation techniques mean that it can only be used for lower value applications – such as short fibre reinforcement or filler in new composite materials – limiting the economic case for using recycled materials. This is especially relevant for glass fibre reinforced plastics, as the low price of virgin glass fibres (£2-3/kg) does not incentivise the use of recycled glass fibres that may be a higher price and lower quality. Addressing these issues to strengthen the business case is a key aspect of establishing a functioning supply chain for recycled glass fibre[46].

APPROXIMATELY 60% OF WASTE FIBRE REINFORCED PLASTIC IS LANDFILLED, WHILE ANOTHER SIGNIFICANT PORTION OF IT IS INCINERATED FOR ENERGY RECOVERY AS HEAT.

LANDFILL

Landfill used to be the most economic form of disposal for many municipal solid wastes, with many negative environmental impacts. These could include fires and explosions, vegetation damage, potential health hazards, unpleasant odours, landfill settlement, ground water pollution, air pollution, and global warming[47]. The landfill tax in England is currently £94.15 per tonne (2020-2021 rate), however, including the cost of gate fees and transportation, the total cost to landfill waste is typically £130 to £140 per tonne[48].

Although landfill tax is not expected to rise dramatically, Germany, Scotland, Wales and several other European countries have already begun to ban or severely limit the landfill of wind turbine blades[48,49]. Their materials can, and often are, considered as recyclable and there are concerns about their environmental impacts due to the associated carbon emissions during decomposition. By 2030, the European Commission's Circular Economy Package seeks to reduce the amount of municipal waste that can go to landfill to 10% by increasing the rate of recycling[48].

The European Waste Framework Directive (2008/98/EC) established the basic principle that the 'polluter pays', known as extended producer responsibility. This requires EU Member States to apply the waste management hierarchy: Prevention, Re-use, Recycling, Recovery, Disposal. Article 11.2 stipulates that "*by 2020 a minimum of 70% (by weight) of non-hazardous construction and demolition waste… shall be prepared for re-use, recycled or undergo other material recovery*"[50].

When blades are removed from a wind turbine during decommissioning or repowering, they can require specialist vehicles, if transporting the structure as a whole, or they must be cut into manageable sections. Both options can be costly, with the process of cutting larger and strong blades requiring sizeable machinery such as vehicle mounted wire or diamond-wire saws similar to those used in quarries. It has been noted that there are so few options to recycle wind turbine blades in the USA that the vast majority of blades are taken to landfill or long-term storage facilities[51].

THERMAL RECYCLING

Thermal recycling involves the incineration of composites to reclaim the fibres for reuse. Pyrolysis of 500- 600°C breaks the polymer down to components of wax, oil, char and gas. The oil and wax are high in calorific content which, when reclaimed through the pyrolysis process, can be reused to produce thermal energy. The gasses produced are hydrogen, methane, ethane and propane which can be fed back into the plant furnace to fuel the process. Any gases or particulates that cannot be reused within the system are passed through a scrubber to remove harmful elements before being released into the atmosphere. The fibres are recovered for reuse; however, the mechanical strength can be severely reduced by the pyrolysis process.

MECHANICAL RECYCLING

There are two main methods for mechanical recycling where the end material can either be in the form of powdered material or short fibres. The main advantages of this method are the low cost for recycling and the low energy requirements, in addition to the fact that no hazardous fluids are released during the process (as long precautions are taken to prevent the release of fine dust where employees are present). However, the end material has significantly lower value due to the reduction in mechanical properties[52]. As shorter fibres have lower mechanical properties, the real commercial value lies in subsequent reprocessing of the fibres into products such as matts or pellets.

MECHANICAL RECYCLING TO FINE FILLER

Glass reinforced plastic can be ground to a fine filler, and this is done in-house together with manufacturing waste in some cases. However, it is not generally economical since the energy input is not viable for grinding a filler that would only replace a low value product such as calcium carbonate.

Mulching involves regrinding the composite down to suitable size to be used as filler material in new products. This can happen through cutting, grinding or chipping the material. In this process, the continuous fibres are broken down into smaller fragments and lose their ability to provide high durability and stiffness[53].

MECHANICAL RECYCLING WITH FIBRE RETENTION

Glass reinforced plastic can be ground to a lesser degree, leaving bundles of fibres that have reinforcing properties. This uses less energy and provides a more valuable product than fine filler. This is done in-house to a small degree, but there is potential for higher volume applications in the UK, such as in infrastructure products with recycled mixed plastics[48].

A significant barrier for further application of this process is the provenance of material and therefore the expected or known quality of the recyclate. Currently, there are ongoing projects in the aerospace industry for recycling composite prepreg waste offcuts from the manufacturing process. The aviation industry's health and safety regulations require high-quality materials, but these offcuts can be used as they have not been stressed in operation. For mechanical recycling with fibre retention, it is of great importance to be able to trace the quality of the original source in order to ensure quality and strength of the reprocessed materials. Certification methods and bodies could play a crucial role in enabling this technology and establishing methodologies for reprocessing composite.

COMPOSITES SECTOR BY SECTOR

Composite recycling is a huge cross-sector challenge and is not solely an area of concern for the wind industry. It is expected that the waste produced from the wind industry will account for only 10% of the total estimated thermoset composite waste in Europe by 2025[52]. With this relatively low volume and low quality of production materials, it is difficult to make an economic case to build a recycling business or supply chain based exclusively on the wind turbine blade waste stream. It is therefore essential to engage actively with all the composite-using sectors, manufacturers and authorities to develop cost-effective and sustainable economic and environmental solutions and strong material value chains.

The following sections provide a brief overview of the current composite recycling and disposal methods used across other industries.

AEROSPACE

Among the first uses of modern composite materials in the aerospace industry was in the late seventies when boron-reinforced epoxy composite was used for the skins of the empennages of the U.S. F14 and F15 fighters.

In aircraft and space product applications, the weight of structures is a critical parameter in determining performance, fuel economy, and therefore lower operating costs. The need for lowest possible structural weight led to development of high-performance composites initially only for secondary aircraft structure, but as knowledge and development of the materials improved, their use in primary structure such as wings and fuselages increased. The global aerospace composites market size is projected to grow from USD 23.8 billion in 2020 to USD 41.4 billion by 2025, at a compound annual growth rate (CAGR) of 11.7% during the forecast period[54].

The significant use of composite material in a commercial aircraft was by Airbus in 1983 in the rudder of the A300 and A310, and then in 1985 in the vertical tail fin. To date, composite materials constitute up to 50% of most modern civil and defence aircrafts, with average weight savings of up to 20%[55,56].

The average lifespan of a civil aircraft is 25-28 years old[57], and 30-40 years for freight aircraft. Aircrafts are retired when they become uneconomical to operate due to higher costs of maintenance, overhaul or fuel consumption. It has been reported that approximately 9,526 passenger fleets and 785 cargo fleets will have been retired worldwide between 2017 and 2027[58].

IT IS DIFFICULT TO MAKE AN ECONOMIC CASE TO BUILD A RECYCLING BUSINESS OR SUPPLY CHAIN BASED EXCLUSIVELY ON THE WIND TURBINE BLADE WASTE STREAM.

Due to the current global coronavirus pandemic these numbers are now likely to be considerably higher as airlines accelerate their retirements[59].

The common practice over many years has been to remove usable parts from retired aircraft[60] to be re-manufactured and reused as spares in younger aircraft of the same type. The largest portion of recycled aircraft materials consists of aluminium, titanium, nickel-based superalloys, stainless steel and electrical components (about 60%). The remaining 'non-recyclable' aircraft have been stored beside airports (or in deserts around the globe up until a few years ago) and in aircraft graveyards[61].

The number of stored aircraft on landfill sites has become a greater issue now that there are fewer markets for old models, particularly since previous demand markets such as Indonesia, China and Russia have introduced import restrictions for used aircraft over 10-20 years of age. The few that have been re-purposed have become water bombers to fight wildfires, atmospheric aircraft, private jets, props for the film industry and hostel accommodation.

Composite scrap from the aerospace industry can be divided into two categories: wastes generated during the manufacturing process and parts from end-of-life aircraft. Composite recycling is a growing consideration, driven not just by the potential economic benefits, but also by government research incentives, and by society's changing expectations. Studies have reported that the cost of manufacturing virgin carbon fibre was around USD 15 -30 per pound in 2011, while only USD 8-12 per pound is needed for recycling. Numerous research projects are seeking to gain more value from recyclates, particularly using chemical and thermal processes such as pyrolysis and fluidised bed process for carbon fibre recovery.

Recycling of aircraft is currently not regulated by legislation. The European Waste Framework Directive (2008/98/EC) is the closest applicable guidance and sets out the basic concepts and definitions related to waste management. It requires EU Member States to apply the waste management hierarchy of Prevention, Reuse, Recycling, Recovery. In anticipation of future legislation, the International Civil Aviation Organization (ICAO) and the Aircraft Fleet Recycling Association (AFRA) together with industry members[62] have formed partnerships to develop a best practice for end-of-life aircraft[63], but challenges remain in terms of a lack of commercially viable composite recycling technologies and market demand.

In the last 15 years, the industry has picked up pace in leading initiatives to develop chemical and thermal recycling technologies for composites. Boeing and Airbus, two of the world's largest aircraft manufacturers, have been leading much of the research into composite recycling over the past few years. Boeing, with its industry partners in AFRA, Airbus and PAMELA (Process for Advanced Management of End-of-Life Aircraft), is championing R&D to advance pyrolysis for composite recycling.

In 2018, Boeing announced a partnership with British-based ELG, a leading international composite recycling firm, to reclaim carbon fibres from production at 11 Boeing manufacturing sites using pyrolysis. The project claims to have recovered 380,000 lb (172,000 kg) of carbon fibre from cured and uncured waste that was to be sold to other sectors (e.g. automotive and electronics firms) or used to build several prototype aircraft interior components. When the project is expanded to the Boeing facilities, it is estimated that it will recover around three times as much carbon fibre and will help the company reduce its total solid wastes by up to 20% by 2025.

In 2020, ELG Carbon Fibre Ltd[64] formed a collaborative partnership with Belgium recycling start-up Aerocircular in order to establish a recycling scheme for aircraft composite waste streams through a process expected to save 20 tons of Global Warming Potential CO^2eq (carbon dioxide equivalent) at only 1/10th of the energy required for producing virgin carbon fibre.

IN THE LAST 15 YEARS, THE AEROSPACE INDUSTRY HAS PICKED UP PACE IN LEADING INITIATIVES TO DEVELOP CHEMICAL AND THERMAL RECYCLING TECHNOLOGIES FOR COMPOSITES.

MARINE

The lightweight strength and durability of glass fibre reinforced plastic was transformative for the marine industry in the late 1950s, enabling the mass production and sale of small, streamlined leisure boats.

Unfortunately, as vessels built in these early decades reach the end of their life, solutions for their safe retirement are required. Some of the more common practices for disposal have been to sink them by opening drainage holes, drilling and shooting holes in the hull, burying, cutting to pieces for landfill, grinding for use as filler in concrete, or creating garden features.

The challenge remains to find good solutions for the volume of vessels that have reached the end of their functional life or have become damaged, such as the 63,000 boats in the Caribbean that were damaged or destroyed by hurricanes Irma and Harvey in 2017[65]. As most boats currently end up in landfill or abandoned, there are concerns that they can present physical, navigational and environmental hazards as they eventually degrade into local ecosystems. Researchers have begun to investigate the potential impacts these abandoned vessels could have on marine environments. Abandoned vessels may contribute to a loss of habitat, pose an entrapment risk for wildlife, and can act as a local source of contamination[66].

In 2016, concerns were raised to the London Convention and London Protocol (LC/LP) governing bodies about the end-of-life management of vessels made from fibre reinforced plastics. As a result, the International Maritime Organization (IMO) commissioned a study that reviewed current options for the disposal and recycling of boats made from this material and to advise that further work is required[67]. The study found that while financially viable options for recycling are limited, research is ongoing into pyrolysis and solvolysis for the separation of resins and fibres for reuse. Manufacturing levies have been suggested as one method of achieving financial sustainability in the disposal of reinforced plastic vessels and France will potentially trial a programme of charging users for disposal[67].

A COMBINATION OF LEGISLATION AND BUSINESS OPPORTUNITY HAS SPARKED SEVERAL WASTE REDUCTION AND RECYCLING DEVELOPMENTS ACROSS THE AUTOMOTIVE INDUSTRY.

AUTOMOTIVE

The automotive industry is one of the largest sectors to use fibre reinforced plastics in manufacturing, thanks to properties that make vehicles lighter, stronger and more fuel efficient.

They can also make cars safer as the energy absorption of thermoplastic composites is 7-8 times higher than that of steel. In addition, the sector has an extensive number of regulations and legislation concerning the end of life of vehicles. The End-of Life Vehicle Directive (ELV, 2000/53/EC) set targets that 85% (by weight) of vehicles must be reused or recycled, and 95% reused, recycled or recovered ('recovered' here means burnt for energy recovery)[48].

The Chinese government is also introducing legislation on vehicle end of life. The new legislation targets the scrapping of vehicles and aims to improve the standardisation practices. All recycling enterprises will be required to upload information regarding gearbox, engines and chassis, such as serial numbers and models. This will enable the tracking of materials and create an opportunity for the development of a supply chain focussing upon recycling and reusing materials[68].

An article from 2018 estimates that recovery of carbon fibres can be achieved at USD 5-15 per kilogram, depending on the technology used and the plant capacity[39]. This accounts for up to half of the cost of virgin carbon fibres. Much carbon fibre reinforced plastic waste is produced during the manufacturing stage, where it is then used in stitched, non-wovens, car seats and roof structures (such as in the BMW i3 and i8). In total, 10% of this material used in the BMW i-series comes from recycled carbon. Utilising recycled composites can reduce the overall weight of cars by replacing aluminium and steel in non-structural parts of the vehicle. Short fibres, for example, can be used to reinforce thermoplastic matrices through injection moulding, with the resultant composite used as interior panels and other low load bearing components. The short fibre reinforced composite also improves crashworthiness[69].

A combination of legislation and business opportunity has sparked several waste reduction and recycling developments across the automotive industry. In 2012, for example Boeing and BMW signed a collaboration agreement to participate in joint research for carbon fibre recycling[70]. Toyota and Toray Industries (a manufacturer of carbon fibre) announced the development of a solvolysis test plant in 2016[71]. There are also multiple projects that focus on specific car products that could be developed from recycled composites. In the FiberEUse project, car supports were manufactured using end-of-life fibre reinforced plastic. Another project with similar results is RECOMP which recycles glass fibre reinforced plastic and uses a ground version in automotive compound moulding.

OIL & GAS

Traditionally, the oil and gas industry has used carbon steel due to its general low cost and availability throughout the hydrocarbon value-chain, from the construction of wells and rig systems to pipelines, storage tanks, and refineries. A significant downside of carbon steel is its limited design life due to corrosion, and the economic cost associated with repair, maintenance, and corrosion monitoring.

Composite materials have been used in the oil and gas industry for three decades, though sparingly. The willingness of the industry to adopt composite components has been directly related to the operational risks of the components considered. As a result, the industry has made greater progress in adopting composites, primarily glass fibre reinforced plastics, for less operation critical components in secondary structural applications such as grids and gratings, handrails, ladders, and flooring for offshore platforms[72]. More notable adoption has been for lifeboats and vessels.

In the 1990s, there was a surge is the development of composite materials for pipe applications. This led to the development of reinforced thermoplastic pipe (RTP)[73], typically consisting of a thermoplastic liner overwrapped with unbonded aramid or glass fibre composites, then coated with thermoplastic. RTP is suited to lower pressure and less demanding temperature applications with the distinct advantage of having a fast installation time, but demand for its application has remained limited.

With higher pressures and temperatures, deeper water, deeper wells and more corrosive environments, the past decades have seen research and development activities in thermoplastic composites (TCP)[74] for use in components such as pipes[75], umbilicals, flexible and floating risers, flowlines, jumpers, casings, tendons and downhole tools used for well drilling and interventions[76]. TCP consists of a similar set of materials to RTP but uses higher performing thermoplastic resins such as polyetheretherketone (PEEK), and higher strength reinforcement such as carbon fibre layers bonded to each other through a melt-fuse manufacturing process. This gives TCP higher performance properties than RTP made from the same materials, making it suited to higher pressures and a greater temperature application. Fully qualified usage[77] of TCP at pressures exceeding 12,000psi and in water depths as low as 3,000m have been deployed in the past three years. In 2017, Petronas installed the world's first pilot TCP Flowline in Malaysia for offshore hydrocarbon service. With this pilot's success, TCP solutions for hydrocarbon production, water, gas lift, and chemicals injection are expected to be installed in West Africa, Australia, and the North Sea [78].

The underpinning advantages of composites over metallic alloys is in providing:

- **High strength-to-weight ratio enabling the use of smaller, less costly vessels for transporting equipment to drilling and production sites**
- **Greater cost advantages when replacing expensive corrosion-resistant metals such as copper-nickel alloys, duplex / super duplex stainless steel, titanium etc., that are used in offshore platforms for various applications. Their resistance to corrosion helps in improving reliability and safety and also leads to lower life-cycle costs**
- **Good thermal insulation, excellent damping, and fatigue performance**
- **Greater design flexibility**

Challenges in commercialising new applications remain a significant hindrance due to the absence of qualification standards for specific design applications. This is compromised further by significant lack of long-term performance data[75]. The market was set to reach an estimated USD 1.98 billion by 2021[79], this is still significantly less than established markets in the aerospace, defence and automotive industries, and is now likely to decline due to the Covid-19 pandemic. It is expected to be 20-30 years before the currently deployed composite pipes are decommissioned, so as yet their end-of-life reuse or recycling has not become an issue for imminent resolution.

IT IS EXPECTED TO BE 20-30 YEARS BEFORE THE CURRENTLY DEPLOYED COMPOSITE PIPES ARE DECOMMISSIONED, SO AS YET THEIR END-OF-LIFE REUSE OR RECYCLING HAS NOT BECOME AN ISSUE FOR IMMINENT RESOLUTION.

REUSE AND ALTERNATIVE USE OPTIONS

Many offshore installations and subsea structures in the Gulf of Mexico and the North Sea are approaching decommissioning and would need to be repurposed or decommissioned. Most of these installations and their associated subsea structures contain very little composite material, if any. Where there have been composite materials in recently decommissioned structures, these have been secondary structural components that have been shredded and sent to landfill. For lifeboats and vessels, there is the option of re-purposing them as floating caravan homes, although this has often been impeded by the economic cost of repurposing and market demand. To date, lifeboat end-of-life options have tended to be crude, and generally involve shredding composite structures and reducing them to fragments for landfill.

In the future, flexible flowlines, umbilical and power cables could readily be recovered by reverse reeling as part of a decommissioning programme. Such materials could theoretically be reused but proving that the integrity of the composite components has not been compromised during service life, as well as during the handling process, may be difficult.

OPPORTUNITIES FOR FUTURE DEPLOYMENT REUSE AND RECYCLING CONSIDERATIONS

Traditionally, subsea tiebacks – where small fields are 'tied back' to floating production facilities or platforms – have been developed in a bespoke way, with the technology designed specifically for each deployment and much of it located topside. OGTC has initiated a programme called Tie-back-of-the Future[80] which focusses upon developing a circular economy approach for subsea tie-back solutions in marginal fields. Marginal field developments are generally only expected to produce for four to five years.

A significant proportion of the cost of conventional subsea tiebacks is due to flow assurance mitigations which may demand high levels of insulation, chemical injection systems and heat input. Composites offer important properties with regards to corrosion resistance, thermal insulation and weight reduction compared to traditional steel components to mitigate some of the challenges associated with these costs.

Several projects are currently exploring composites for disassembly and reuse. If the equipment used to develop them was designed to be mostly installed subsea and then recovered and reused three to four times, subsea tiebacks for small pools could be more economically attractive. These options offer reduced cost on first use and suitability for reuse, resulting in greater cost savings and environmental benefits.

CONSTRUCTION

Glass fibre reinforced plastic is used extensively for many different applications in the industry, both in domestic and commercial buildings. Its strength and insulative properties, as well as ready availability in large quantities and ease of installation, make it an ideal product to use.

It is thought the industrial production of glass fibre products in the construction industry started as early as the 1930's, with the process, and types of products produced, being refined ever since[81]. Existing uses within the industry include[82]:

- **Concrete reinforcing fibre**
- **Fibreglass (combined with a resin) for panels and structures: these can be for waterproof external cladding and roofing, translucent panels, strong storage tanks or linings of steel tanks and structural members to replace steel or wood**
- **Composite rebar in place of steel**
- **Glass fibre insulation used for thermal and noise insulation in floor, wall, and roof cavities**

Disposing of glass fibre waste materials is a challenge within the construction industry. Resin products can be used as a fuel source to burn with the remaining fibres being reused for applications such as concrete feedstock. Depending upon the composition of the product, other recycling options are available, such as using parts of the materials for textiles and aggregates. However, this is not always possible, so landfill is the commonly used alternative.

SPORTS

There are multiple sports that utilise composites for their light weight, excellent mechanical properties and easy manipulation into various shapes. Some of this equipment includes but is not limited to:

- **Tennis and badminton racquets**
- **Golf clubs and hockey sticks**
- **Bikes**
- **Skis and other plate-like structures (snowboard, windsurf)**
- **Boats**

All of these products commonly use continuous fibres, making them hard to recycle and turn into new sports equipment[53]. Since most sports' equipment is sold individually to customers and contains relatively small amounts of carbon fibre, there are no national or industrial retrieval programmes that recycle them. There are many initiatives where sports equipment can be donated to be refurbished, reused or used for spare parts, but they generally have a limited catchment area and the volume that can be processed is far smaller than is necessary to address the issue of the waste produced each year.

A notable project is ReSurf which salvages old surfboards as part of a community project for under-privileged children and Project Green Ball which recycles tennis balls and runs local programmes and shops for bikes. There are also multiple initiatives that turn skis into new furniture – Reeski, Green Mountain Ski Furniture and SnowSource General Store[83].
In the USA, the Snow Sports Recycling Program retrieves all ski equipment, shreds it, and sells it to manufacturers for the production of composite lumber and synthetic cultured rocks[84].

Compared to other sports, the leisure boats sector has the largest volume of composites within a single product, most of which are disposed of in landfill or abandoned. However, if there was a stronger economic case there would be potential to reclaim the fibres for reuse in boat manufacturing. The Rhode Island Fiberglass Vessel Recycling (RIFVR) Pilot Project retrieves used and abandoned boats, mulches the fiberglass and uses it as filler for cement production[85].

COMPARED TO OTHER SPORTS, THE LEISURE BOATS SECTOR HAS THE LARGEST VOLUME OF COMPOSITES WITHIN A SINGLE PRODUCT, MOST OF WHICH ARE DISPOSED OF IN LANDFILL OR ABANDONED.

DEFENCE

The defence sector uses composite materials across many areas, some of which have been discussed in previous sections such as military aircraft, helicopters and land vehicles. Additional applications that have not been mentioned include body armour, arms and ammunition and military shelters.

Fibre reinforced plastic is frequently used to build aircrafts (turbine, propellers, deck, armament), submarines and offshore patrol vessels (hull, decks, propellers, sonar), main battle tanks and infantry battle vehicles (tank floor, armour, internal navigation systems, ammunition), missiles (sensors/seekers, frames) and many more[86].

In 2017, the European Defence Agency started a project for assessing the opportunities and constraints that could be encountered when applying circular economy principles in the defence industry. Following the project, a roadmap was established proposing actions and alternatives for areas that are not suitable for a full circular economy[87].
In 2019 the UK Ministry of Defence opened an innovation challenge fund to encourage industry to develop prototype systems for defence waste management within a circular economy context[88]. In addition, the Dutch Ministry of Defence established circular principles to cut down waste from uniforms, helmets and other Personal Protective Equipment (PPE)[89].

No other information has been identified in the public domain for reuse and recycling in the defence sector and none of the strategies identified are specifically applicable to carbon and glass fibre reinforced plastics.

REVIEW OF COMPOSITE RECYCLING METHODS

Composites can be defined as two or more materials that when combined have superior properties than the individual materials alone. Typically, they are comprised of reinforcement material (fibres) encased within a matrix material (resin). The fibres can take on several different weave architectures, resulting in plies that can be layered up and positioned at different orientations to provide the resulting composite product with the optimum performance characteristics for the chosen application.

Composite materials are therefore often beneficial in high-performance applications that also require low mass. However, the symbiosis of fibres and resins, particularly in the case of thermosetting resins, makes the end-of-life options for composites more difficult than their metallic counterparts. Nevertheless, processes to recycle composite products are available and becoming an increasingly popular option.

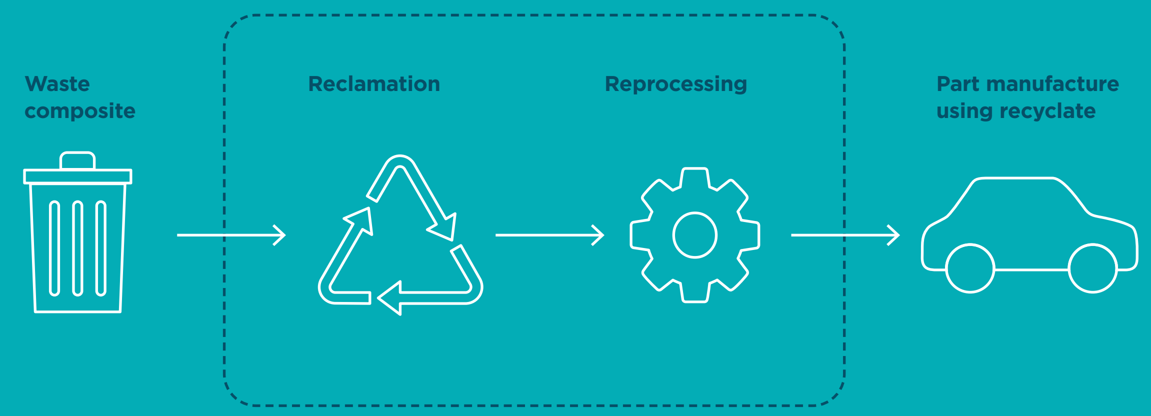
There are generally two stages that make up composites recycling: the reclamation stage and the reprocessing stage (Figure 13). The reclamation stage involves reclaiming material from the original composite to be used in a secondary application. In most composite recycling processes, this stage mainly concentrates on reclaiming the high-value material from the composite (the fibres), but some processes are also able to reclaim resin components or energy that can power subsequent processes. Once the fibres have been reclaimed, they need an additional reprocessing stage to turn them into a format that enables them to be used in another product. These recycling stages are discussed in more detail in the following sections.

RECLAMATION

There are a range of different fibre reclamation processes available for composite materials at varying technology readiness levels (TRL), depending on the materials that are to be recycled. Generally, carbon fibres have a very high tolerance to heat and thermal degradation which allows them to be taken to very high temperatures[90]. This is less so for glass fibres, which following exposure to elevated temperatures (upwards of 150°C) show significant reductions to mechanical properties between 20% and 65%, with higher exposure temperatures generating greater levels of degradation[90,91]. The resin system used can also influence the recycling method chosen, with the main factor being whether the resin is thermoplastic or thermoset.

Thermoplastics can be reheated and reformed due to the reversible nature of the bonds that hold them together. Therefore, when considering consumable thermoplastics that are not combined with reinforcement, these are considered to be easily recyclable compared to thermosets. In reality, however, it is not that straightforward, as there are still challenges around separating and retrieving the resin from the fibres. In some exceptional circumstances, larger composite panels may be suitable for softening and reforming, but this is highly

Figure 13.
Recycling Stages: Reclamation and Reprocessing



CARBON FIBRES HAVE A VERY HIGH TOLERANCE TO HEAT AND THERMAL DEGRADATION, BUT THIS IS LESS SO FOR GLASS FIBRES.

IT IS CRUCIAL FOR THE GROWTH OF COMPOSITES RECYCLING THAT APPLICATIONS FOR THE RECYCLATE ARE SOUGHT

dependent on the geometry of both the primary and secondary application and is therefore not commonplace. Thermosets on the other hand, form more permanent chemical crosslinks upon solidification, which once formed are irreversible, and thus often require extreme conditions to break down.

Whichever method is chosen, either the method itself, logistics of transport or the space restrictions of the infrastructure (furnaces, reactors, grinders) generally lead to continuous fibre composites being reduced in length to shorter, discontinuous fibres. Considering mechanical properties are affected by fibre length, with longer fibres producing higher mechanical properties, this reduction in fibre length through recycling often leads to a reduction in the mechanical performance of the resulting material. It is therefore crucial, for the growth of composites recycling that applications for recyclate are sought in order to make use of the material as it becomes available.

In addition to this, fibre reclamation processes remove the fibre sizing (a thin homogenous coating applied to the surface of fibres during manufacture), which greatly affects the quality of the fibre and matrix adhesion. This isn't as much of an issue for carbon fibre as it is for glass fibre, as the surface energy of carbon is similar to the surface energy of the resin systems used (the closer the better for good adhesion). Despite this, many potential end users of recyclate prefer resized fibres to maximise the properties of the composite. Fibre sizing happens at a specific point in the production of virgin fibres, and currently isn't directly re-creatable in the available recycling processes. This therefore presents an area of opportunity for further development in composites recycling in the future.

There are four main categories of reclamation for composites recycling that sit at different technology readiness levels (TRL) levels depending upon the materials to be recycled. These are summarised in Table 2 and discussed in more detail in the following sections.

Table 2.
The Technology Readiness Level (TRL) of the Reclamation Processes According to Fibre Type[52]

RECYCLING PROCESS	TRL CARBON FIBRE	TRL GLASS FIBRE
Mechanical	6	9
Thermal	9	5
Chemical	6	5
Electrical	4	4

MECHANICAL

GRINDING

A large-scale, low-cost option that produces powder for filler or reprocessing at TRLs 9 (glass fibre) and 6 (carbon fibre) but low-level concerns around microplastic pollution and dust remain.

Mechanical recycling techniques predominantly refer to grinding of cured composite material, reducing it down to a significantly finer material. This technique is a two-stage process. Firstly, the material is shredded to turn the composite into more manageable sized pieces. This involves a slow speed cutting mill that reduces the original part into pieces that are approximately 50-100mm in size. Metal inserts can also be removed at this stage[92]. Following this, a high-speed mill is used to grind the composite pieces into a finer material, with particles ranging from fibrous strands (up to 10mm in length), down to finer powders (less than 50 microns in size)[92]. The recyclate is then classified based upon its resulting size using cyclones and sieves. In this process there is no separation of the resin from the fibres, thus the resulting recyclate is a mixture of the two materials.

The recyclate can be used as a filler in other applications if derived from thermoset composites, or re-extruded for further processing if derived from thermoplastic composites. There is also a growing interest, particularly in Germany, in using the recyclate from wind turbine blades in cement co-processing. While this technology is, strictly speaking, recovery rather than recycling, its popularity means it is worthy of inclusion in this review.

Whilst this process can be used for all types of composite waste, and is one of the cheapest recycling options, it is only available on a commercial scale for glass fibre reinforced polymer. It is not economically viable for polymers reinforced with carbon fibres due to the higher value of the fibre, especially considering the low cost of other commercially available filler materials such as calcium carbonate and silica. As a result, processes that allow for fibre and resin separation are preferred for carbon fibres[90].

CEMENT KILN CO-PROCESSING

A large-scale, low-cost option suitable for glass fibre reinforced plastics that allows for energy recovery and production of cement clinker; currently at TRL 9, but environmental and health concerns remain over dust and other potential pollutants.

Already operating at commercial scale, cement co-processing is seen as one of the most promising options for the end of life management of wind turbine blades.

Following the mechanical reclamation of glass fibre waste, the composite particulate is mixed with other solid recovered fuel and fed into cement kilns. The organic content (resin, core materials, adhesive) burns and helps to fuel the process while the inorganic glass fibres provide minerals (such as alumina-borosilicate) for the cement clinker. This clinker is then used to produce cement.

While it could be argued that this processing method is not strictly recycling, as there is no prospect for reusing the recyclate in a composite application, it does have some advantages over incineration to recover Energy from Waste (EfW):

- **Lifecycle Analysis (LCA) has reported a 16% reduction in CO_2 emissions compared to using sand to provide silica to the kiln**[52]**.**
- **There is also a reduction in the amount of coal, lignite and petcoke used in the process.**
- **Resins used in composites have a high calorific content. This can be undesirable for energy recovery from waste, as capacity is limited by energy release rather than tonnage burned.**
- **The mineral content of the glass fibre reinforced plastic, which falls as ash in energy recovery, is incorporated into the clinker.**

Aside from potential issues arising from the release of pollutants and particulate matter, the major drawback of recycling blade waste via this method is that it is currently limited to glass fibre materials. Due to health and safety issues around the presence of unburned carbon fibres in the clinker (similar to the situation with asbestos), the method cannot be used to process blades containing carbon fibre reinforced plastics[93]. More recently, the move to bigger blades has increased the use of this material, effectively putting a time limit on the viability of co-processing for wind turbine blade waste.

THERMAL

PYROLYSIS

An energy intensive way of recovering oils from resins that is available at limited scale and only at a relatively high cost; suitable for carbon fibre recovery (retaining up to 90% of mechanical properties) but currently unsuitable for glass fibres due to the lower quality of outputs.

Thermal recycling techniques involve the use of high temperatures to break down the composite from both uncured manufacturing waste, and cured components[90]. The most studied and commercially available thermal recycling process is pyrolysis. This process allows for reclamation of the fibres, fillers and inserts through thermal degradation of the resin system. Due to the high temperatures involved, pyrolysis is often only used on carbon fibre composites, as they are less susceptible to thermal degradation at high temperatures. The degradation point of glass fibre, however, is much lower, and similar to that of many of the resins used to manufacture composites. Therefore, it is not possible to thermally remove the resin without causing significant heat damage to the glass fibres. These temperatures cause changes to the crystalline structure, decrease fibre diameter and cause surface cracks, all of which will reduce the mechanical performance of the resulting glass fibre.

Similar to mechanical grinding, the first stage is to shred the composite waste to reduce its size before entering the pyrolysis process. Pyrolysis processing parameters have a significant impact on the physical state of the reclaimed fibres. These therefore need to be selected and optimised to suit the materials going into the process and the onward application. Typical processing temperatures are reported to lie anywhere between 350°C and 700°C depending on the resin system[94]. The lower temperatures are adapted more towards polyester resins, whereas epoxies or thermoplastics like PEEK require higher temperatures[90]. Under these conditions, the resin breaks down into lower molecular weight organic substances (liquids and gases)[92]. The gases (typically CO_2, hydrogen, or methane) can be used as energy feedstock in the process itself, while the liquid (oil) can be reused as fuel or chemical feedstock. Therefore, despite the high energy demand of high temperature processing, pyrolysis can feed products back into the system, and is therefore a low waste process. It is also often a continuous process that helps to improve its efficiency.

A common side effect of pyrolysis is the formation of a solid char residue. The amount of char build-up on the fibres can adversely affect the fibre-matrix interfacial bonding in post processing (decreasing resin wet-out and reducing mechanical properties), so its formation is undesirable[95]. Therefore, a subsequent post-pyrolysis treatment (oxidation in air between 450°C and 600°C) is often required to obtain clean fibres[90,91]. This secondary process can lead to further degradation of the fibres, so should be approached with caution[81]. The resulting fibre is then chopped to create the final product.

A UK-based company, ELG Carbon Fibre Ltd, is capable of pyrolysing carbon fibre in this manner from diverse feedstock, including different types of carbon fibre and most thermoset resin systems. As a result, fibres reclaimed from industrial processes generally present a distribution of properties; however, they blend their products to minimise property variation within the material. ELG claim that the resulting mechanical properties of their recycled carbon fibre are equivalent to approximately 90% of that of virgin fibres[96]. ELG was one of the first companies to pioneer this process, but there are now multiple companies across the world that can also reclaim carbon fibre in this way.

FLUIDISED BED PYROLYSIS

A high-cost and energy-intensive process currently available at limited scale; produces good-quality and clean carbon fibres (up to 70-80% of mechanical properties retained); currently at TRL 4 (glass fibre) and TRL 5 (carbon fibre).

This is a variation of the pyrolysis process that has only been achieved at large lab scale (Technology Readiness Level 4/5) and therefore has not yet been commercialised. The University of Nottingham has conducted extensive research in this area to recycle carbon fibre[92], and more recently, the University of Strathclyde has conducted similar work to extract glass fibre[97].

In this process, the shredded scrap composite is fed into a bed of silica sand which is fluidised by hot air. This acts to heat the material quickly, and results in attrition of the resin through abrasion by the moving sand. Similar to classical pyrolysis, a small amount of oxygen is required to minimise char formation. The operating temperatures are typically between 450°C and 550°C, which are lower than typical pyrolysis conditions. At these temperatures, the thermosetting polymer volatilises and, once the polymer has been removed, the fibres and any mineral fillers are released and carried away in the gas stream before being separated by a cyclone. The gases from this process are fed to a high-temperature combustion chamber for full oxidation and energy recovery, producing a clean high-quality fibre with good mechanical properties[92].

A benefit of the process is that it can be used to treat mixed and contaminated materials including painted surfaces, foam cores and metal inserts. However, the fluidised bed process does not allow recovery of products from the resin apart from gases, whereas traditional pyrolysis can enable recovery of oil containing potentially valuable products. Furthermore, carbon fibres seem to become more damaged in this process in comparison to the traditional pyrolysis process, which has been attributed to abrasion by the fluidised sand[90]. In a study by the University of Nottingham, carbon fibre showed a reduction in its mechanical properties of 25% when pyrolysed at 550°C. This is a greater reduction than those previously reported for the traditional pyrolysis technique. Various academic institutions are investigating ways to remedy fibre damage caused in the processing of glass fibres using this method in order to increase its commercial viability for glass fibre composites[97,98,99].

MICROWAVE ASSISTED PYROLYSIS

Suitable only for carbon fibre-based materials; high-cost and available at very small scale; produces good-quality carbon fibres (at up to 75% of mechanical property retention) and achieves lower energy intensity than other thermal methods.

Microwave assisted pyrolysis is a relatively immature process in comparison to traditional pyrolysis, but it has shown some promise with cured carbon fibre/epoxy on an academic scale (Technology Readiness Level 4) at the University of Nottingham[90]. This process uses microwaves to heat the material in an inert atmosphere, which degrades the polymer into gases and oil.

The main advantage of this process is that it allows for targeted heating, making it fast and efficient. Furthermore, this method heats the material from its core outwards, further improving the speed of heat transfer and efficiency. This means lower energy consumption, as well as providing environmental and cost benefits over other processes. Tensile testing of the resulting fibres reclaimed from a carbon/epoxy composite indicated a reduction of 25% for tensile strength and 12% for tensile modulus[100] in comparison to virgin fibres, which is comparable to other recycling processes. These promising initial results demonstrate the potential of this technology for more widescale use if further process development and scale-up can be achieved.

STEAM PYROLYSIS

An energy intensive process at TRL 4 that yields high-quality carbon fibres (more than 90% of mechanical property retention) but only at very small scale to date.

Steam pyrolysis (or thermolysis) is a relatively new process for composite materials, and thus it currently sits at a low Technology Readiness Level (TRL 4). A report generated by Alpha Recyclage Composites discusses the nature of the technology with some promising initial results[101]. The process used superheated steam to remove epoxy resin (Hexcel HexFlow RTM-6) from carbon fibres. It was possible to remove high levels of resin (more than 99% by weight) without any significant changes in the quality of carbon fibre that was reclaimed.

Furthermore, fibres showed minimal signs of surface degradation in comparison to those recovered from traditional pyrolysis. This was indicated by the absence of the pitting effect that is seen on fibres reclaimed using the traditional pyrolysis method.

Comparisons of mechanical properties between virgin fibre tows and those reclaimed from steam pyrolysis also yielded promising results. Values for tensile strength and elastic modulus were reported to be comparable between the two, with the tensile strength reported as 136MPa (in comparison to 141MPa in virgin fibres) and the elastic modulus reported as 8.4GPa (in comparison to 8.9GPa in virgin fibres). However, the authors acknowledged that more tests are needed to validate these initially promising results in addition to industrial feasibility studies[101]. The effect of this process on glass fibres is currently unknown and warrants further research.

CHEMICAL

SOLVOLYSIS

More developed for carbon fibres (at TRL 6); high cost and small-scale availability; an energy intensive process that yields high-quality glass (up to 70% mechanical property retention) and carbon fibres (90%).

Chemical recycling methods involve treatment of the composite using heat and solvent to degrade the resin, allowing for reclamation of the fibres with no char formation. Solvolysis currently sits at Technology Readiness Level 6, offering a wide range of processing possibilities using different solvents, temperatures, pressures and catalysts. During the last decade this method has been more intensively used to recycle composites, in particular carbon fibre reinforced polymers, as the recovery of carbon fibre has become of commercial interest, but it can also recover glass fibre and aramid from cured or uncured material[90].

In many cases, carbon fibres recovered through solvolysis retain approximately 90% of the properties of virgin material as the carbon fibres are not degraded by the process, and in this way, it is comparable to pyrolysis. For glass fibres, which possess a lower tolerance to high temperatures and acidic/alkaline conditions, the reduction in mechanical properties is greater. In a study conducted by the University of Exeter, glass fibre and polyester composites exhibited significant reductions in tensile strength and failure strain (up to 70%), however modulus did not appear to be significantly affected by the water-based solvolysis process[102].

Solvolysis has started to gain more attention as under the correct conditions it offers the ability to recover matrix materials in another form, which is not possible with processes such as pyrolysis. Another advantage compared to pyrolysis is that lower temperatures are generally necessary to degrade the resin. Solvolysis can also avoid the formation of char that contaminates the fibre surface and prevents good interaction between the recycled carbon fibres and the matrix. However, fibres recovered from a solvolysis batch reactor require further processing to remove organic surface residue, which is often a long and expensive procedure. This can add further time, energy and costs and is therefore one of the main drawbacks. Solvolysis also removes the sizing from the fibres, affecting the fibre/matrix interactions of resulting materials.

Among the tested solvents, water appears to be the most used, sometimes neat or with a co-solvent (alcoholic, phenolic, amine); others include methanol, ethanol and acetone. The process is usually executed between 350°C and 500°C, which is lower than the general temperature range for pyrolysis. The nature of the resin determines the temperatures and solvents needed for effective degradation: for example, polyester resins are generally easier to solvolyse than epoxy resins and so require lower temperatures to be degraded. Often solvolysis is used with alkaline catalysts like sodium hydroxide or potassium hydroxide, but less often with acidic catalysts. Acidic catalysts are used to degrade more resistant resins such as PEEK, or to degrade epoxy resins at lower temperatures[90].

HIGH-TEMPERATURE, HIGH-PRESSURE SOLVOLYSIS

Currently at TRL 4 with associated high cost and limited availability; produces good-quality and clean carbon fibres; environmental and safety concerns are its high energy intensity and the high-pressure corrosive nature of the procedure.

High pressure solvolysis using supercritical fluids has been investigated at an academic scale (Technology Readiness Level 4). Supercritical fluids display properties that are between those of gases and liquids. They offer a range of advantageous properties that provide the ability to closely control the solvent properties and reaction rates through pressure manipulations. Water is a useful option because of its temperature and pressure dependent properties. Depending on the conditions, it can support ionic, polar non-ionic or free radical reactions, and can therefore be described as an adjustable solvent.

Under supercritical conditions, the most stable thermosets (epoxies) and thermoplastic (PEEK) resins can be fully degraded using solvents such as water, methanol, ethanol, propanol, and acetone without the need for additional catalysts[103]. It does, however, require specific and expensive reactors that can achieve high pressures and corrosion resistance[90]. This is a limiting factor on its widescale use, especially for lower value material such as glass fibre, but it has been reported to produce good-quality, clean carbon fibres[90].

LOW TEMPERATURE, LOW PRESSURE SOLVOLYSIS

TRL4; produces good-quality and clean carbon fibre and epoxy monomers; less energy intensive than the previous entry but involves use of acids that are problematic to dispose of sustainably.

Low temperature, low pressure solvolysis is generally carried out below 200°C and at atmospheric pressure. Catalysts and additives are necessary to degrade the resin as the temperature is very low and stirring can also be necessary. The main advantage of this method is that it offers better control of the reactions and, as the temperature is low, secondary reactions do not seem to occur. This enables higher recovery of epoxy monomers, but not necessarily the curing agent[90]. It is also therefore likely to consume less energy than other solvolysis processes. However, acids are used in the process, which can be dangerous as well as difficult to dispose of or recycle[90]. This process has only been demonstrated on an academic scale, and therefore is Technology Readiness Level 4.

ELECTROCHEMICAL

Low readiness for commercial use (TRL 4) at high-cost and small-scale availability; yields glass fibre of usable quality but is yet to overcome high inefficiency due to the energy use in its process.

The High Voltage Fragmentation process was originally developed for fracturing rocks to retrieve high-value minerals and crystals, such as gold excavation[104], but has since gained interest on an academic scale with composite materials. In this process, the material is placed between two electrodes in an aqueous solution. A series of capacitors are used to generate up to 200kV pulses that are administered rapidly and repetitively in order to weaken the resin material. The repetitive pulse fragments the polymeric resin into smaller sizes and leads to ultimate disintegration of the material[104]. This process is high cost and energy intensive, sitting at a low Technology Readiness Level (TRL 4)[90].

REPROCESSING

Reprocessing stages take the reclaimed materials and turn them into secondary material to be used in another applications. This isn't needed for mechanical grinding recycling processes as the ground material is used in its reclaimed form as a filler, but material from other recycling processes is in the form of a fibre 'fluff' which requires post processing to ensure it can be reused. The typical forms of recyclate that can be produced from reprocessing are illustrated in Table 3. These are all commercially available products from companies such as ELG Carbon Fibre Ltd, with milled and chopped fibres also available from Procotex. Milled glass fibre is also available from companies such as East Coast Fibreglass. These material forms can be used in common composite manufacturing processes, such as resin infusion, injection moulding, press moulding and thermoplastic compounding.

Table 3.
The Main Forms of Recyclate

FIBRE TYPE	IMAGE	FIBRE LENGTH	USES
Milled fibre		80-100mm	Additive/filler for tailored electrical and thermal conductivity
Chopped tows		6mm	Thermoplastic compounding, sheet moulding compounds (SMC) and bulk moulding compounds (BMC) Cement reinforcement Prepreg tapes
Pellets		1mm - 1.5mm	Injection moulding (thermoplastic)
Non-woven mat		40 - 90mm	Press moulding RTM Resin infusion Wet pressing Prepregs, semi-pregs and SMCs

MILLED FIBRE

A well-established method for glass fibre materials (TRL 9) and is under demonstration for carbon fibres (TRL 6); outputs are powder additives and fillers for electrical and thermal conductivity; produces microplastics and dust risks.

Milled fibre is a product of mechanical grinding, and therefore comes in the form of a fine powder. This can then be incorporated as filler or reinforcement if derived from thermoset composites, or re-extruded and reprocessed if derived from a thermoplastic composite. Carbon is also a useful additive where enhanced thermal and electrical conductivity are desirable; but, in most cases, it is not economical to use ground carbon fibre due to other options being available at a much lower cost.

Whatever the incorporation method, it is important to monitor the weight percent (wt%) of recyclate within the composition of the secondary material. This is because the presence of the recyclate within the composition acts to increase the viscosity of the resulting material. It can become extremely viscous and difficult to process if the wt% is too high, and the resin does not uniformly impregnate the ground fibres with a possible knock-on effect to the resultant properties. Due to the very limited fibre length, materials incorporating ground fibre are not suitable for use in structural applications. Alternatively, the recyclate could also be used as an energy source as it is resin rich with a high calorific value[92]. The longer fibres obtained from this process can also be used as reinforcement material in sheet moulding compounds (SMC) and bulk moulding compounds (BMC) where short fibres are required.

CHOPPED FIBRE

Conducted following pyrolysis or solvolysis; a well-established method for glass fibre materials (TRL 9) and at the demonstration stage for carbon fibre materials (TRL 6); a low-cost process that can be used to produce SMC/BMC, prepreg tape and cement reinforcement; can pose a risk to workers handling dry fibres.

Recycled fibres can also be chopped into consistent short fibre lengths for use in alternative products. They typically arise from taking the fibre fluff produced by pyrolysis and solvolysis methods and then organising and chopping the resulting fibres. This allows them to be incorporated into randomly oriented discontinuous fibre materials such as BMC and SMC. For example, ELG Carbon Fibre Ltd produces fibre lengths of 6-12mm.

A potential downside is that failure to chop this material down further can lead to inhomogeneous distribution of the fibres, thus uneven thickness, which results in a lower fibre content and a higher void content[90]. However, when processed correctly these chopped fibres can also be used to modify coatings or other thermoset resin systems[64].

The properties of BMC using recycled fibres can be similar to virgin carbon fibre[90], while recycled fibre SMCs have comparable properties to virgin glass SMCs. Typically, SMC and BMC materials are turned into products via compression moulding, but fibre loading should be considered in these cases as above a certain wt% the properties no longer improve and can begin to deteriorate. BMCs and SMCs using recycled fibres are beginning to find applications in the automotive industry, where the ability to manufacture at high rates and high volumes is advantageous.

PELLETS

A well-established method for carbon fibre (TRL 9) and at demonstration level for glass fibre materials (TRL 6); low-cost but not yet large-scale enough for wind industry requirements; currently used in the injection moulding and over-moulding of composite parts but with associated risks of microplastic pollution and dust.

Recycled carbon fibre reinforced thermoplastic pellets are intended as a low weight replacement for glass fibre filled thermoplastics, a low-cost replacement for virgin carbon fibre filled materials, and as an alternative to aluminium and magnesium castings. Current challenges with the material have been achieving sufficient fibre length and loading, as well as ensuring the product is dust free. Work is ongoing to establish optimum fibre loading and mechanical properties.

Currently, pellets are commonly used in the injection moulding and over-moulding of composite parts. Processing techniques and resulting pellet products have been investigated by Barnes[105]. During this study, pellets were produced from recycled material that was comparable to virgin carbon fibre material for compounds with polypropylene and polyamide 6,6. They established that a 10% loading of recycled carbon fibre provided the same mechanical properties as a 30% loading of glass fibres, allowing them to produce air inlet manifolds at a 15% weight reduction from the original product.

NON-WOVEN MAT

At TRL 9 for both glass and carbon fibre materials; low-cost but requires scale-up; can be used in processes of press moulding, resin infusion, wet pressing, prepregs, semi-pregs and SMCs; carries dry fibre handling risk for workforce.

Non-woven mats provide an easy way to handle reclaimed fibre as sheet material and can either be processed with liquid resins or converted in to a prepreg material. This therefore makes them suitable for processes such as resin infusion, resin transfer and compression moulding.

Feasibility work has been conducted on using recycled fibre in a non-woven mat form for a flame-retardant epoxy composite. The fibre was a T300 fibre supplied by Toray, which was recycled by ELG before being converted into a 100gsm non-woven mat using a papermaking process at Technical Fibre Products Ltd. The non-woven mats were collated with 200gsm resin film, MTM56-2FRB supplied by Cytec, and compression moulded at 120°C under varying pressure between 2MPa and 14MPa, resulting in various fibre volume fractions ranging from 20% to 40%. To evaluate the mechanical performance of the composite, tensile and flexural tests were performed on at least five specimens of each fibre loading[106], with results shown in Figure 14.

It was established that the non-woven mat was successful in enhancing the tensile and flexural moduli of the composite as the fibre volume fraction increased from 20% through to 40% (Figure 14). However, when analysing the strength, such linear correlation between modulus and fibre content only applied for fibre content up to 30%. Beyond this, strength begins to drop again. The drop in strength was attributed to degradation in fibre length distribution and an increase in composite void content as the fibre content increased.

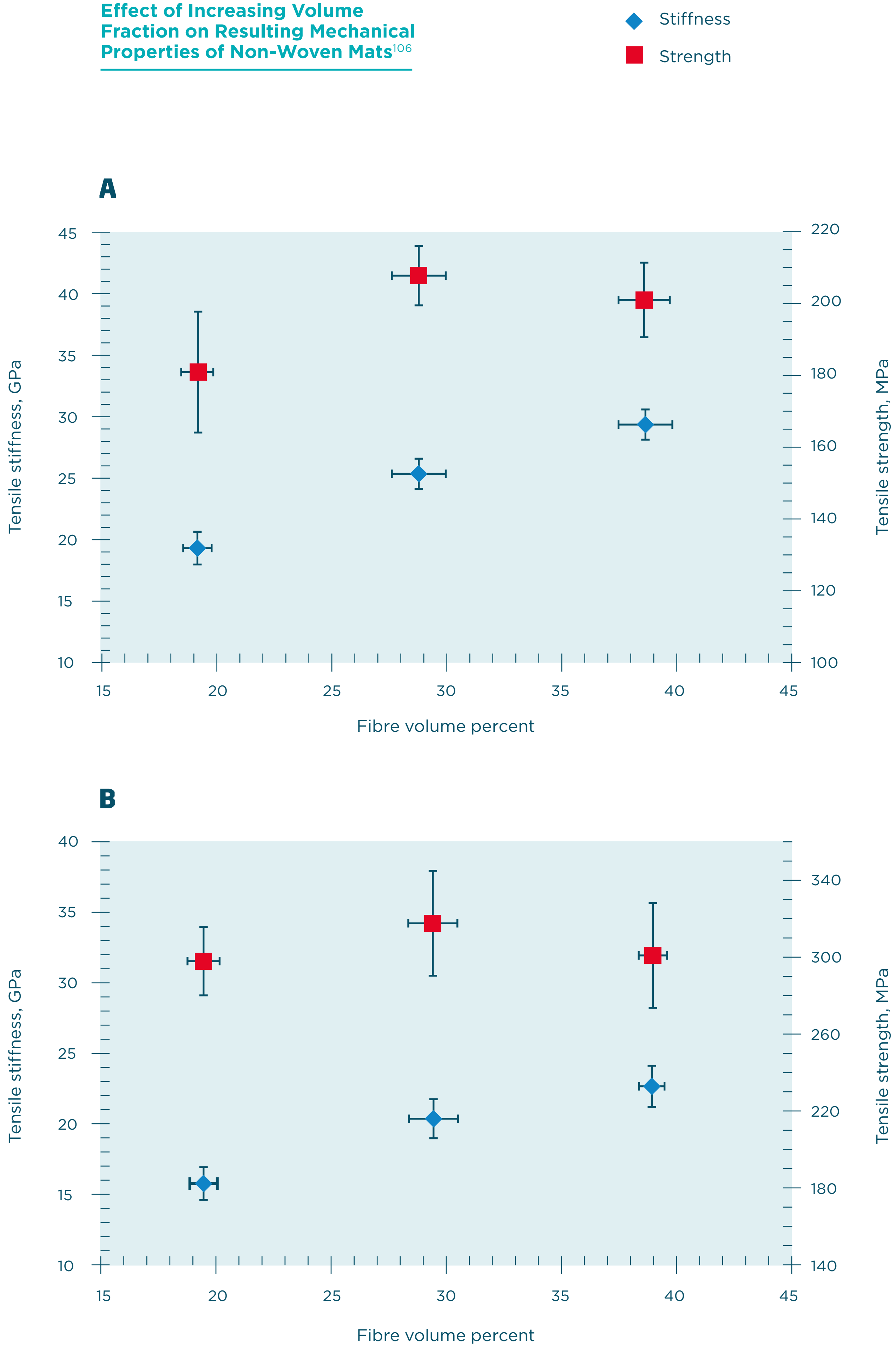
Research has also investigated how to fully utilise the fibre reinforcement potential. It was established that the critical fibre length can be determined from the fibre radius, fibre ultimate tensile strength and composite shear strength respectively[106].

Thermoplastic matrix non-woven materials are also available, such as ELG's CARBISO™ hybrid. In this material, thermoplastic fibres are blended with recycled carbon fibres, creating a mat that is suitable for compression moulding applications.

Fibre alignment

Fibre reclamation typically results in short carbon fibres, making them well suited to direct moulding techniques such as compression moulding of BMC/SMC materials, or non-woven mats. Due to the discontinuity and random orientation of the fibres, these products are typically inferior to the original products from which the materials originated. To improve mechanical performance of recycled fibre composites, high levels of fibre alignment are needed to enable a higher fibre volume fraction. Previous academic research has looked at papermaking techniques and centrifugal alignment[107] of fibres, achieving 80% and 90% alignment levels respectively. One of the most effective to date is the HiPerDiF method[108].

Figure 14.
Effect of Increasing Volume Fraction on Resulting Mechanical Properties of Non-Woven Mats[106]



REUSING THERMOSETS

TRL 8 - about to become commercially available for glass fibre reinforced plastics; moderate cost but very limited number of examples; repurposes blade sections for use in civil engineering and construction; has the lowest environmental impact of all methods reviewed.

Blades can be reused without changing their shape or grinding them. Figure 15 shows the cross-section of a blade that can be repurposed as a whole, for example as a cell tower or as noise barriers along highways and motorways. The blade can also be cut into sections (root, aerofoil sections and shear webs) for use in different applications. The root sections, depending upon the diameter, can be used for quiet pods or storage tanks among many other uses that take advantage of a blade's rounded shape. The shear web is the only flat part on the blade and can be used for various components and even furnishings including window shutters, benches, tables and doors. Profiles of the blade can be used to create complete roof sections and structural features too.

According to the zero-waste hierarchy, reuse of blades (and other composite materials) is the next best option after lifetime extension. Reusing components allows for minimum processing, as the parts only require cutting into the required shapes and sizes, usually with an industrial diamond cutter, such as those used in quarrying. While a number of solutions have been identified and trialled for the reuse and repurposing of wind turbine blades, further development is required to present this as a viable end-of-life strategy. In addition, solutions are very specific to the available size of the blades (solutions for 25m blades are extremely different from reuse solutions for 100m blades). This will continue to be a challenge as blades grow in size.

The **Re-Wind Project** is specifically interested in concepts for reusing blades for different purposes and demonstrating a number of them. One of the first limitations is understanding the overall mechanical properties of blades if they are used as structural components (bridge foundation, roof, electric pole). While wind turbine blades from the same wind farm are expected to have similar mechanical properties, this may not be the case for different wind farms and certainly not for different manufacturers. As a result, this could increase the overall cost of the end product if additional strength testing is required. Another challenge is to develop solutions that can easily be modified or scaled up for larger blades. Furthermore, most of the solutions that have been developed thus far do not offer the scalability required for the bulk demand of the future.

Superuse Studios NL B.V. run multiple projects that repurpose blades as playgrounds, bike sheds, benches and other outdoor installations[109]. There are several other smaller projects and design studios that have utilised blades in the making of benches or other furniture. Depending on the solution, the end value of the product can be higher–in many cases, much higher–than a product made from standard materials (for example, a bookshelf made out of plywood can retail at a lower price than one repurposed from a wind turbine blade section).

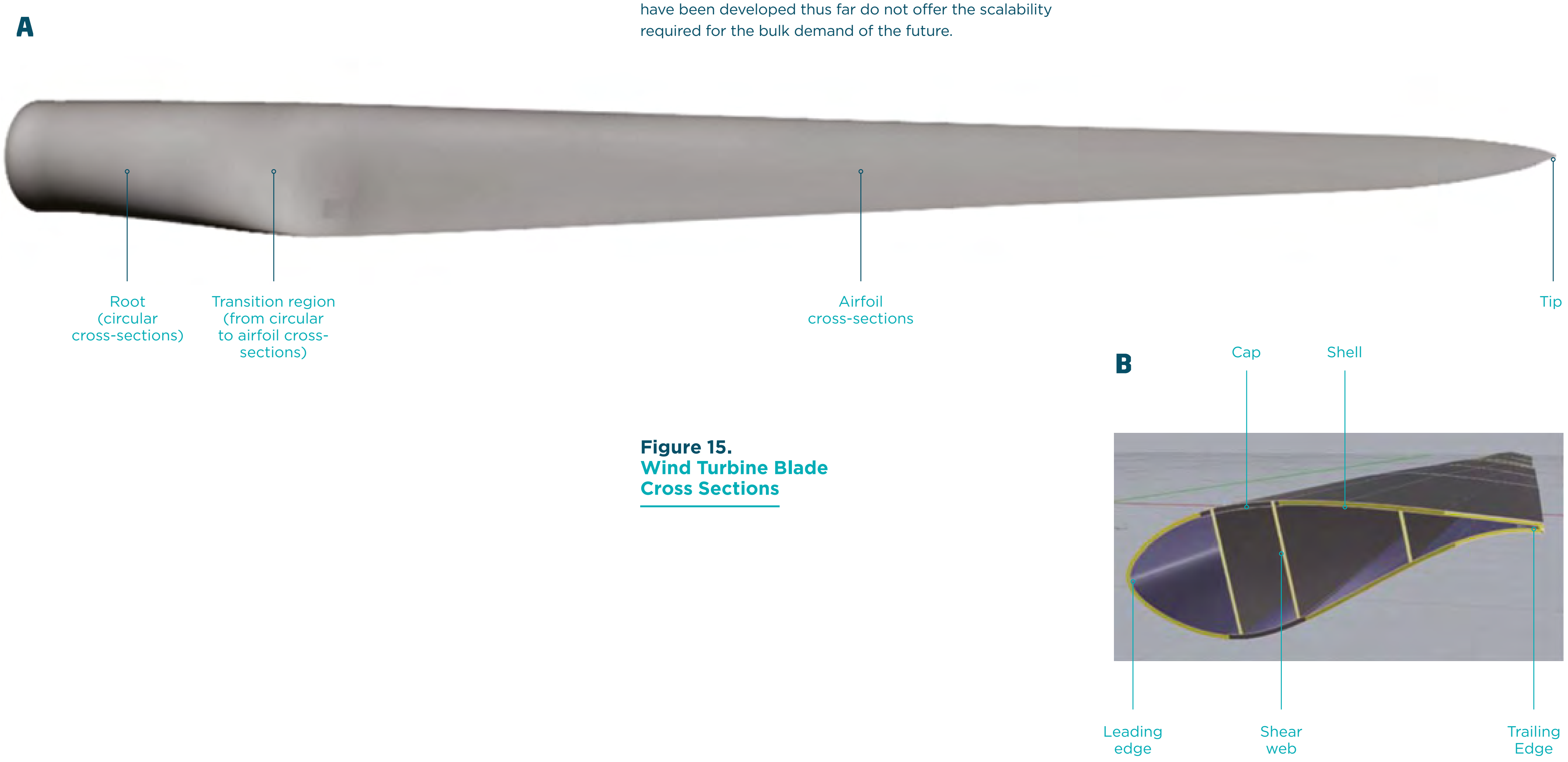
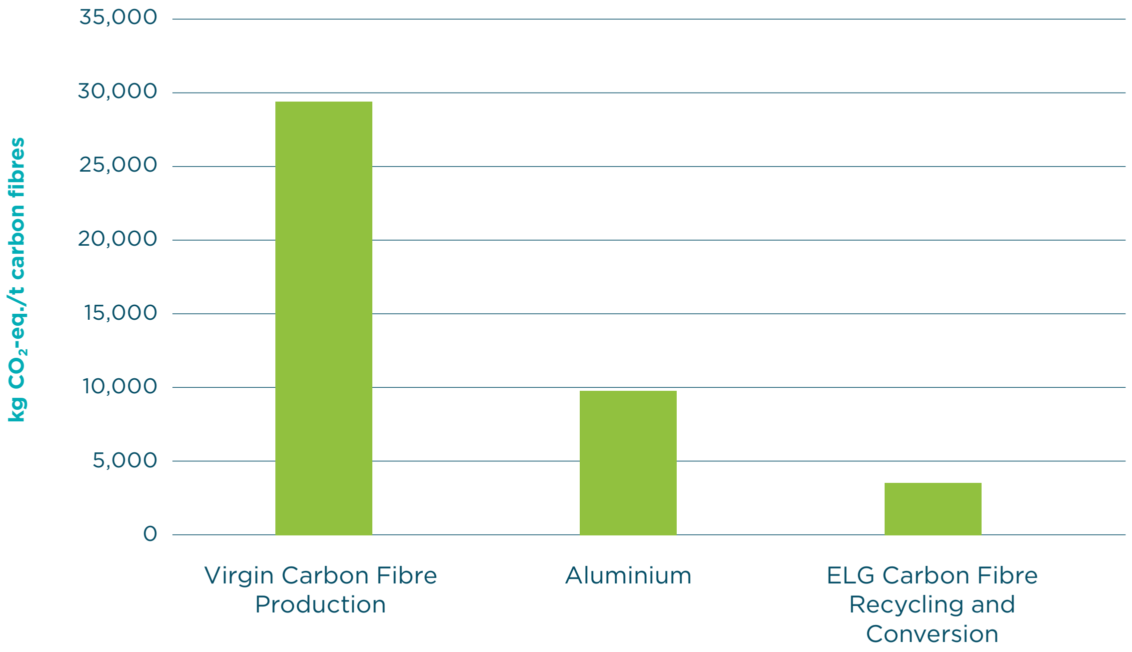


Figure 15.
Wind Turbine Blade Cross Sections

ENVIRONMENTAL IMPACT OF RECYCLING

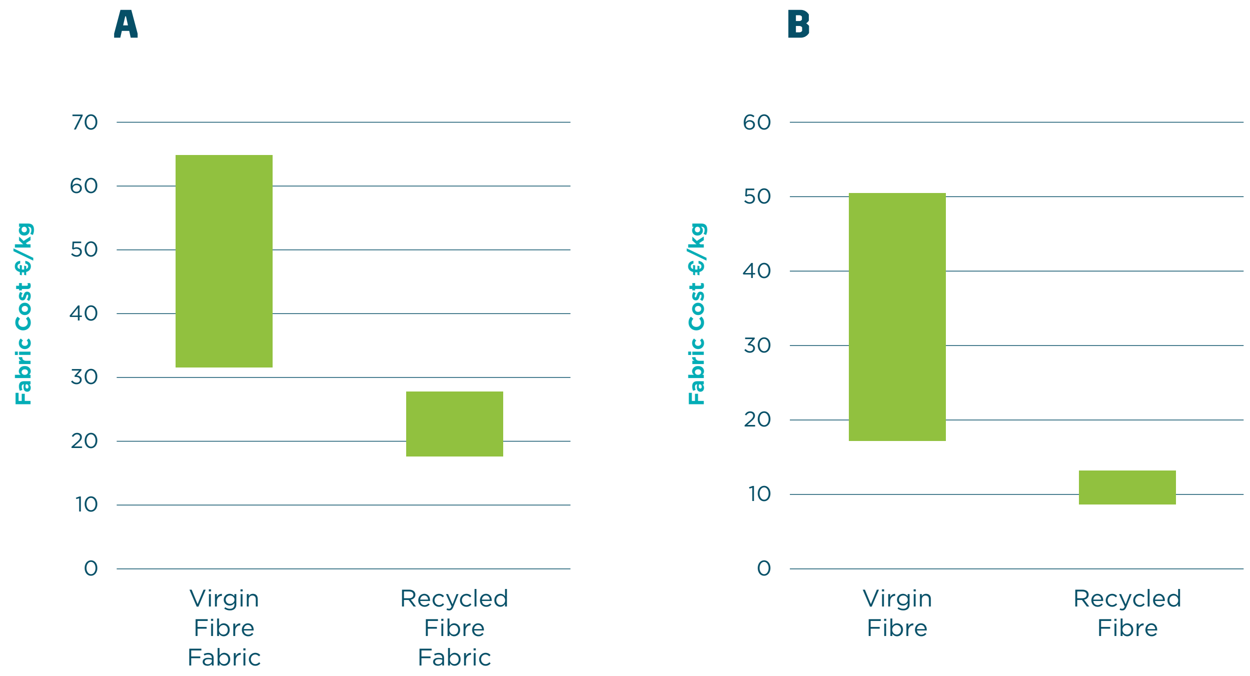


Recycling processes are energy intensive, and therefore impart an environmental impact. It becomes an environmentally viable solution only when the energy demanded is less than that of virgin material production.

Most studies on end-of-life environmental impact focus on carbon fibre reinforced plastic due to its higher economic value and ability to retain properties once recycled. ELG Carbon Fibre Ltd have presented results indicating that, despite the energy demand required for pyrolysis, the Global Warming Potential (GWP) of using recycled carbon fibres is significantly lower in comparison to using virgin carbon fibres (Figure 16). In addition to lowering GWP, utilising recyclate diverts the material away from landfill, and therefore abolishes the need to pay landfill costs as well as reducing the need to consume raw materials.

Figure 16.
Global Warming Potential (GWP) of Recycled Carbon Fibre Compared to Virgin Carbon Fibre[110]

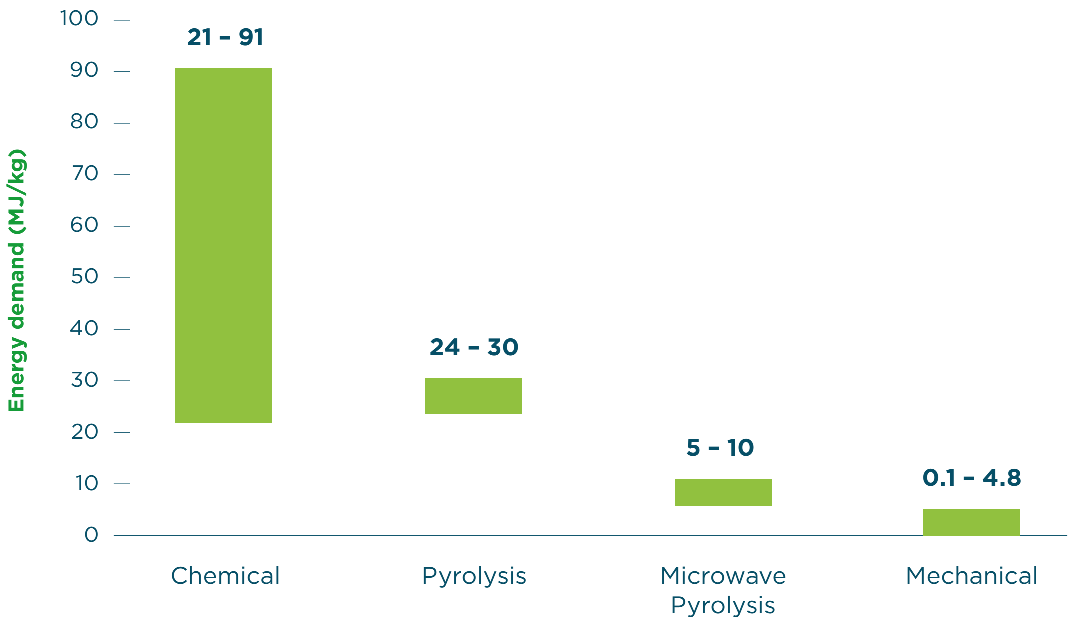
THE LOWER COST OF CARBON, GLASS AND FABRIC RECYCLATES COMPARED TO VIRGIN MATERIAL CEMENTS THE ECONOMIC CASE FOR RECYCLING.



ELG also reports that the recycled material costs less to produce than virgin material. This is the case for both carbon and glass fibres, as well as fabric (Figure 17), demonstrating the economic potential of recyclate if the appropriate applications can be sought.

Figure 17.
Cost Comparison Between Virgin Fibre and Recycled Fibre for a) Fabric and b) Fibres[110]

Figure 18.
Energy Demand (in MJ/kg) for the Predominant Composite Reclamation Technologies[101]



The reported energy demand, and thus environmental impact, of recycling techniques varies widely depending upon their processing conditions (Figure 18)[110]. As illustrated, mechanical processes have been reported to have the lowest energy demand, while solvolysis techniques span the largest range, reaching the highest energy demand. This is due to the high temperatures, and sometimes high-pressure equipment, needed to perform solvolysis. It should be noted that variation in these results will also be influenced by the differences in scale of the studies that produced them[110]. For mechanical grinding, the major contribution comes from energy consumption for powering granulators at room temperature[110,111] and the Primary Energy Demand (PED) can be affected by the processing rate. It was established by Shuaib et al, that higher processing rates led to a more efficient process by displaying lower energy demand/kg/hour[111].

High pressures are not needed for pyrolysis, just high temperature, which is the likely reason for a lower recorded environmental impact than solvolysis (Figure 18). Microwave pyrolysis requires a lower temperature, allowing for a more targeted approach to recycling that takes less time and therefore consumes less energy than other pyrolysis methods.

Khalil (2018) found that solvolysis has a greater human health impact, ecotoxicity and carbon footprint than pyrolysis techniques[112]. However, these results should be handled with caution as in other studies solvolysis has been reported to have the lower environmental impact out of the two. Lee et al, demonstrated that the energy footprint of solvolysis was approximately six times lower than that of pyrolysis, and that the greenhouse gas emissions were five times less[113]. Pyrolysis has also been reported to produce carbon dioxide and methane which contribute to its greenhouse gas emissions.

It is important to note that literature entries for composites recycling are typically 'one offs' for a very specific set of processing parameters and assumptions that are often reported with limited detail. This makes the values generated extremely varied and therefore difficult to translate across different composite products. Furthermore, these results are predominantly focussed upon Primary Energy Demand and there are other environmental impacts that should be assessed through Life Cycle Assessment (LCA), but this research is currently scarce.

Our conclusion is that there remain fundamental challenges in making an accurate Life Cycle Assessment of the techniques discussed, and there will need to be significantly more research in this area before the environmental impact of recycling can be accurately assessed.

THERE REMAIN FUNDAMENTAL CHALLENGES IN MAKING AN ACCURATE LIFE CYCLE ASSESSMENT OF RECYCLING TECHNIQUES AND SIGNIFICANT RESEARCH IS NEEDED INTO THEIR ENVIRONMENTAL IMPACTS.

ACADEMIC RESEARCH

There is a substantial body of research being completed at universities and academic institutions around the world, investigating both the challenge of end-of-life management for fibre reinforced plastics and aimed at creating a circular economy. This section highlights some examples of the ongoing effort in these areas.

THE UNIVERSITY OF STRATHCLYDE

Research on the reuse or recycling of composite materials has been underway at the University of Strathclyde across several disciplines, including Mechanical and Aerospace Engineering, Marine Engineering, Advanced Manufacturing and Materials, and Design Manufacturing & Engineering Management (DMEM). Some examples of these projects are:

Dynamic Hybrid Pyrolysis

Research is currently ongoing into Dynamic Hybrid Pyrolysis which combines the traditional process and principals of a fluidised bed. This unconventional new process aims to separate glass fibres and resin into usable forms for reuse. There is also investigation into the effects of adding a metal catalyst to the thermal recycling of glass fibre reinforced epoxy. A copper oxide (CuO) nano-powder has been integrated with epoxy to assess its ability in reducing thermal stability, in turn reducing the typical temperature required for the thermal recycling process. It was found that the addition of CuO enabled recycling at 400°C with a yield of up to 59%, as it reduces the epoxy matrix decomposition temperature by up to 120°C to produce the same yield without the copper oxide[114].

Remanufacturing Processes

A variety of treatments have been investigated for maintaining or regenerating the strength and surface functionality of recycled glass fibre from decommissioned wind turbine blades. It was found that soaking recycled fibres in a sodium hydroxide (NaOH) solution and silane treatments could restore the interfacial shear strength between the glass fibres and epoxy, increasing the tensile strength of the glass fibre by up to 130%[97].

Recycling Composite Wind Turbine Blade for High-Performance Composite Manufacturing

This project aimed to develop a commercially competitive, cost-effective recycling process for large-scale recycling of wind turbine blades, with a focus on reducing the energy demand of the recycling process, improving the quality of reclaimed fibres, and improving their manufacturability[115].

THE UNIVERSITY OF BRISTOL

The Bristol Composites Institute, created in March 2017, continues to build upon the esteemed reputation of the Advanced Composites Collaboration for Innovation and Science (ACCIS) which was established in 2007. The Institute is a world leader in the field of advanced composites research, covering a wide range of areas, such as structural design and analysis, novel materials development, nanotechnology and biomaterials.

The work is often collaborative in nature, with key relationships and networks established between faculties, universities around the world and major industrial partners. Examples relevant to the current work include the University's partnership with the Offshore Renewable Energy (ORE) Catapult under the Wind Blades Research Hub (and a milestone invention by a Bristol University team of High-Performance Discontinuous Fibres (HiPerDiF).

Wind Blades Research Hub

The **Wind Blades Research Hub (WBRH)** is a £2.3million, five-year research partnership between ORE Catapult and the University of Bristol that aims to help unlock larger, more powerful wind turbines than ever before. The Wind Blade Research Hub's objective is to support turbine blade research that will reduce the cost of wind energy through cost reductions in capital and operational expenditure and increased energy yield, or a combination of these. The WBRH is set up to focus on three key aspects of blade research to achieve this:

- **Enabling 10MW-plus turbine platforms to come to fruition through advances in blade design and structural modelling, reducing blade loads and facilitating the transition to longer, larger blades without losses in operational performance.**
- **Improving the longevity and structural integrity of blades by developing the next generation of materials tailored to operational conditions, preventing degradation and maximising aerodynamic performance.**
- **Maximising operational performance through novel condition monitoring methods which identify blade damage and performance degradation.**

HiPerDiF (High Performance Discontinuous Fibre)

The **HiPerDiF method** has been in development at the University of Bristol since 2012 and has proven to be an effective way of aligning fibres of varying lengths (from 1mm up to 12mm). The current scale-up work is funded by a grant from the European Technology and Innovation Platform on Wind Energy (EPSRC) that was awarded in 2017. The project is examined in more detail in the next section of the report.

THE UNIVERSITY OF NOTTINGHAM

Fluidised Bed Process Development

The Composites Recycling Group at Nottingham University was initiated in the early 1990s in collaboration with car manufacturer Ford to demonstrate the end-of-life compliance of glass and polyester body panels. Although the research themes are applicable to multiple sectors, there is a clear leaning towards aerospace and automotive applications. Led by Professor Stephen Pickering, this group pioneered the development of a fluidised bed recycling process that is capable of processing contaminated and mixed waste from components[116]. This pioneering work led to a major collaboration with Boeing in 2012, with the company investing over USD 3 million into building a commercial scale, fluidised bed pilot plant on the Nottingham campus. The fluidised bed process has now been developed at commercial scale, and the recovered recycled fibres have been demonstrated to be of a desirable reuse quality.

Solvolysis at Atmospheric Pressure and Hydrodynamic Fibre Alignment

While the processes of pyrolysis and fluidised bed have been extensively investigated and developed, oxidation remains a challenge, as it can significantly reduce the fibre's mechanical strength. To overcome this, the group have also investigated alternative processes involving solvolysis at atmospheric pressure to establish if the polymer could be successfully removed from carbon fibre within a short time[117], leaving cleaner individual filaments that lend themselves for manufacture into high-grade applications such as structural reinforcement. While the mechanical properties of the fibre were found to be retained to 90% of their virgin properties, the process is yet to be optimised in terms of the production costs and environmental impact associated with solvents and catalysts used.

A current feasibility study focusses upon an advanced hydrodynamic fibre alignment process[118] that allows composites with high-fibre content to be manufactured at lower moulding pressures and with minimised length degradation. It is possible to achieve high-fibre volume content with competitive mechanical properties at almost 100GPa tensile modulus and over 800MPa tensile. Further work is ongoing to verify this initial outcome.

TARF-LCV: Towards Affordable, Closed-Loop Recyclable Future Low Carbon Vehicle Structures

Led by Brunel University, this **TARF-LCV programme** (2011-2016) brought together a consortium of eight research teams, including the University of Nottingham and 17 other UK academic institutions as well as leading global automotive manufacturing companies. It received £4.2 million funding from the European Technology and Innovation Platform on Wind Energy (EPSRC). The project's main themes included holistic vehicle design and closed-loop recycling of vehicles with focus areas on the development of closed-loop recyclable aluminium (Al) and magnesium (Mg) alloys, metal matrix composites (MMCs) and recyclable polymer matrix composites (PMCs) for body structure and powertrain applications [119 and 110].

Environmental and Economic Assessment of Carbon Fibre Recycling Technologies and Markets

In addition to experimental and computational research in recycling processes, research is also underway on the development of applications for use of recycled carbon fibre and comparative analysis of their environmental and economic viability[120,121].

THE UNIVERSITY OF LEEDS

Offshore wind research at the University of Leeds is characterised by a high degree of interdisciplinarity, whole system approaches and co-production with stakeholders.

Research and Innovation Priorities for Low-carbon Infrastructure Circular Economy

In 2017-2018, a collaboration between the £7 million Resource Recovery from Waste programme, the University's Cities research group and Innovate UK delivered a research and innovation agenda for circular economy and the end-of-use management of low-carbon infrastructure with stakeholders in government and industry as well as research and innovation organisations.

Six low-carbon infrastructure sectors (solar photovoltaics, heat, grid, electric vehicles, onshore and offshore wind) were prioritised and eight cross-cutting issues identified: (1) Value and critical materials; (2) Resource recovery infrastructure; (3) Inventory; (4) Durability; (5) Whole-system analysis; (6) Skills and expertise; (7) Policy, regulation and legislation; and (8) Economics and business models[122].

The results were integrated into ORE Catapult's Offshore Wind Innovation Hub (OWIH) **technology innovation roadmaps**.

Offshore Wind Material Inventory

The £450,000 **Undermining Infrastructure Project** developed a model to analyse the criticality of materials for low-carbon infrastructure, showing that the dynamics of criticality – and less so the actual criticality – are challenging to manage for practitioners, as was demonstrated by an offshore wind case study[123]. This study also demonstrated how the optimal mix of low-carbon infrastructure deployed depends upon the particular technical and social context of a region. One example is that the deployed infrastructure has to match that available for both operations and maintenance (O&M) and end-of-use management[124].

The **Resource Recovery from Waste** programme carried out a study on low-carbon materials in three parts[2]:

1) **The criticality of materials that are required to sustain offshore wind growth ambitions were analysed within the context of materials demand for broader low carbon infrastructure.**

2) **The exact volumes deployed in offshore wind in the UK were inventoried.**

3) **Decommissioning programmes were reviewed and concluded that waste management procedures are unnecessarily underdeveloped, focussed upon the lower regions of the waste hierarchy instead of planning to maximise values, and create high cost uncertainty, with most of these issues rooted in poorly positioned decommissioning legislation.**

Circular Economy and Decommissioning Governance

The University of Leeds is collaborating and engaging with devolved governments and a range of UK government departments. The most notable policy-focussed outputs are:

- **A policy and practice note on the recovery of materials from legacy landfills and closed mines, which are used in the manufacturing of low-carbon infrastructure components.**
- **A framework repositioning circular economy to open up the concept to include the sourcing of materials and the full scope of end-of-use management strategies including the reintegration of materials into natural biogeochemical processes, demonstrated with a case study on steel for offshore wind[125].**
- **A policy brief with Lord John Prescott entitled *Building Future Industries on the Strength of the Humber*[126].**
- **Consultation responses, such as *Offshore renewables decommissioning guidance for industry: proposed updates* (2018), Marine Scotland *Offshore renewables decommissioning guidance* (2020) and the Environmental Audit *Committee's Technological Innovations and Climate Change: Offshore Wind* (2020).**
- **Several workshops, meetings and ad hoc interactions to offer immediate advice to government.**

Integrated Geoscience, Engineering, Materials and Modelling

The University has a combined geoscience, engineering, materials and modelling expertise that can be applied to:

- **Site investigation for substrate and seabed mobility and impact on foundation stability and degradation, including monopile design interaction with seabed, open data system development and the development of repowering strategies.**
- **Material durability and fatigue testing for composites, concrete and steel, test accelerated ageing of small pieces, ageing models to predict lifetimes, and digital image correlation equipment for remote monitoring of turbines and measuring impacts (e.g. of vibrations on turbine components).**
- **Design for reuse and repowering from a geoscience and structural perspective and modular design to enable reuse and repurposing of North Sea oil and gas infrastructure for the energy transition.**

The University is also a global leader in Concrete Science and has the facilities to investigate a variety of applications relevant to blade recycling, such as: the use of mechanically processed blade pieces as alternative aggregates; use of fibres recovered after pyrolysis in concrete; processing blades into synthetic sand replacements (or even smaller particles) as partial synthetic substitutes of cement (i.e. cement co-processing); and thermal treatment using blades as fuel for the production of cements.

This research is augmented by the University's broad offshore wind expertise. Current research into offshore wind is progressing via a project with the Engineering and Physical Sciences Research Council (ESPRC) titled *A Sustainable Circular Economy for Offshore Wind.*

THE UNIVERSITY OF HULL

The University of Hull set up the Aura Consortium in 2015 in order to innovate and collaborate in offshore wind projects covering the full spectrum of technical, operational, economic and societal issues. The Aura brand, which the University leads, has since grown to include: an Aura Innovation Centre (AIC) that aims to turn carbon-reducing business ideas into reality; the Aura Doctoral Training (CDT) which provides funded PhD scholarships in the offshore wind industry; and the Offshore Wind Library (OWL), an online resource for industry-related research.

The University is now partnering with ORE Catapult in its Circular Economy for the Wind Sector (CEWS) joint industry partnership, investigating areas for innovation in the lifetime extension, repowering, end-of-life management and decommissioning of wind farms.

From Textile Waste to Advanced Carbon Materials for Wind Turbine Blade Manufacturing

Carbon fibre reinforced polymers are normally within the 'spar' of a turbine blade, as this is the primary load bearing component and benefits from their high tensile, compression strength, low weight, and anti-corrosion properties. This project has explored the utilisation of textile waste as a raw material for nano-carbon filament production and consequent application as a filler.

The **project** also aims to address the cost efficiency of bulk blade material production and low carbon transitions by optimising waste management and decreasing the volumes of waste sent to landfill[127]. Two modern techniques in nanomaterials manufacturing are being used in combination:

- **Thermal Chemical Vapour Deposition (TCVD) technology, which can produce versatile nanostructured carbon filaments from waste textiles.**
- **And carbon filaments processed by an electrospinning technique that produces nano / microfibrous carbon fibre reinforced plastic.**

INTERNATIONAL INSTITUTIONS

There are many more academic and research institutions around the world currently investigating the challenges of wind turbine decommissioning, composite recycling and the circular economy, notably:

- **DTU (Technical University of Denmark)**
- **Georgia Institute of Technology**
- **City University of New York**
- **University of Tennessee**
- **Technische Universität Dresden**
- **Leibniz University Hannover**
- **Fraunhofer**

INDUSTRY INNOVATION PROGRAMMES

CIRCULAR ECONOMY FOR THE WIND SECTOR JOINT INDUSTRY PROJECT

ORE Catapult's **Circular Economy for the Wind Sector (CEWS) JIP** was established to investigate new solutions for the bulk recycling of wind turbine blades and conduct techno-economic analysis of their suitability for large-scale redeployment. CEWS has targeted an at-scale demonstration of wind turbine blade recycling in the UK within the next five years.

As part of this project, ORE Catapult aims to lead and facilitate the development of industry best practice and the supporting tools for the detailed understanding of true end-of-life potential for pilings, to reduce the environmental and ecological impacts. As well as the reuse, recycling or sustainable disposal of decommissioned offshore wind turbines, CEWS aims to lay the foundations of a new circular economy supply chain for the sector, allowing wind turbine components to be disposed of in the best possible way.

The project will focus on four key areas:

- **Blade Recycling**
- **Cost Strategy**
- **Monopile Remaining Useful Life (RUL)**
- **Recycling Route Map**

A SUSTAINABLE CIRCULAR ECONOMY FOR OFFSHORE WIND

The **project** was initiated in August 2020 and will run up to the end of March 2021. It has a budget of £78,277, co-funded by the Engineering and Physical Sciences Research Council (EPSRC) and the project partners are the ORE Catapult, Department for International Trade (DIT) and the University of Leeds.

This knowledge transfer project aims to start to integrate circular economy into offshore wind infrastructure design, operation and end-of-use management. A series of outputs are being delivered such as industry and government events, policy and practice briefings, and a framework for circular economy in offshore wind and baseline of current circular practices. It also supports knowledge exchange across low-carbon energy, oil & gas and offshore wind sectors, and prepares the ground for a five-year joint industry partnership on circular economy and wind systems. The project's objectives are to:

- **Raise awareness of the added value of circular economy approaches for offshore wind;**
- **Develop strategic responses to the forecasted steeply rising levels of criticality of materials on which offshore wind growth is dependent;**
- **Identify business opportunities and circular business models to increase the sustainability potential of offshore wind.**

SUSWIND

SusWIND was launched in October 2020 and is designed to be a multi-year programme across three waves of activity. Coordinated by the National Composites Centre, the project's launch partners include Vestas, SSE Renewables, the Crown Estate, Shell, BVG Associates, RenewableUK, OGTC and ORE Catapult.

The budget is flexible depending on member contributions with additional funding drawn from the Sustainable Composites Initiative (a partnership between the National Composites Centre and the Centre for Process Innovation - CPI).

SusWIND's goal is to establish a more circular and sustainable future for wind turbine blade technology.

There are three waves of activity:

Wave 1 is designed to stimulate the supply chain for blade recycling and find ways of leveraging the broader supply chain for composites in other sectors. Work packages include landscape mapping, exploitation routes for upscaling viable technologies and demonstration of the effective use of recycled materials in value-add products for other applications.

Wave 2 will demonstrate options to reduce the environmental footprint of blade manufacture through the use of more sustainable and lower impact material feedstock, and through minimising or recycling waste streams.

Wave 3 will develop robust guidelines to improve design for end of life, ensuring waste is minimised and that composite components can be disassembled for cost effective repair, reuse, remanufacture and recycling.

MOONSHOT CIRCULAR WIND FARMS

Launched in August 2020, the **Moonshot project** is funded by the Dutch Ministry of Economic Affairs and Climate Policy. Details of the budget have not been made public. Partners are the main funder together with the Dutch Ministry of Infrastructure and Water Management, VNO-NCW, MVO Nederland and Het Groene Brein.

The aim of the project is to find solutions to preserve critical materials from wind farms in the resource cycle and form a basis for new business cases in wind farm circularity. By transforming the wind industry into a circular driven value chain where the necessary resources can be maximised and more efficiently utilised, the project aligns to the Dutch Government's targets of at least 50% less virgin material usage (minerals, metals, and fossil) by 2030 and no virgin material usage by 2050.

Figure 19.
Design for a Pedestrian/Cyclist Bridge by the Re-Wind Project

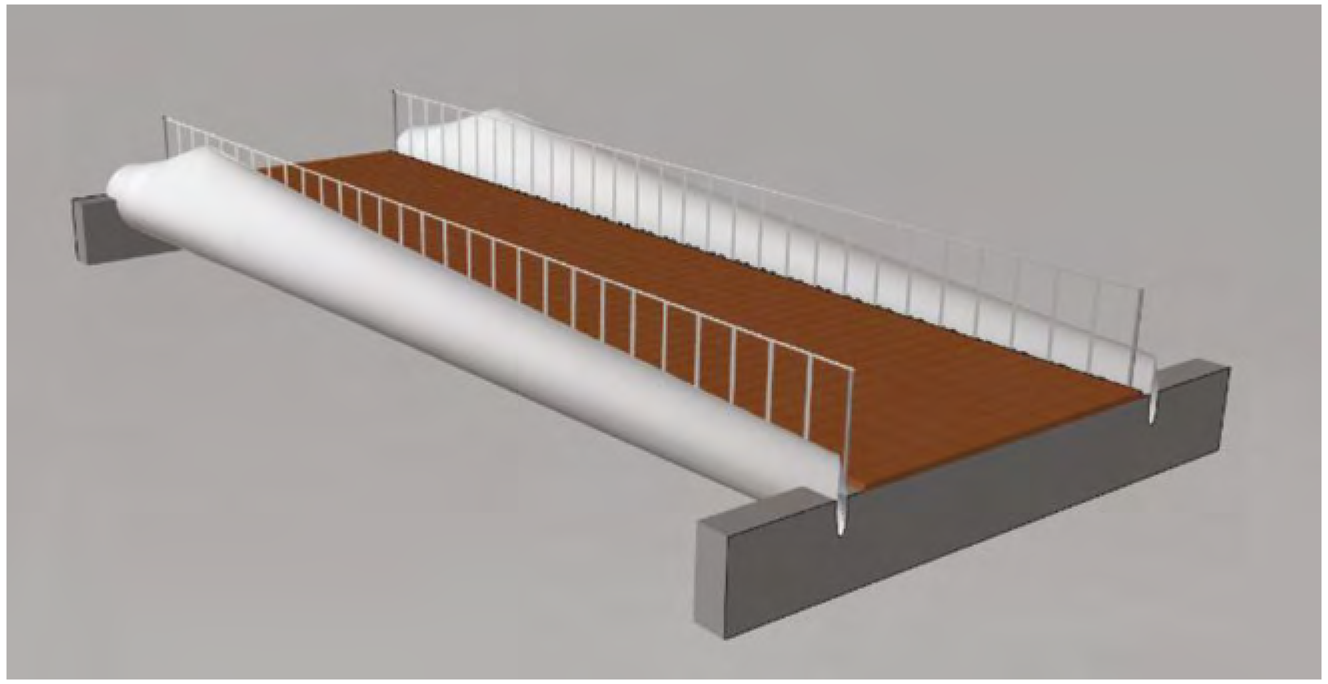


Figure 20.
40m² Housing Constructed with Roof from 100m Blade

RE-WIND

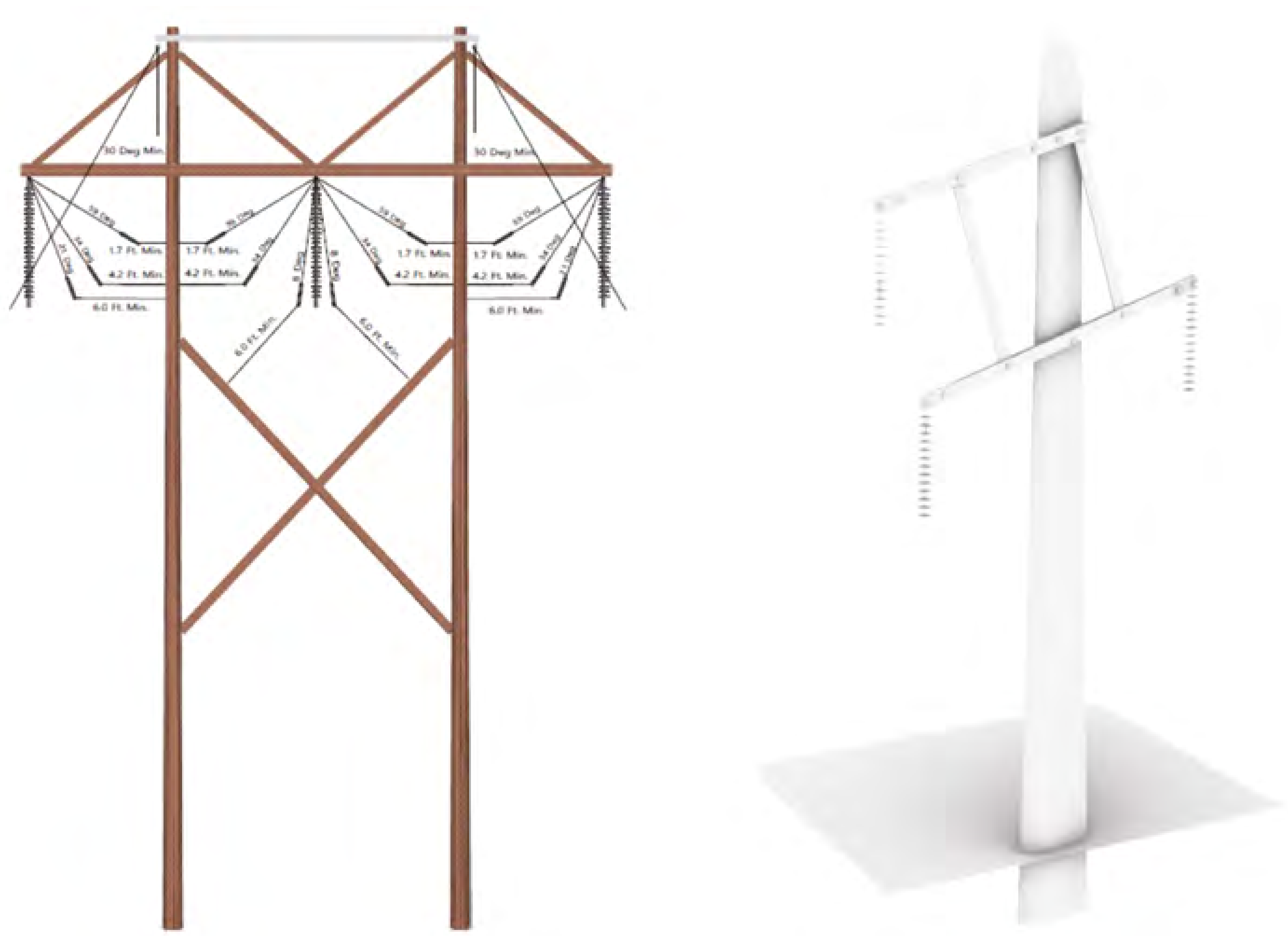
The project's start date was June 2017 and has since been extended beyond its planned 36 months. Work is supported by grants from Invest Northern Ireland (under the Department for the Economy - DFE), Science Foundation Ireland and the US National Science Foundation. Project partners are Georgia Institute of Technology, Queens University Belfast, the City University of New York and University College Cork.

The **Re-Wind project** brings together multiple academics from the USA and Ireland focusing on reuse and recycling of wind turbine blades, with the emphasis being placed upon reuse. The solutions proposed consist of reusing entire fibre reinforced plastic blades (or large parts of them) in new structural applications. Besides identifying reuse opportunities, the project will also model turbine blades to establish their load history and better understand their residual strength and appropriate uses.

The Re-Wind project is currently working with Cork County Council to design a short span pedestrian/cyclist bridge using two decommissioned blade sections (Figure 19). Under an additional project, the consortium has been experimenting with use of large blades in the construction of emergency housing or shelter rooftops (Figure 20). Structural analysis results have been promising: the biggest challenge identified is related to building permissions rather than the blades themselves. There are as yet no government building codes for structures made out of fibre reinforced plastics in this way.

The last type of blade repurposing being investigated by the Re-Wind project is their use as transmission line poles (Figure 21). Static analysis of critical load cases indicate that the blade can easily resist the expected loading, and future project activities will now focus on the experimental validation of the product.

Figure 21.
Design Prototype for Transmission Line Poles Made from Used Wind Turbine Blades



INTERNATIONAL ENERGY AGENCY WIND TASK PROPOSAL

A project proposal has been submitted to IEA Wind for a €54,000 three-year programme that would be led by the Technical University of Denmark (DTU), National Renewable Energy Laboratory (NREL), University College Cork and the University of Leeds. The purpose of the proposed project is to identify and mitigate the barriers to recycling wind turbine blades with a focus on three main areas:

- **The technical aspects of recycling wind turbine blades**
- **Analysis of the recycling value chain and the environmental, social and economic impact**
- **Standards, certification and legislation framing the activities related to recycling wind turbine blades**

Through a structured forum for international collaborations between researchers, industries (wind industries, recyclers, material provider and more) and associations, the project aims to produce recommended practices and guidelines that can be used by practitioners.

HIPERDIF (HIGH PERFORMANCE DISCONTINUOUS FIBRE)

This project initiated in December 2017 and is due to run until June 2021. It received £1,036,426 of funding from the UK Engineering and Physical Sciences Research Council (EPSRC) for a period of three years.

The University of Bristol leads the 10-strong consortium which also includes: Airbus Group, BAE Systems, Coriolis Composites UK, ELG Carbon Fibre, Hexcel Composites, Hitachi, Oxford Advanced Surfaces, Solvay Group (UK) and Toyota.

The **HiPerDiF project** has developed a new process for layup and alignment of carbon fibre tape from recycled waste materials. The process uses a water stream to enable the suspension of fibres, which are then diverted through nozzles into gaps between parallel plates to align them. The number of nozzles and alignment plates can be varied depending on the required width of tape. The fibres then fall onto a conveyor belt where water is removed by suction and the aligned fibre preform is dried using infrared radiation. The dried preform is then coupled with a resin film and partially impregnated through the application of heat and pressure to form a prepreg tape[99]. Aligned mats can also be produced[99].

Previous studies have indicated that the tensile modulus, strength and strain at failure of the aligned material produced by the HiPerDiF process were close to those of continuous virgin carbon fibre, providing a high level of alignment and fibres that meet the critical fibre length. Another benefit of this process is that material can be reprocessed multiple times[99].

STEAM TO VALUE STREAM

Initiated in June 2020, the **project** is funded through the Sustainable Composites Partnership (National Composites Centre and Centre for Process Innovation - CPI) and adds Longworth as a project partner.

Research focusses upon the opportunities for using super-critical steam to reclaim high performance fibres and investigates whether the same process can recover some of the matrix material from glass and carbon fibre reinforced composites.

The DEECOM ® process uses a combination of superheated steam pressure swings or compression/decompression cycles to remove polymer resins and reclaim fibres, maintaining their tensile strength and mechanical performance properties so that they can be reused for remanufacture.

ECOBULK

The project runs from June 2017 to May 2021 using €12 million funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 730456. Partners cover an extensive number of European academic institutions, research bodies and industries.

ECOBULK is, as the name suggests, a large-scale demonstration project. The preliminary demonstration spans a total of seven EU-countries, comprising 11 demonstrators that will conduct 21 individual demonstrations within the three target product sectors: automotive, furniture (indoor/outdoor) and construction.

One of the demonstrations is recycled glass fibre reinforced polymers from wind turbine blades, the first thermoplastic composite to incorporate it as a reinforcing material. Below is a summary of the demonstration products and activities:

1. **Design and manufacture of easy-to-replace and refurbished internal car parts from recycled plastics**
2. **Development of new resins for particle board furniture with lower formaldehyde concentration**
3. **Production of weather resistant extruded composite components for outdoor benches and tables from recycled plastics and waste wood fibres**
4. **And use of wind turbine blade composites to create extruded composite profiles and panels for structural applications (various type of shelters and cabins)**

The consortium members are: VERTECH GROUP (VTG), Polytechnic University of Catalonia, Spanish Association for Standardisation, Delft Technical University, TOMRA, TECNARO, ITENE, Next Technology, Microcab, MAIER, Intermunicipal Waste Management of Greater Porto (LIPOR), Kneia, Kastamonu Entegre (KEAS), International Solid Waste Association (ISWA), IRIS, Italian National Research Council (CNR), Exergy, Granta Design, Moretti Compact, French Institute of Technology for the Forest-based and Furniture Sectors (FCBA), Research Center Fiat, Cranfield University, Conenor, Coventive Composites, Aimplas, AkzoNobel, BELLVER PLA GROUP, Oakdene Hollins and Technoplants.

EURECOMP

The **EURECOMP project** ran from May 2009 to July 2012 with an overall budget of €2.5 million including an EU contribution of almost €2 million. The aim was to develop a route for recycling fibre-reinforced thermoset composites and commercialise recycled components from cars and boats. During the project, a prototype of a solvolysis reactor was developed (4ml to 1,000ml reactor capacity) and the parameters were studied (temperature, processing time, pressure, chemical to composite ratio, etc). The first results showed that solvolysis allows the removal of up to 90% of resin and retrieval of liquids, such as benzoic acid, that have a commercial application.

The second phase of the project built a large scale solvolysis reactor with a capacity of 20 litres. Recovered fibres maintained 60% of the maximum mechanical performance of virgin fibres. They were reprocessed into a prototype of an electrical box using 20% recycled content and 80% new fibres which was proven to achieve the required mechanical performance. However, truck parts that were manufactured from 20% recycled fibres showed degradation of material following mechanical testing.

The project's partner organisations were: WindEurope, Cefic and EuCIA, British Plastics Federation, Plastic Omnium Auto Exterieur, University of Exeter, Volvo Technology Corporation, University of Bristol, Xietong Automobile Accessories, COMPOSITEC, SACMO, ECRC (European Composites Recycling Services Company), URIARTE Safybox, ICAM Nantes, GAIKER and the University of Limerick.

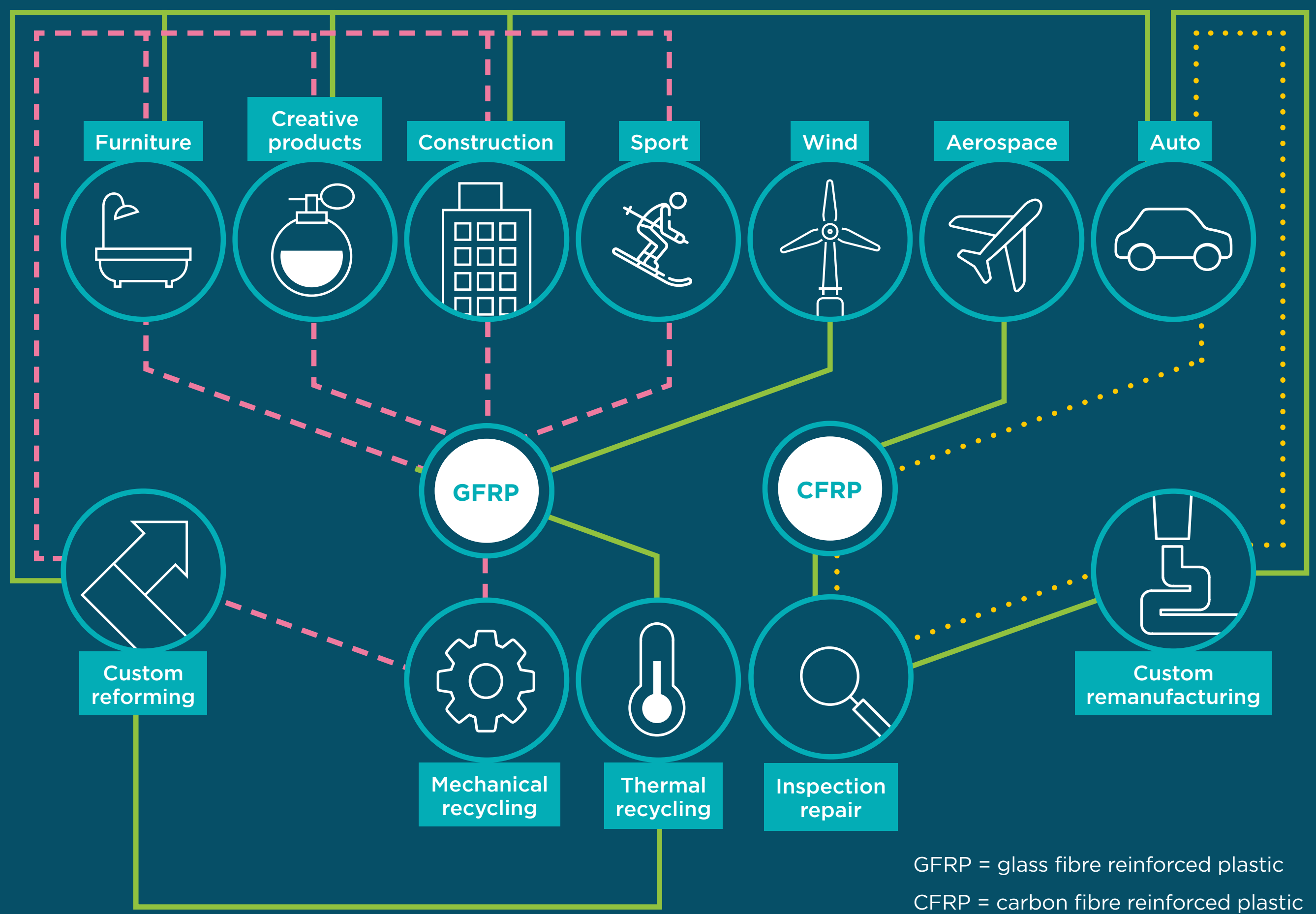
FIBEREUSE

This **€9.8 million research project** funded by the European Union (GA No. H2020-730323-1) has been running since June 2017. It aims to enhance the profitability of recycled glass and carbon fibre and their reuse in value-added products by holistically integrating different innovative solutions. Three macro use-cases are fuelling eight demonstrators:

1. **Macro use-case 1** (represented by the pink stream in Figure 22) is the mechanical recycling of short glass fibre reinforced plastics and reuse in added-value customised applications such as furniture, sport and creative products. It includes demonstration of manufacturing technologies such as UV-assisted 3D-printing and metallisation by physical vapour deposition.
2. **Macro use-case 2** (represented by the green stream) is thermal recycling, via controlled pyrolysis, of long glass and carbon fibres from end-of-life wind turbine and aerospace components for reuse in high-tech, high-resistance applications in the automotive (aesthetical and structural components) and building sectors via custom remanufacturing methods.
3. **Macro use-case 3** (represented by the yellow stream) is the inspection, repair and remanufacturing of carbon fibre reinforced products in high-tech applications with adaptive design and manufacturing for a complete circular economy demonstration in the automotive industry.

The project partners are drawn from seven EU countries and include: the University of Strathclyde, Novellini, Tecnalia, Siemens Gamesa, Batz, Maier, Aernnova, Fraunhofer, Edag, Invent, Avk, Tampere University of Technology, Head, Saubermacher, Design Austria, Politecnico Milano, Rivierasca, Holonix and GreenCoat.

Figure 22.
FiberEUse use-cases and industrial sectors involved[128]



GFRP = glass fibre reinforced plastic
CFRP = carbon fibre reinforced plastic

LIFE-BRIO

LIFE-BRIO brought together Iberdrola, Gaiker-Ik4 and Tecnalia and ran from July 2014 to June 2017 with a total budget of €1,107,626, including EU funding of €553,812. The project investigated and demonstrated sustainable end-of-life methodology for each stage of blade decommissioning, including rotor blade dismantling, material resources recovery and incorporation of recovered materials into new products.

Foams and supports were separated from the main composite content before going through mechanical recycling (shredding) for a combination of long fibres and short fibres with polymer. After separation of the two, the long fibres could be used as filler material in precast concrete, while the shorter fibres could be used as cores for multilayer structures.

Blades were supplied through the decommissioning of Coal Clough Wind Farm in the UK (24 Vestas WD34 turbines): 5.6% of the blade's composition was metallic and was provided for smelting, 43.9% of the blades structure was recycled as reinforcement in concrete, and 50.5% (short fibres and polymer) was used to make thermoset and thermoplastic multilayer panels[129]. All the resulting products had their performance tested. The concrete's performance showed improvement while reducing the use of both concrete and aggregates and without altering the manufacturing process. The panels showed a similar mechanical performance to panels made of non-recycled materials.

The project also offered guidelines for more specific regulation regarding wind turbine decommissioning.

GENVIND PROJECT

The **GenVind project** ran from June 2013 to November 2016 with funding of DKK 43.5 million (just over €5 million in today's values), including a grant from the Danish Agency for Science, Technology and Innovation. The 25 consortium members included Danish companies in the wind turbine industry, the building sector and the colour/lacquer industry: Technical University of Denmark (DTU), Aalborg University Esbjerg, University of Nottingham, Danish Technological Institute, and FORCE Technology as well as the Danish Plastics Federation.

The goal of the project was to identify new strategies for sustainable recycling of composites and develop existing ones. The consortium also aimed to develop enabling technologies for a sustainable recycling of plastic composites and demonstrate that waste can be used in many different products, components and structures. Products that were manufactured from waste plastic composites were furniture, building panels, noise barriers, new wind turbine blades, paints, textiles, fibre reinforced concrete, mortar and brick, stronger concrete and plastic constructions.

REROBALSA

The **project** ran from August 2017 to June 2019 with funding from the German Federal Ministry of Education and Research (BMBF). It was coordinated by Fraunhofer Wilhelm-Klauditz-Institut, and other partners included the Technische Hochschule Nürnberg (Nuremberg Tech), MATETEC, Kovalex GmbH, BINOS GmbH, Sachverständigenbüro Otto Lutz, Mau und Mittelmann GmbH, Airex AG, 3A Composites Core Materials, Schweiz, rub Berlin – Gesellschaft für Recycling and Umwelt und Biotechnologie GmbH.

The main objective of this research project was the development of an innovative recycling technology for the recovery of balsa wood and plastic foam from rotor blades. It also developed innovative recycling technologies for use of recyclates in insulation and building materials.

Key outputs included: reuse of balsa wood during wind turbine dismantling at location; ultra-lightweight wood fibre insulation mats; and extruded floorboards mode from wood polymer composites (WPC).

DECOMTOOLS

DecomTools has run since December 2018 with €4.7 million funding from EU's Interreg North Sea Region Programme. It formed part of a whole system investigation into end-of-life management of offshore wind farms. The aim was to devise and develop eco-innovative concepts that would reduce decommissioning costs by 20% and environmental footprint by 25% (measured in CO_2 equivalents) while increasing the know-how and expertise of stakeholders.

The thirteen European partners include: Hamburg Institute of International Economics (HWWI), University of Applied Sciences (UAS), FYNS Maritime Klynge, New Energy Coalition, Western Norway University of Applied Sciences, Port of Grenaa (Denmark), POM, De Lavwershorst Groep, Samso Kommune, University of Aberdeen, Port Oostende, Energy Innovation Cluster and Virol.

SPARTA

The **SPARTA project** runs for two years and launched in September 2020 with funding of €349,542 from the EU's Horizon 2020 programme. It is led by the Technological Institute of Plastics (AIMPLAS) and the Tekniker Research and Technology Centre.

The objectives are to find more efficient methods of recycling and reprocessing composite thermoplastic materials and to design more eco-efficient manufacturing methods. The project includes development and optimisation of an innovative mechanical scrapping process and attempts at improving material reprocessing through automatic deposition and compression moulding.

This method will make it possible to use up to 80% of current aerospace waste compared to other mechanical recycling methods and cut processing times by as much as 50%. This will be achieved by reducing the number of steps in waste recovery, using more efficient automatic reprocessing methods, reducing CO^2 emissions up to 30% through the use of waste and curb production demand for virgin material.

ELIOT

ELIOT launched in July 2020 and will run for a duration of 32 months with funding from the EU's Horizon 2020 programme. Partners are AIMPLAS and TNO (Dutch Organisation for Applied Scientific Research). Research is aimed at developing novel cost-effective recycling technologies that will guarantee the sustainability of aeronautics components. Different recycling methods are being analysed, including mechanical, thermal, chemical and biological recycling.

DREAMWIND

Dreamwind ran until March 2020 under a grant of DKK 17.6 million (€2.3 million equivalent) from the Innovation Fund Denmark. Partners were Aarhus University, Danish Technological Institute and Vestas Wind Systems.

Researchers developed a chemical to enable the separation of composite materials within wind turbine blades, allowing for easier recycling opportunities. The separated glass and carbon fibres can then be cleaned and reused in the manufacture of new components. Possible reuses have been highlighted within the wind, automotive and aerospace industries.

RECY-COMPOSITE

The **project** was initiated January 2016 and ran until September 2020 with a budget of €3,180,556 (including €1,590,278 from the European Regional Development Fund under the "Interreg V-A-Belgium-France (France-Wallonie-Vlaanderen)" Operational Programme for 2014-2020 [130]. The project partners were Certech, Crepim, VCK-Centexbel, CTP and Mines de Douai – Armines.

The project was set up meet the challenge of composite materials recycling through a three-level, cross-border approach that comprised:

1. **Material recovery**
2. **Thermochemical recycling (pyrolysis, solvolysis)**
3. **And energy recovery (only as a last resort)**

ETIPWIND

The European Technology and Innovation Platform on Wind Energy (ETIPWind) is funded by the EU's Horizon 2020 programme and was originally established in 2016 to inform research and innovation policy at both a European and national level. ETIPWind activities combine two prior initiatives: the European Wind Energy Technology Platform and the European Wind Industry Initiative. By providing a public platform for wind industry stakeholders to identify common research and innovation priorities, ETIPWind fosters breakthrough innovations in the sector and communicates these to European institutions and decision-making bodies in order to support progress to a decarbonised economy by 2050.

ETIPWind also contributes to the European Strategic Energy Technology Plan (SET-Plan), an initiative that aims to accelerate the development and deployment of low-carbon technologies by coordinating national research efforts and helping finance projects. The SET-Plan promotes research and innovation efforts across Europe and supports the most impactful technologies for the transformation to a low-carbon energy system. The role of ETIPWind is to give recommendations to policymakers on how to improve new technologies and reduce costs. This includes an energy road map[131] and strategic research into wind turbine blade circularity[6].

CARBO4POWER

Carbo4Power is a four-year project that is funded by the EU's Horizon 2020 programme. Led by the National Technical University of Athens (NTUA), it comprises a network of academic and industrial partners drawn from across Europe, including ORE Catapult.

Carbo4Power will develop a new generation of lightweight, high-strength, multifunctional, digitalised multi-materials for offshore wind and tidal turbine rotor blades that will increase their operational performance and durability while reducing the cost of energy production (below 10ct€/kWh for wind turbines and 15ct€/kWh for tidal), cost of maintenance and their environmental impact. The innovative concept is based on nano-engineered hybrid (multi)materials and their intelligent architectures.

The project foresees the following results:

1. **Nanocomposites based on dynamic thermosets with inherent recyclability and repairability and tailored nano-reinforcements to enhance mechanical properties.**
2. **Multifunctional nano-enabled coatings to improve turbine protection (e.g., against lightning and biofouling).**
3. **Blade segments that will be designed and fabricated by advanced net-shape automated multi-material composite technologies that will allow ca. 20% scrap reduction.**
4. **An innovative design of modular rotor blade and an optimal design for 'one-shot' manufacture.**
5. **Increased recycling of blade materials by up to 95% due to the advanced functionalities of 3R resins and adhesives with debonding on demand properties.**

ZEBRA (ZERO WASTE BLADE RESEARCH)

ZEBRA launched in September 2020 and will run for a period of 42 months under a €18.5 million budget. Its aim is to design and manufacture the world's first 100% recyclable wind turbine blade[132] and to demonstrate a full-scale, technical, economic and environmental thermoplastic wind turbine blade, eco-designed to facilitate recycling.

The project has representation from across the full value chain, including the development of materials, blade manufacturing, wind turbine operation and decommissioning, and recycling of the decommissioned blade material. Project partners are: Arkema, Engie, LM Wind Power, Owens Corning, SUEZ, CANOE and the Jules Verne Institute for Technological Research (IRT).

SURFACE

This project is currently under proposal. The grant application is to the Mission-driven Research, Development and Innovation subsidy scheme (MOOI) subsidy scheme. The coordinating partner of a 23-strong consortium is TNO (Dutch Organisation for Applied Scientific Research).

The aim is development of a cost-effective and sustainable end-of-life solution for fibre-reinforced composite wind turbine blades using pyrolysis to extract carbon and glass fibres for reuse. The project will research the capability of processing large blade sections and longer fibre lengths (2m+).

FIBROUS

The project was initiated by TNO, the Dutch Organisation for Applied Scientific Research, in 2020. The current budget is unknown, but it submitted for additional funding to the HER+ subsidy programme at the end of 2020. The objective is the development of a cost-effective and sustainable end-of-life solution for fibre-reinforced composite wind turbines blades used at offshore wind farms.

The chosen recycling technology is pyrolysis because of its high maturity level and the ability to extract carbon and glass fibres from the blades for reuse. This technology will be developed for processing large blade sections and large fibre length (2m+). The end product cost will be optimised to meet Europe's rapidly growing need for sustainable circular solutions for the volumes of wind turbine blades reaching the end of their useful life.

The partner organisations are Fairphone, Appletree, Enerpy, Virol, ITRI, Port of Amsterdam, Groningen Seaport, Shell, Amsterdam Ijmuiden offshore ports and Suzlon.

DEMACQ RECYCLING INTERNATIONAL

This project was initiated in September 2016 and there is little public information on its continued activity (which ceases after 2019). The budget is unknown as it appears to have been a commercial venture launched by Demacq in partnership with NWEA and DWP System Supplier.

The work was based upon Demacq Recycling International's breakthrough in finding a way to dismantle large composites in a sustainable way and give them a new use, such as in shore protection.

GEOCYCLE BY LAFARGEHOLCIM

Launched in 2017 by LafargeHolcim, **Geocycle** is now a global commercial enterprise. Its key achievement is the development of a process for a sustainable recycling of used rotor blades. The service starts with a first cut and collection of rotor blades at a wind turbine site, complete incorporation of rotor blade ashes into the clinker matrix (material recovery) as well as use of the thermal energy content of the blades (thermal recovery). In this way, it saves natural resources by substituting primary raw materials (like sand) and fossil fuels.

To avoid the need for transport with special permits, a mobile cutting technique, similar to concrete dismantling procedures, breaks down large-scale components into smaller fragments on site or the intermediate storage areas. The humidification of the cutting location secures a maximum reduction of generated dust. The sawdust is then collected and returned to the material flow of the treatment plant. After this preparatory step, the fragments are shipped in lengths of 10m to a recycling plant in Melbeck.

Automated saws cut the turbine blades into pieces of about 1m in length. Shredder units then crush the components in an encapsulated system into pieces less than 50mm long. The thermal energy content of the waste stream is used as a fuel substitution at around 900°C for the calcination process of raw material. The accrued ashes are then combined with the calcinated raw materials in the sintering zone of the cement kiln. Finally, the clinker is ground together with a small amount of gypsum to make the cement.

UNIVERSITY OF TENNESSEE BLADE RECYCLING PROGRAMME

In September 2020, the University won USD 1.1 million of funding from the Department of Energy (DOE) Small Business Technology Transfer (STTR) programme and Wind Energy Technologies Office.

The **programme** aims to develop a new technology for large-scale recycling of wind turbine blades into new recycled composites. This will be a pilot-scale glass fibre composite recycling system that will serve as the basis for the deployment of a full-scale commercial wind blade waste processing plant to recover both the glass fibre for recycling into new composite applications and the organic components which can be turned into useful petrochemicals for energy production.

The participating companies are: Carbon Rivers, a start-up company owned by Tennessee University alumnus Bowie Benson; GE Renewable Energy; Berkshire Hathaway Energy's MidAmerican Energy Company and PacifiCorp utilities.

SER

Under **SER**, the European wind industry has been engaged in dialogue with other stakeholders to reach an international Responsible Business Conduct agreement for the wind sector, which they aim to sign before summer 2021. The dialogue concerns not only composites, but the entire value chain of the wind industry.

The industry's goal is to identify, prevent and address risks to people and the environment across the entire supply chain, from risks related to the extraction of raw materials for wind turbines through to the decommissioning of wind farms.

The intention is to commit the parties to implementing the Organisation for Economic Cooperation and Development's Guidelines for Multinational Enterprises and the UN's Guiding Principles on Business and Human Rights (UNGPs) in their operations and throughout their supply chains.

At this stage, they will explore how to identify and address the risks for people and the environment in the supply chain of the wind energy sector before offering shared solutions to address problems that companies cannot solve entirely by themselves. To increase their leverage, organisations will actively pursue collaboration with international initiatives that share their goals.

Partners are WindEurope, NWEA, NVDE, TKI Wind op Zee, Eneco, Engie, RWE Renewables, Ørsted, Vattenfall, ENERCON, MHI Vestas Offshore, Siemens Gamesa, Van Oord, Action Aid, the North Sea Foundation, FNV, the Dutch ministries of Foreign Affairs and Economic Affairs and Climate Policy, Pels Rijcken and the SOMO knowledge centre.

RECOMMENDATIONS AND NEXT STEPS

CONCLUSION 1

Carbon fibre recycling at scale will pave the way for advances in glass fibre recycling.

Our view is that carbon fibre recycling at scale for wind turbine blades will be feasible within five years. ORE Catapult's Circular Economy for the Wind Sector Joint Industry Project JIP (CEWS JIP) is working towards this target.

There are two provisos:

- **Investment in R&D must be increased to drive down costs and environmental impacts**
- **The demonstration system must receive a steady and consistent flow of blades**

CONCLUSION 2

The approach to R&D needs to shift to focus on the supply chain that will produce the end products rather than the production of recyclates with no clear destination.

We have discussed the definition of 'recycling' and ambiguities in its use by UK regulatory bodies. Some count recycling as the recovery of a material, even if that material does not go on to be used in an end product. We recommend adopting the more precise definition that recycling must result in a usable end product for it to be both environmentally and economically meaningful. Only by recyclates replacing the deployment of new virgin materials, and by delaying disposal, can environmental impact be mitigated. Likewise, the chance to increase job creation depends upon achieving viable end products from recycling.

If ORE Catapult is to achieve its target of an at-scale blade recycling demonstration within five years, co-ordination is required with the many composite recycling projects that are underway across the world. As our review of the current R&D landscape makes clear, the focus to date has been on producing recyclates without matching these recovered materials to the supply chain needs and ultimate products. Phases 2 and 3 of the Energy Transition Alliance Project and the CEWS JIP will focus on stimulating the future supply chain for recyclates.

A further imperative is to raise awareness of the circular economy business opportunity amongst UK supply chains and policymakers. As highlighted earlier, the opportunity goes beyond the recycling of composites: it spans various remanufacturing and reprocessing solutions for every wind turbine component. Investment now presents a golden opportunity to not just support the sector's job creation targets by 2030, but also to extend them by an estimated 20,000 jobs.

CONCLUSION 3

Wind turbine blade recycling will only be achieved by leveraging the diversity of active R&D projects on composites across different sectors.

The study has highlighted 28 major collaborative R&D projects focusing on carbon and/or glass fibre composites and numerous in-house recycling drives by the most prominent players in industries such as aerospace and automotive. The wind sector is increasingly adding its considerable weight behind the development of composite recycling technologies: 2020 became a landmark year for the launch of projects specifically on wind turbine blade recycling.

We recommend that the focus is on cross-sector collaboration and finding synergies between the many disparate composite recycling projects summarised in the full report. Collaboration with the oil and gas industry, in particular, will be essential in bringing in the necessary scale of investment and prove crucial to finding good recycling solutions.

NEXT STEPS

From an economic perspective, we have a confluence of recycling technologies on the cusp of commercial viability and an urgent requirement by industry. Composite recycling can be seen as the first step towards creating an advanced circular economy that will serve UK industries and yield exportable IP, services, skills and technologies.

The wind industry can play a central role in the UK realising these economic benefits: it is the composite user that has the fastest future growth pathway thanks to its criticality for the energy transition. Our study shows that the wind industry cannot solve the composites challenge alone, however, and the collaborative cross-sector nature of many of the projects studied illustrate this point.

While that is the wind industry's ambition, the sector with the strongest track record on tackling composite recycling to date has been automotive. A great deal of the stimulus has come from EU directives that have legislated environmental assessments and impact analysis. A similar situation is developing for the wind sector. Several agencies are now working to investigate and develop similar guidance, best practice and industry standards for end-of-life wind turbine blades. We can anticipate these standards being brought into local, European, and potentially international regulations in the future.

It must be recognised that reclamation and reprocessing of recyclates from blade materials must also be a financially attractive option for the wind industry to ensure rapid adoption. That is why the next phase of the Energy Transition Alliance's Blade Recycling Project, of which this report is just the first phase, will focus upon the environmental, social, economic and technical costs and benefits of blade recycling. In Phase 3, we will take forward the most promising technologies for development and demonstration.

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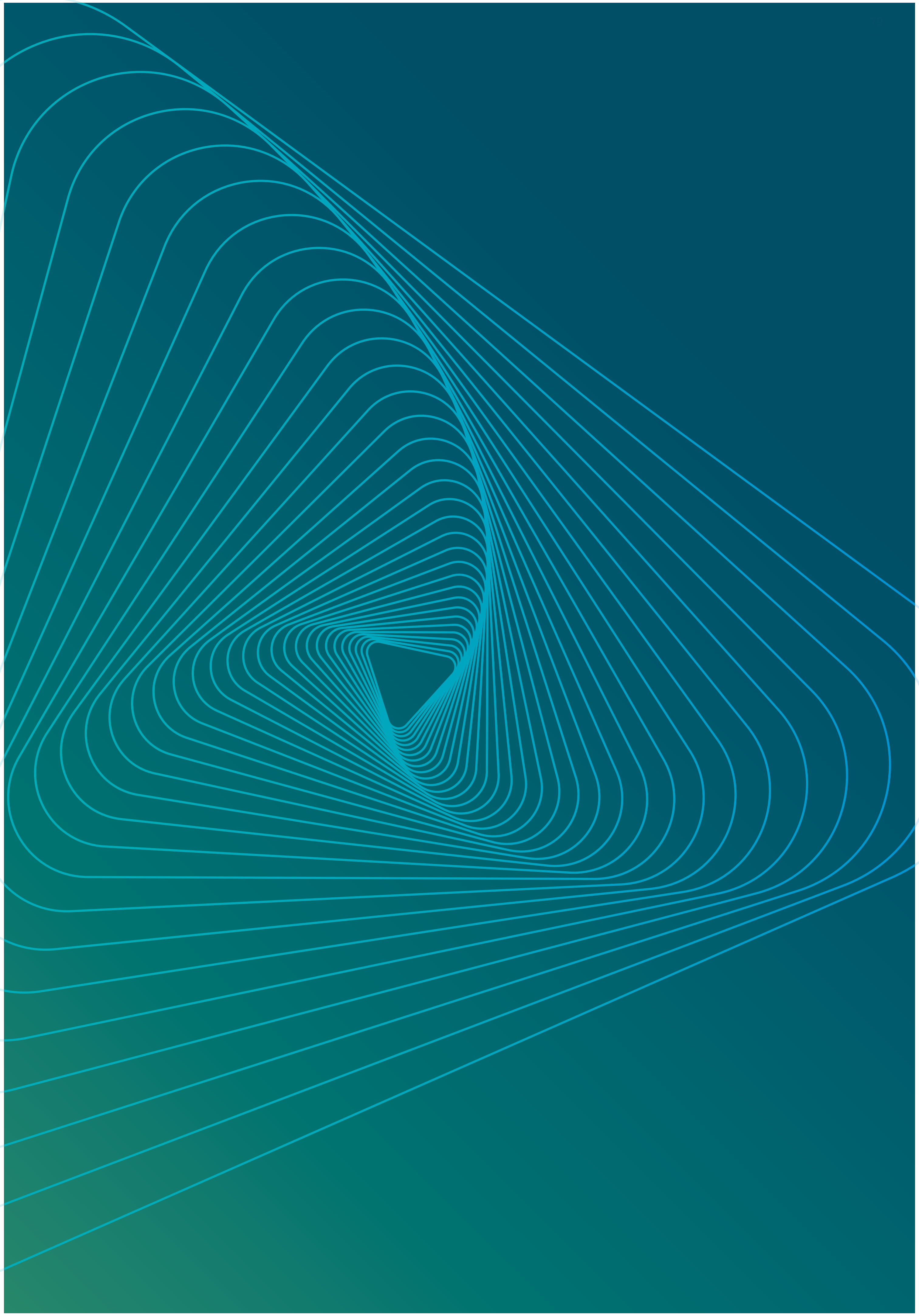

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